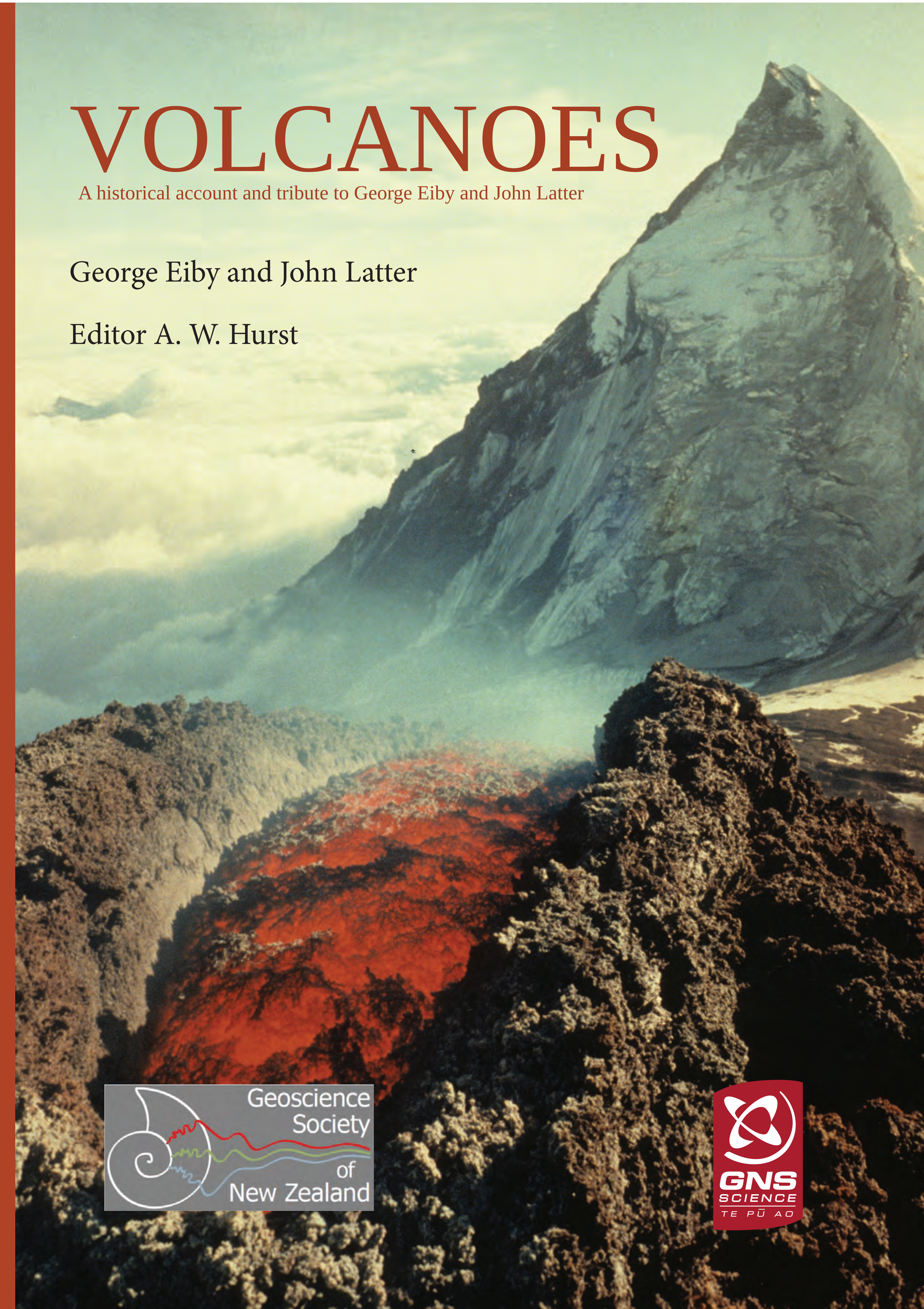

VOLCANOES

A historical account and tribute to George Eiby and John Latter

George Eiby and John Latter

Editor A. W. Hurst

Geoscience Society of New Zealand

GNS SCIENCE
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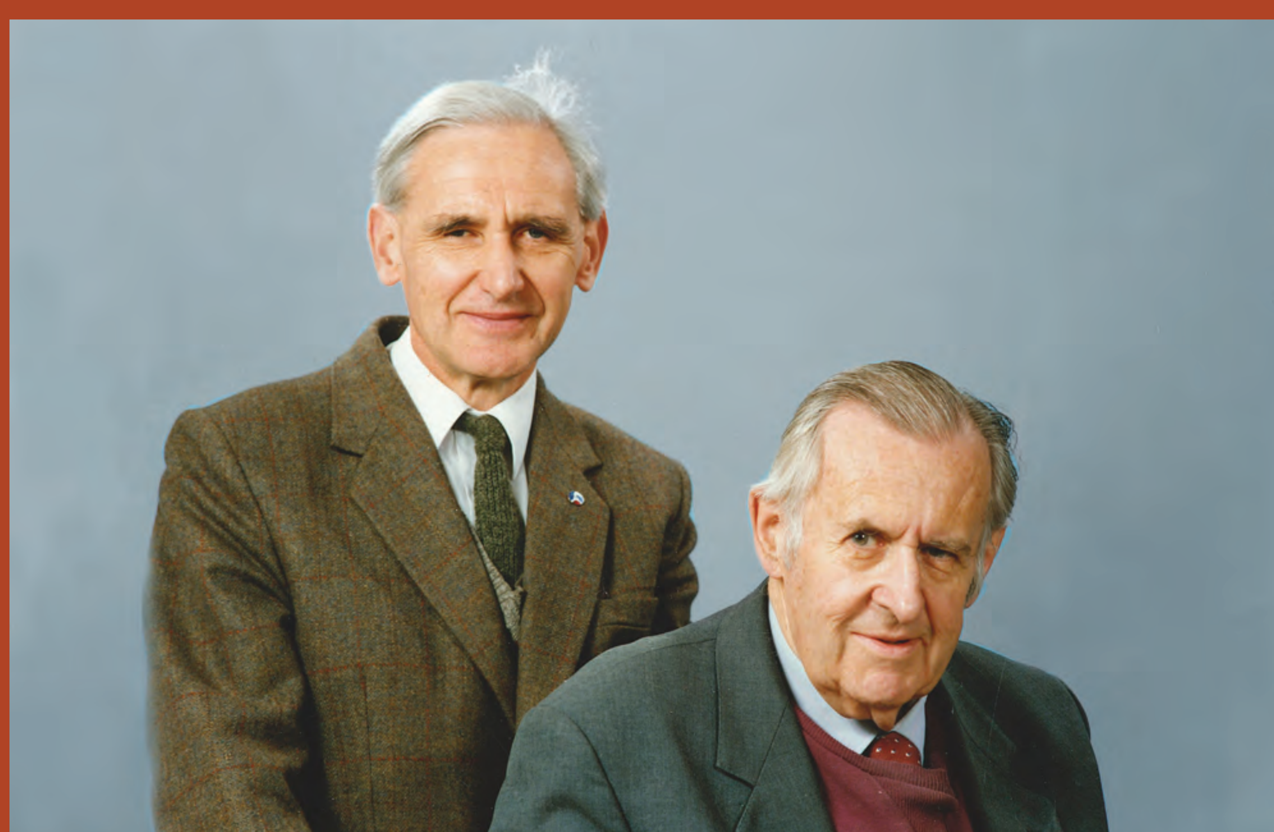
A night view of the fountains of lava that played along the Krafla rift at the climax of the 1980 eruption. (Solarfilma ht, Iceland).



John Latter (L) and George Eiby (R).

George Allison Eiby

George Allison Eiby was born in Wellington, New Zealand in 1918, and spent most of his life in that city. He joined the New Zealand Public Service as a cadet in the Department of Scientific and Industrial Research (DSIR) in 1939, where he studied seismology and positional astronomy. In that era astronomical observations were still important for timing purposes. In 1941, after the commencement of World War II, he joined the Royal New Zealand Air Force as a radar mechanic, and served for four years in Britain.

When he returned to New Zealand and DSIR he enrolled at Victoria University College, graduating B.Sc in 1948 and M. Sc. (in Physics) in 1950. He worked as seismologist for his whole career, retiring in 1979 as Superintendent of the Seismological Observatory, at that time part of Geophysics Division of the DSIR.

A large part of his work was on historical earthquakes, and since in 1950, there were effectively only seven local seismometers recording New Zealand earthquakes, much of this involved interpreting oral and written descriptions of the felt effects. He continued this work after his retirement, and had made considerable progress on producing isoseismal maps for all the significant New Zealand earthquakes recorded from European settlement until the 1950s by the time of his death in 1992.

As the network improved he was able to look at New Zealand seismicity in more detail, and one of his most important papers was “The New Zealand sub-crustal rift” in 1964, in which he identified the dipping seismic zone which is now identified with the subducting Pacific Plate, three years before Oliver and Isacks first published the concept of subduction. This paper also proposed that within this region, the density was about 1% less than normal for depth, a radical suggestion at this time.

His book “Earthquakes”, aimed at the general public, was first published in 1957, and ran to five editions. He was working with John Latter on this book as a companion volume when he died in 1992.

George maintained his interest in astronomy and served for a long time on the Board of the Carter Observatory.

He had many interests outside his areas of science. He was very interested in theatres and stagecraft, and produced or designed over 100 plays. He was also one of those who set up the Film Society in Wellington. He was also a keen musician, and the sound of him playing the recorder in his office at lunchtime was a feature of the Kelburn Office of Geophysics Division.

He was a keen collector of books about the early development of Geophysics. This valuable collection that included works from the 17th and 18th centuries was donated on his death to the Alexander Turnbull library, part of the National Library of New Zealand.

Based on an Obituary by Martin Reyners in the Geological Society of New Zealand Newsletter.

John Latter

John Latter was born in 1933 in Johannesburg, South Africa, where his father was working as a geologist at the Rand mines, and for long periods as an exploration geologist in East Africa. His parents were British, and the family returned to England in 1937.

John went to Cambridge University, and while a student there in the mid-1950s he took part in expeditions to Greenland and Spitzbergen. He recollected that as well as collecting rock samples, his duties included ringing geese for zoological migration studies. Later when doing his National Service in the British Army he was again sent to Spitzbergen to reconnoitre the islands from a military point of view, this being the height of the Cold War.

His first acquaintance with the Pacific came when he worked in the Solomon Islands as a geologist for mining companies in 1957. It was there that he met Helen, whom he married back in Britain where he went to complete a DIC (Diploma Imperial College) course in Geology. Then in 1959 he moved to Rabaul, where he worked with G.A. Taylor, the Government Volcanologist from the Australian Bureau of Mineral Resources, on volcano monitoring of volcanoes such as Manam, Langila and Balbi. He did not see any major eruptions, although he visited the Mt Lamington area to see the effects of its catastrophic 1951 eruption.

In February 1962 he moved to Canberra, where he joined a field party mapping the geology of the Dixon Range in the Kimberley Division of Western Australia, after which he left Australia in September, and returned to Britain.

In Febuary 1963 he moved to work at the Geodetic Institute in Copenhagen, Denmark, under the distinguished seismologist Dr Henry Jensen, with the hope of working in Greenland again. Unfortunately his knowledge of Danish was not thought adequate for him to be working in such isolated areas.

In 1963 he went to Edinburgh University to do a Doctorate on volcanic seismology, working on Italian volcanoes, under Dr.Patrick Willmore at The Global Seismology Unit.

Then in 1965 he came to New Zealand to work for the D.S.I.R., initially at Taupo. After a short period there, he moved to the Wellington office, which was suggested by his team leader, Peter Macdonald, as offering more scope for his science than Taupo. Here he worked on the application of seismology to volcano research and monitoring. In the pre-computer era, earthquake locations were done by protractor, and tremor amplitudes measured with plastic rulers, making these studies very time-intensive. John produced many studies on the volcanic activity of Ruapehu, Ngauruhoe, White Island and Raoul Island during the next 28 years. He was not confined to the office, and was one of a party of four who were lucky to survive an eruption of rocks and mud at Ruapehu while surveying close to Crater Lake on 8 May 1971. This was reported with the understated title “Ground and aerial inspection of crater lake, Ruapehu before and during eruption of 8th May 1971”. He retired in 1993, and so was not on hand for the Ruapehu eruptions of 1995-1996, but he contributed to the 1999 review of long-term Ruapehu seismicity. In 1982 he travelled to Seattle,Washington, and Vancouver, Oregon, where he discussed volcanic risk and seismicity at Mt.Rainier and visited key localities on Mt.St.Helens. In 1985 he was invited to the Smithsonian Institution in Washington, D.C. by Tom Simkin in order to merge data from an unpublished catalogue of volcanoes which he had prepared, with the Smithsonian catalogue “Volcanoes of the World”, which had been published in 1981. He also wrote a major study of the tsunami produced by the 1883 eruption of Krakatoa.

After his retirement he and Helen moved to the Bundaberg area of Queensland. Here he was involved in some public outreach projects illustrating the use of smoked-paper recorders for seismology, reminiscent of the technology he had started his scientific career with.

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FRONT COVER

Lava issuing from Klyuchevskaya Volcano, Kamchatka in 1988

Photo: Anatoli P Khrenov.

Foreword

George A. Eiby and John H. Latter prepared this book on volcanoes in the tradition of Eiby's earlier 168-page standard work Earthquakes that was first published in 1957 by Frederick Muller Ltd (London) and achieved its 5th and final edition in 1989. The original manuscript was prepared nearly three decades ago with the title Volcanoes, and was provisionally accepted for publication prior to the death of Eiby in 1992. It was planned to be published in late 1994 with the title The Worlds Volcanoes: A Panorama in Science and History, but publication was delayed and finally abandoned when the New Zealand publisher was unable to sign up an overseas co-publisher. By this stage, John Latter had added a postscript regarding the eruptions in 1991 of Pinatubo and Unzen volcanoes.

John Latter made further efforts to get a publisher for the book, but without success. He eventually passed the manuscript to A.W. (Tony) Hurst to see whether it could be published on a non-commercial basis by GNS Science. It was apparent that it would not be possible to make the major changes required to update it without losing its original style. It has accordingly been published with essentially the original text, so there is no claim for it to be an up-to-date treatise on the subject of volcanology. Indeed, our knowledge and approach to volcanic studies have developed well into the 21st century, and several significant eruptions have aroused the attention of Society since. Instead, the primary purpose of this publication is to acknowledge the important contribution that Eiby and Latter made to volcanology and to preserve their work as an historical record of volcanic knowledge towards the end of the last century.

However, the content of this book still provide a useful resource to a broad spectrum of the public. To the volcano specialist, the book acts as a reminder of the breadth of the volcanology and its wide outreach to society; perhaps every specialist needs to step back and revise forgotten knowledge. To the teacher, the authors have provided an abundance of anecdotes, stories and interesting facts that could be replicated in any classroom or public presentation. To any member of the public, much of the fundamental knowledge is still valid and presented in an interesting and captivating style.

The book follows a logical account of the discipline of volcanology. The initial chapters (1–3) provide a clear context and rationale for understanding volcanoes. This is followed by a detailed description of the fundamental concepts of primary volcanism (4–13), and hydrothermal and related processes (14–16). The book then takes on an applied approach, including topics on volcanic monitoring, dating eruptions and eruption size (17–19); volcanic warning signs, hazards and hazard management (20–22); volcanic resources – geothermal energy, minerals and soil fertility (23–25); and returning to the origin of Earth's heat that drives volcanism (26). The final one-third of the book is a global geographical tour of volcanoes and an account of significant historic volcanic events within each region (27–40). In the final chapter (41) the volcanic record is 'updated' by postscript to 1991, including the eruptions of Pinatubo (Philippines) and Unzen (Japan), the latter infamous for the pyroclastic flow that shocked the volcanological community by claiming 43 lives including renowned volcanologists, Maurice and Katia Krafft, and Harry Glicken.

Volcanoes: A historical account and tribute to George Eiby and John Latter has a unique style blending history and culture with science communication, and it is endowed with a range of informative illustrations. I hope that each person that opens this book is captivated by the topic of volcanism; I believe that was the intention of Eiby and Latter.

Adrian Pittari

Immediate Past-President, on behalf of the Geoscience Society of New Zealand

Preface

Some little time ago our publisher, encouraged by the reception of Earthquakes, suggested that I write a companion book on volcanoes – believing, I suppose, – that a seismologist should know something about them. What I did know about volcanology made me certain that I could not do the subject justice without the help of somebody working daily in the field. Fortunately my friend and colleague Dr John Latter occupied the office directly across the corridor, and I was able to persuade him to add his much broader and deeper knowledge of the subject to mine.

Writing Volcanoes proved much more difficult than writing Earthquakes. Seismology could be treated in terms of physical principles and recent historical examples. Volcanoes have more individuality than earthquakes. Not only does their behaviour change from one eruption to the next, and even in the course of a single eruption, but the complex physical and chemical processes involved are far from completely understood.

All kinds of people have written books about volcanoes – geologists and explorers, engineers and journalists, sociologists, and even novelists – but there still seemed to be a need for a work in one volume that covered the whole subject in plain language, and we hope we have supplied it. Most of our illustrations have not previously been published, and we have tried to find more than one picture to illustrate a definition, so that the chance features of a single example do not appear to be essentials.

Volcanoes is a collaboration, not a compilation of independently written sections. There was much discussion, and innumerable drafts passed between us, but it seemed important that the final version should have a uniform style, and the task of writing it fell to me. In return for the last word, I must accept the blame for residual shortcomings.

George Eiby

A jet of hot fluid lava thrown from a tiny pool during the Krafla eruption in 1980. (Solarfilma hf, Iceland).

Contents

Acknowledgement

The originally prepared acknowledgements are followed by an update of new or newly-identified images. Some photo sources may have been lost since the preparation of this book began. Apologies for any material that has not been credited.

Without the large contribution from friends and colleagues in many lands this book would not exist. We are greatly indebted, and offer our most sincere thanks. Help has taken many forms from supplying or helping to trace illustrations to checking and criticising sections of the manuscript. Particular thanks are due to Stephen Hicks and Stephen Ede who searched the entire manuscript for passages that could prove obscure or misleading to non-technical readers, and to colleagues in the Geophysics Division of the New Zealand Department of Scientific and Industrial Research (now merged with the Geological Survey), who readily shared their specialised knowledge and offered encouragement. We must also thank the Division's librarians, Cally Ward and Sue Brown, for indispensible and uncomplaining support.

We thank the following for permission to use copyright material:

- The "Auckland Star", for a picture of the Tangiwai railway disaster (Fig. 12.10)
- Dr Friedrich Bender for Figure 16.3, from his "Geology of Burma" (Gebrüder Borntraeger, Berlin/ Suuttgart, 1983)
- Mr Charles Honnywill, for his picture of the eruption of Mount Hekla (Fig. 36.5)
- Mrs Patricia Jenkins for the late Capt. John Jenkins's photograph of a pumice raft (Fig. 12.2)
- Solarfilma hf, Reykjavik, Iceland, for pictures of eruptions of Eldfell (Fig. 7.4), Krafla (Figs 36.3, 36.8), and Surtsey (Figs 7.18, 8.12, 13.2)
- The Royal New Zealand Air Force for the photograph of Home Reef (Fig. 13.3)
- The Superintendent, Seismological Observatory, Wellington, for a seismogram of volcanic tremor (Fig. 17.2)

Many people and organisations have helped us to locate suitable illustrations. Mr Jeff Knapp photographed Taal (Fig. 11.24) especially for this book, W.H. Allen provided pictures of the Barringer meteor crater (Fig. 16.7), and Mrs Phillis Harding allowed her pictures of Santorin (Figs 11.26, 38.6 to 38.8) to be copied.

The NASA pictures of extra-terrestrial volcanoes were supplied by the United States Information Service, Fig. 37.6 by the African Information Centre in Wellington, and photographs of Paricutin and Novarupta by the US Geological Survey. Figures 15.1 and 15.3 are from the collections of the Bath City Council. Drs Tom Simkin and Richard Fiske of the Smithsonian Institution, Washington, provided pictures of Krakatoa, which originally appeared in their book "Krakatau 1883", and Dr R.S. Williams of the US Geological Survey was helpful in locating sources of Icelandic material. Professor S.A. Fedotov and Dr A.P. Krenov of the USSR Institute of Volcanology, Petropavlovsk-Kamchatsky supplied pictures of Kamchatkan volcanoes, except for those of the Bezymianny eruption, which appeared in the "Bulletin Volcanologique". For Japanese material we owe special thanks to Dr Shigetomo Kikuchi of Aso Volcano Observatory (Kyoto University), and Dr Kazuya Ohta of Shimabara Earthquake and Volcano Observatory (Kyushu University). Dr Franco Barberi of the Università degli Studi di Pisa filled gaps in the coverage of Vesuvius and Stromboli after more obvious sources had failed us and Dr Jacques Dubois of the Institut De Physique Du Globe, Paris located an equally elusive picture of a volcanologist in full protective clothing (Fig. 37.9). Professor George Walker of the University of Hawaii has also helped us greatly. Dr Bill Evans of the US Geological Survey filled a similar gap with his pictures of Lake Nyos (Fig. 20.6).

Many of our colleagues in the New Zealand DSIR placed their large private photographic collections freely at our disposal. They include Drs Tony Hurst, Tom Lumb, David Kear, Tim Stern, Trevor Hatherton, Peter Macdonald, Russell Robinson, and Martin Reyners; and others have supplied single pictures. The monotis fossil in Fig. 10.2 was lent by Dr Helen Anderson.

New Zealand historical material has in the main been drawn from private sources, except for Figure 15.4, which was from the Alexander Turnbull Library. The picture of Waimangu geyser in eruption (Fig. 14.15) was given to one of us by the late James Cowan over fifty years ago. Except for the map of active volcanoes of the world, (Fig. 5.1) which was prepared by John Latter, all black and white maps and diagrams are the work of George Eiby. Figs 16.1 and 34.1 are from Alexander von Humboldt's "Vues des Cordilleres". Figs 7.12, 7.13, 11.19 and 12.7 are from "La montagne Peleet ses eruptions" by Alfred Lacroix.

Credits to individual photographers as known are listed below:

As well as the figures, George Eiby provided Figs 3.1, 8.2, 8.6, 10.3, 11.1, 11.5, 11.13, 11.17, 11.27.12.9, 14.7, 14.12, 14.13, 16.6, 17.5, 23.8, 23.9, 23.10, 24.4, 24.5, 24.7, 24.8, 25.3, 28.4, 28.9, 36.2, 36.6, 36.7, 36.9, 38.3, 39.12 & 39.13.

John Latter provided Figs 3.2, 3.3, 3.4, 3.5, 3.6, 7.6, 7.8, 7.14, 7.15, 7.16, 7.17, 8.4, 8.5, 8.9, 8.10, 10.1, 10.5, 11.7, 11.30, 12.1, 12.4, 12.5, 12.8, 14.2, 14.8, 15.5, 16.4, 18.1, 20.7, 22.2, 22.3, 22.4, 23.7, 25.1, 25.2, 28.8, 28.11, 29.3, 29.4, 29.5, 29.9, 30.3, 30.4, 31.2, 37.3, 37.4 & 37.8.

Tony Hurst provided Figs 7.9, 11.4, 11.16, 12.11, 14.1, 14.9, 17.3, 20.1, 21.1, 21.6, 23.1, 23.11, 24.2, 24.6, 27.2, 29.6, 30.1, 31.1, 31.4, 35.2, 38.1, 38.2 & 38.5.

Fig. 17.4 Robin Adams, DSIR

Fig. 16.7 W.H. Allan

Fig. 11.20 A. Brehme via USGS.

Fig. 4.1 Carter Observatory, Wellington

Fig. 7.3 K.G. Cox

Figs 29.8 & 36.12 Hugh Doyle

Fig. 31.9 I.V. Eroy

Figs 31.5, 31.6 & 31.7 S.A. Fedotov

Figs 38.11 & 38.12 Brian Ferris

Fig. 8.7 Jane Forsyth, GNS Science

Fig. 30.2 Kurt Fredrickson, USGS

Fig. 17.1 Brett Gillies

Figs 31.8, 31.10 & 31.11 G.S. Gorshkov

Figs 13.1, 18.2 & 29.2 J.C. Grover

Fig. 3.7 Chris Hadfield, NASA

Fig. 35.3 Trevor Hatherton, DSIR

Fig. 7.5, 11.6, 28.7 & 28.12 Lloyd Homer, GNS Science

Figs 11.6, 11.12, 11.21, 28.6, 28.10 & 37.5 David Kear, DSIR

Fig. 11.24 Jeff Knapp

Fig. 14.3 Ted Lloyd, DSIR

Figs 7.19, 8.8, 16.2 & 24.1 Tom Lumb, DSIR

Figs 11.22, 21.4, 35.4 & 38.10 Peter Macdonald, DSIR

Fig. 34.3 Hugo Moreno

Figs 14.10. & 14.11 Muir and Moodie photograph

Fig. 40.2 Mt Wilson Observatory

Figs 40.3, 40.4 & 40.5 NASA

Fig. 7.10 Ian Nairn, Rotorua

Figs 11.10,11.23 34.2, 39.8 39.11 & 39.14 Martin Reyners, GNS Science

Fig. 7.22 Russell Robinson, GNS Science

Fig. 36.6 Michael Ryan, USGS

Fig. 17.8 Steve Sherburn, GNS Science

Fig. 11.2 Warwick Smith, GNS Science

Fig. 35.1 Tim Stern, DSIR

Fig. 29.7 G.A. Taylor

Figs 7.11 & 20.3 UNESCO

Figs 11.15, 32.2, 33.1, 33.2, 33.3 & 39.9 USGS

Fig. 17.6 Paul Vanderwerff, DSIR

Figs 11.29 & 22.1 G.P.L. Walker

Fig 26.2 Peter Whiteford, DSIR

Fig 17.7 & 17.9 GNS Science

1—Introducing a Heated Subject

It is certaine, that of all the powers in Nature, Heat is the Chiefe.

FRANCIS BACON: Sylva

Volcanology is an untidy subject. It is usual to claim it for geology; but that is far too narrow a view. Physics and chemistry play large parts in it, and volcanoes intrude themselves into sociology and botany, meteorology, astronomy, and medicine. They have inspired poets, painters, and philosophers, left their mark on history, law, and legend, and figured in theological speculation. Their heat has been harnessed to provide power, and they have filled mines with sulphur, salts, and metals. It is too much to expect volcanologists to weave all this into a connected tale.

Two threads can be traced – the Earth's internal heat, and its physical and chemical structure. Long ago when the Earth was formed, the two threads were one, but there is no way to confine the whole of their subsequent tangled wanderings within the covers of one book. The chapters that follow are like a partially assembled puzzle. Some pieces are possibly missing, and others in the wrong place, but we hope we have fitted enough together to give the reader a reasonable idea of the subject of the picture and the style of the artist.

This is a book for ordinary readers, not for specialists. We have tried to be simple, without limiting ourselves to the elementary, and have supplied as much background as was possible without inflating the book to a monstrous size. There is a full index, and anyone startled by the premature appearance of a technical term is advised to use it. There should be no need to consult other references, but a good atlas – one that shows details of the ocean floors as well as the height of the land – is always a useful companion. Maps and descriptions in the text should locate places too small and obscure to appear in ordinary atlases.

A problem to which there seems no satisfactory solution is deciding upon names and spellings. Where there are long-established English forms, they have been preferred. Where there are not, we have done our best to steer a safe course through the narrows of politics, sentiment, and synonym, and beg the pardon of any reader whom we might inadvertently affront or offend by our choice.

Choosing which volcanoes and eruptions to describe has also proved difficult. Most readers will expect us to mention Vesuvius and Etna, Krakatoa and Fujiyama, but we have also tried to include less familiar volcanoes like the lonely Erebus in the Antarctic, and the African Ol Doinyo Lenggai, the "Mountain of God" given to erupting washing-soda. We have also looked for fresh examples and new pictures of volcanic landforms, springs, geysers, and mud-flows.

Our daily newspapers are evidence enough that most of us are morbidly fascinated by disaster, and the horrors of Pompeii, Mont Pelée, and lately of Nevado del Ruiz have a place in our story; but if disasters were all there was to volcanology we could leave the field to journalists. Here we shall invite the practically-minded to consider volcanoes as a source of fertile soils, of minerals, and of power; the aesthete to appraise the beauty of crater-lakes and craggy lava-flows, of coral atolls, and high symmetrical cones smoothly clad with snow. There to be enjoyed are the lugubrious heavings of mud-pools, the spritely caperings of hot springs charged with gas, and the sudden leap of a great geyser. If this is too frivolous, we may sample the civilised pleasures of the Pump-Room at Bath, or seek some more retired spot for studious reflection upon the host of unsolved scientific problems, geological, physical, and chemical, that volcanology offers in abundance.

2—The Birth of a Volcano

Everything that happens happens as it should, and if you observe carefully you will find this to be so.

MARCUS AURELIUS: Meditations

The features of the Earth's crust are changing and impermanent, but most of the changes take place so slowly that the ground beneath our feet has become a symbol of solidity. We view earthquakes and eruptions as a menace and a threat to what we prefer to regard as a stable natural order. Volcanoes are common enough, but in the course of a single human lifetime only about one per cent of them erupt, and most of us are spared direct experience of their habits. Geologically speaking, the life of an individual volcano is short, yet they have existed throughout most of the Earth's history, and new ones have appeared well within recorded time.

What is a volcano? During its active history, a single volcano can exhibit characteristics as different as those that distinguish frogs from tadpoles, which are nevertheless forms of the same creature. The result is that those authorities rash enough to venture upon a definition fall into two nearly equal groups. Members of the one declare that a volcano is a mountain, and members of the other that it is a hole. Not all volcanoes belong to a single species, and it is wise to withhold allegiance to either party until we have looked at some particular examples. Let us then start with a Mexican volcano that began as a hole, and ended as a mountain.

The city of Uruapan lies three hundred kilometres west of Mexico City, and twenty-five kilometres farther west is the spot where, early in 1943, Dionisio Pulido, an Indian farmer from the village of Parícutin, was preparing to plant his corn-field. It was one of the most fertile thereabouts, and he had the help of Paula his wife, his young son, and a hired labourer. All this was usual enough, but matters in Parícutin were not quite normal. For the past fortnight there had been earthquakes and rumblings under the ground, and in nearby San Juan Parangaricutiro walls had been cracked.

San Juan was three times the size of Parícutin. Not only was it the administrative centre of the district, with a telephone on which one could speak to Uruapan and a generator that lit the church and the government offices, but the imposing church housed El Señor de los Milagros, Our Lord of The Miracles, a greatly revered crucifix that attracted pilgrims from other parts of the region. Relations between the townships were strained. Pulido's field had once belonged to San Juan, and the transfer had been attended with allegations of sharp practice. In conservative San Juan there were still those who thought that the new-fangled agricultural methods in vogue in Parícutin could have something to do with the earthquakes. But earthquakes were common enough in the district. All the same, El Señor was moved from the church and erected in the market place. Meanwhile, ploughing went ahead.

In one corner of Pulido's field there was a kind of hollow. It had been there a long time. Old Señora Murilla could remember playing in it as a child, more than fifty years before. Her father used to scold her about it, for there was a dangerous hole at the bottom, and sometimes you could hear deep noises inside; but the children liked playing there, for the hollow was pleasantly warm. Pulido found the hole a nuisance. Season after season he tipped rubbish into it, but it never seemed to fill up.

All day Saturday February 20, Pulido and his wife had been hearing noises. Paula said there was a roaring, and a noise like stones falling down a deep well and hitting the sides. About half past four Pulido first noticed a crack several hundred metres long, extending from the hollow and heading south-east towards the Piedra del Sol, a big rock that marked the boundary between Parícutin and San Juan. He went and had a look, but it was only about half a metre deep and he went on piling dead branches for burning, but before he could light his bonfire, things started to happen.

Figure 2.1 The earliest picture of Parícutin, taken at 5 p.m. on February 20, 1943, about half an hour after the eruption was first noticed.

First, the ground about the fissure leapt a couple of metres into the air and then, in Paula's words, "It swallowed itself". Another crack had formed, and it was making a whistling noise like some gigantic singing kettle. From it rose a column of fine grey ash, like a wisp of smoke. They unyoked the oxen and fled back to the village (Figure 2.1).

They were not the only ones to see the outbreak. Aurora de Cuara from San Juan had been on a visit to San Nicolas, about twenty kilometres away, and was on her way home with her children. When the ground opened she was close to the Piedra del Sol. Curiosity overcame fear, and she climbed the rock to see what had happened. Fifty metres away was the rising column of ash and Pulido was in the next field, but she could not see Paula, who was hidden by trees. By six o'clock everyone could see the eruption. Pulido's brother went to look and got to within about eight metres of the vent before being driven back by falling stones. Low mounds of the grey dust were forming in an oval pattern.

About the same time, a party rode over from San Juan. In view of the possible danger of their mission they had waited for the priest's benediction, a precaution they felt was justified when they narrowly escaped from a cave-in of the sides of the hole. Before that it had been about half a metre across, throwing red-hot stones to a height of about five metres. It had now become pear-shaped, and about two metres wide. The column of ash had grown wider and darker, and sand was 'boiling' in the vent with a noise like boulders being rolled along by a stream in flood. The ground was jumping up and down, and there was a choking gas in the air. They took two stones and a handkerchief full of ash back to the priest. They were still hot when he carried out an exorcism over them, praying that the eruption might cease. It would be some time before his prayers were answered.

Figure 2.2 Parícutin on the following day. A cone about 30 metres high has appeared above the tree-tops.

By nightfall the noises had ceased, but the fountain of incandescent rocks could be seen from San Juan, and just before midnight they started again, more thunderously than before. The ash-cloud was lit by internal flashes of lightning. By morning, the ground had stopped shaking. Pulido went back to his field and reported the presence of a cone ten metres high and erupting impressively. Meanwhile the town council met, and decided that the new cone should become known as 'Vulcano de Parícutin'. The telephone conveyed the resolution to San Juan and along the official chain of command to the President.

The eruption continued all day Sunday and the cone went on growing. Whether its height reached fifty metres or only thirty is impossible to say (Figure 2.2). Incandescent material kept coming out, though there was less ash, and some time within the next two days the first lava appeared. It was black and viscous, a mass of torn and jagged fragments that advanced across the fields at no more than five metres an hour. Life in Parícutin and San Juan Paringacutiro would never again be the same.

The first reaction of people who had friends and relatives in nearby villages was to flee to them for shelter, but before long curiosity brought them back. It also brought an influx of scientists, and soon after them of government officials, reporters, and sightseers. One of the first on the spot was Mexico's veteran geologist, Don Ezequiel Ordónez. Because of his age he was carried on a litter, only to be abandoned by his bearers when he insisted on remaining within range of falling rocks.

It was three months before the real evacuation started. On March 18 the original explosive phase of the eruption had been succeeded by increasingly heavy falls of ash, and when the seasonal rains began in May they became a rain of mud. Within a radius of twenty-five kilometres conditions were most unpleasant, and it was obvious that there would be no harvest. Pine-trees in the nearby forests were dying and local industry, the collection and distillation of resin for turpentine, was threatened. Livestock became ill from eating the ash-covered vegetation, there were no more wild fruits and berries to be gathered, and honey-bees and game had disappeared.

The worst of the ash-falls was over by June 9, but not the problems they posed. The drifts were readily eroded and the debris was shifted by wind and water. Slopes became deeply gullied; fields were buried, uncovered, and buried again. Meanwhile the lava continued its slow advance (Figure 2.3, 2.4).

In mid-June the government decided that Parícutin should be abandoned. The lava was heading in the direction of the village, and although the geologists thought that it would probably be diverted by the lie of the land, other problems had become acute. Water supplies had failed, and the weight of ash had made the roofs of the Church and many of the houses collapse. The people were to move to Calzonzin, five kilometres from Uruapan.

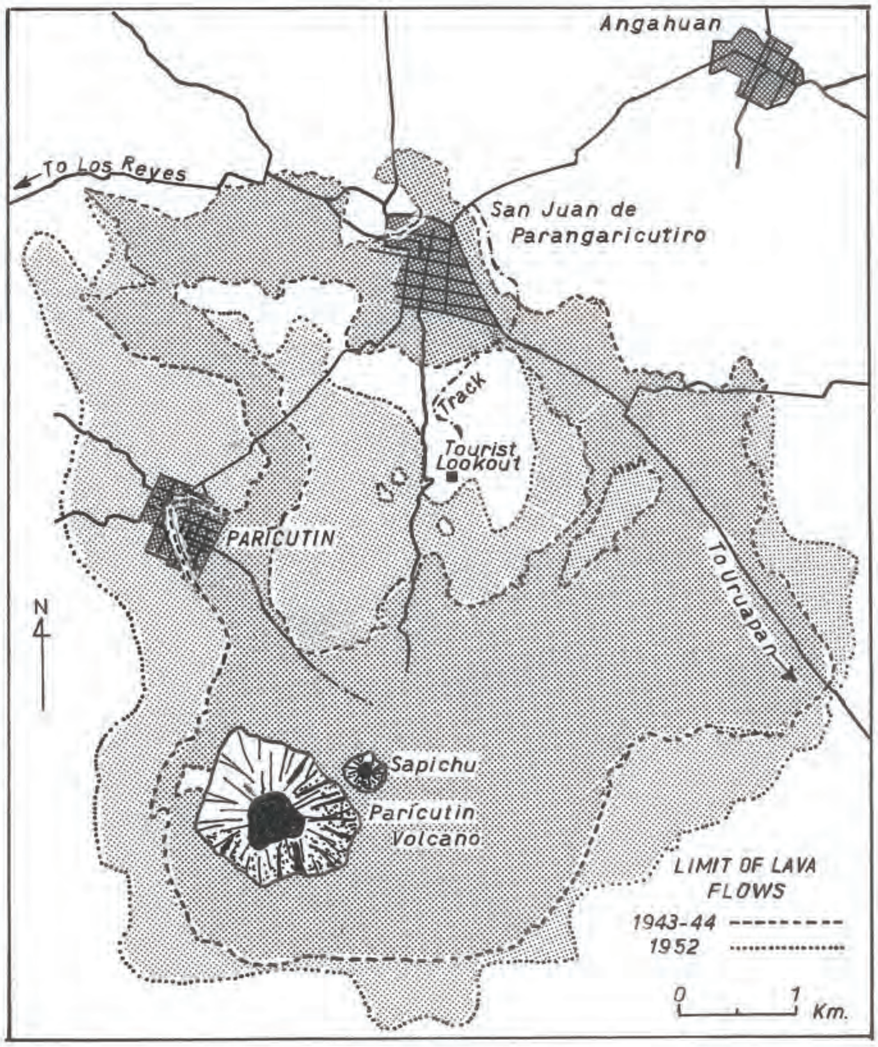


Figure 2.3 Parícutin showing the area covered by lava-flows, and place-names mentioned in the text.

Those most ready to move were the younger, richer, Spanish-speaking members of the community. Rapid social and technological change was occurring in Mexico, and they had already considered the possibilities of a changed style of life. They went to the cities and not to the refugee camps of Calzonzin. Some of the richer folk felt they had too much tied up in land and property for them to leave, but most of the reluctant ones were old and poor. There was plenty of well-intentioned aid, but the people's deeper feelings were hard to understand. Why did they seem so ready to die covered by lava, rather than agree to abandon their homes; and why were they so insistent that any new village must be called Nuevo Parícutin? Meanwhile, they could make some money by selling bits of rock to tourists.

It was more than a year before the lava finally engulfed Parícutin, but by then all the people had left, and there were only a few scientists to watch it. Meanwhile, the eruption had entered a new phase and interest centred on San Juan. The fiesta of Our Lord of the Miracles in September attracted a record crowd of pilgrims, who feared that the shrine was doomed and expected that this fiesta would be the last. Town meeting after town meeting was held to discuss a possible move, and even the President came to persuade them to shift, offering them the right to select the new site.

On October 17 yet another phase of the eruption began. At the base of the cone on the north-east side a break-out occurred, and a small secondary cone began to build up. Meanwhile, the main vent began to quieten down. In March it had sent its cloud of ash to a height of 6,000 metres and rained stones on anyone who approached, but by November it had become possible to climb the new mountain, which was now 160 metres high (Figure 2.5).

The new cone was named Sapichu, and continued to erupt until January 8 when there was a fresh outbreak of lava. The original flow had ceased in late March, but there was now a flow from Sapichu and another that came from vents at the base of the south-west flank. The lava flowed round the cone and down the slope towards San Juan. At the beginning of April it met the older flow and hopes that it would be diverted from the town began to rise. It was a false hope. It had not stopped, but was tunnelling underneath, and on April 14 it burst out once more. A moving wall of lava nine metres high continued to advance upon the main road and the pipe that carried water to the town.

Both the geologists and the local clergy had been trying to persuade the townsfolk to leave, and at a meeting in March they agreed that they would do so when the lava reached the cemetery, hoping that in the meantime either the good offices of Our Lord of the

Figure 2.4 Parícutin

Figure 2.5 On October 20 a new vent broke out at the base of Parícutin and erupted a fountain of viscous lava bombs that built the cone of Sapichu.

Figure 2.6 A year after the eruption began lava flows had engulfed the town of San Juan Parangaricutiro and destroyed the church.

Miracles or the powers of the geologists' seismograph would make the move unnecessary. On May 7 the bishop decided that the time had come to act. Taking the crucifix from the church, he carried it in solemn procession through Angahuan and on to Uruapan, where he found the whole city in fiesta to welcome it. Three days later the procession reached the Rancho los Conejos, site of the new settlement, formally re-named San Juan Nuevo Parangaricutiro.

The burial of San Juan soon followed. Only a shattered remnant of the church protruded through the lava to mark the spot (Figure 2.6). The ash had covered 233 sq. km, and the bulk of Vulcano de Parícutin rose 410 metres above the level of Pulido's field. It was not until March of 1952 that the eruptions finally stopped. During 1950 explosions and earthquakes had hinted at the possibility of further destruction, but nature and human effort were combining to establish a new normality.

It was not proving easy to restore agriculture. Seeds were planted in the ash, but they failed to grow, and the original soil had to be uncovered painstakingly by hand. Dust-storms arose and covered the soil again, and the rains carved deep and unstable gullies in the slopes. Yet mosses and lichens began to appear on the lava-flows, the bees returned, and wild berries and crab-apples were to be found once more. Trees started to sprout, livestock were beginning to thrive, and nature had found a different kind of grass to clothe the deep ash.

As life in the countryside resumed its former rhythm, the refugee settlements were developing social problems, which became most acute in Miguel Silva, about eighty kilometres south-east of the volcanic zone. During the summer of 1943 refugees from Zirosto, one of the villages affected by the ash-fall, decided to move to Miguel Silva and farm unoccupied land in the vicinity. In October, it was formally declared a re-settlement area and they were joined not only by the rest of their community, but by refugees from San Juan, perhaps 1,200 people in all. Trouble began almost at once. Of the 2,600 hectares that they had been allotted only 350 proved suitable for cultivation. The population was more than the land could support, and it had not been properly surveyed. In early 1944 the local ranch owners declared war on the refugees. Their leaders were murdered, their stock slaughtered, and their crops destroyed.

Violence was not the only problem. The height of Zirosto had been a thousand metres above that at Miguel Silva. The climate was not uncomfortable, but it was unfamiliar. The seeds they had brought failed to germinate, the water was bad, and malaria and dysentery broke out. Older people lost the will to carry on, and there were many deaths. At the end of 1946 only three hundred of the refugees remained at Miguel Silva. Some had returned to the volcanic area, some had emigrated to the United States, and most of those from San Juan had decided to join friends and relations in San Juan Nuevo.

The pattern of readjustment in the different settlements varied greatly. The remnant at Miguel Silva recalled the past of their settlement at Zirosto and began to see themselves as pioneers rather than refugees, with a consequent improvement both in morale and material well-being; at San Juan Nuevo they built an imposing new church for Our Lord of the Miracles, and successfully fostered an increasing flow of pilgrims from distant places; at Calzonzin the former inhabitants of Parícutin who had indignantly criticised the design of the houses provided for them, set energetically about remodelling them to their taste, and upon resisting the physical and cultural encroachment of the growing settlement of Uruapan by reviving and re-planning their traditional festivals. They also resolved that whatever officials might call their new home, their sports teams would retain the name Parícutin.

Some new occupations appeared. Visitors called for guides and souvenirs, and local contractors soon found that lava could be used on the roads, and that some of the ash made good concrete. As fertility returned to the soil old arguments over land-boundaries revived. Markers had been buried under the ash, or carried off surreptitiously. There were also disputes between the new settlements and their neighbours, for while the fields were individual property, the forest land was owned communally.

Throughout the 1950s court battles over land went on, and there were occasional outbreaks of violence. In 1965 hired gunmen were involved; in 1967 a government investigator documented 128 cases of arson. Yet agreement was finally reached, and the government took a hand. In 1970 surveyors moved in. Electricity, water-supplies, post-offices, schools, and bus services appeared. Peace had returned. Geological, agricultural, and social eruptions alike were over.

3—A Variety of Eruptions

…flaming from th'ethereal sky with hideous ruin and combustion…

JOHN MILTON: Paradise Lost

Not until the parish priest at San Juan Parangaricutiro had consulted a book on Vesuvius in his church library and shown it to members of his flock did they recognise that what was happening at Parícutin was the outbreak of a volcano. Yet Parícutin is not an isolated volcano, but lies in a volcanic field. Unlike most volcanoes, which erupt many times from the same crater, it is usual for each new outbreak within a field to open a new vent. Memories are short, and nothing of the earlier activity remained to alert the farmers of the district to the significance of their surrounding hills. Parícutin's brief but spectacular outburst lasted only nine years, and when the eruption stopped the hot springs and steam vents about it disappeared.

There are many volcanic fields in Mexico, and the high Sierra is dotted with old cinder-cones whose first appearance must have been rather like that of Parícutin. Jorullo, a hundred kilometres to the south-east, formed in much the same way in 1759. The individual cones are not very old, and although they are probably extinct, this is far from being true of the fields.

The New Zealand city of Auckland is built on and around more than fifty cones which also comprise a volcanic field. Here too most outbreaks have been from fresh vents, but few citizens have pondered upon the consequences of a new one opening in the main street. The prominent island volcano Rangitoto (Figure 3.1) is an exception, whose shape displays obvious proof of more than one outbreak, the last of them about 500 years ago.

Volcanology remains to a great extent a matter of systematised observation rather than a body of physical theory, and in this chapter we shall look at two historic eruptions that are very different from each other, and from the one at Parícutin. Early speculation about the causes of volcanoes now interests only the historian of science and the seeker after the curious, but the accounts of early eruptions of volcanoes with a long history of activity retain their value and interest.

Whatever connection there may be between Chinese dragons and some early experience of lava eruptions, for once there is little evidence that the sages of ancient China were first to enter the field of volcanology. Holy writ is very reticent about volcanoes. The eruption while Moses was on Mount Sinai rates but a single verse, and the fall of brimstone on Sodom and Gomorrah only two. Lofty Mount Ararat in eastern Turkey is certainly a volcano, but Noah has nothing to say about hydrothermal activity and the resting-place of the ark must be sought elsewhere.

Figure 3.1 Rangitoto, most recently active of the cones in the Auckland Volcanic Field.

Figure 3.2 Vulcano, in the Aeolian Islands, was anciently considered to be the chimney of Vulcan's forge, and has given its name to all volcanoes.

Figure 3.3 La Fossa, the crater of Vulcano, dormant since 1890.

The writers of classical Rome are more forthcoming, and the poets are generally agreed that the crater of Vulcano, in the Aeolian Islands just north of Sicily, is the chimney of Vulcan's forge (Figures 3.2 and 3.3). Here Vulcan, god of fire, forged thunderbolts for Jove, and armour, shields, and arrows for the lesser Olympians. Why he chose this particular spot is unexplained, for Vulcan was the Romans' name for the Greeks' Hephaestus. Doubtless the fact that the mainland of Greece has only one active volcano has something to do with it. We should be grateful that it has saved volcanology from some awkward nomenclature.

By far the most celebrated of the ancient accounts is contained in two letters from Pliny the Younger to the historian Tacitus. In them he describes the eruption of Vesuvius in A.D. 79 that killed his uncle, and buried the cities of Pompeii and Herculaneum. The Elder Pliny – Caius Plinius Secundus to give him his formal style – was commander of the Roman fleet stationed at Misenum, near Baiae on the northern side of the Bay of Naples. He was also the author of a Natural History containing not only his own observations, but material culled from almost every work he had ever read. Sir Thomas Browne has denounced it as a prodigious source of vulgar error, but that is a charge that could be brought against almost every readable work on a serious subject.

It was just after lunch, and Pliny was reading when his sister drew his attention to a curious cloud. It stood above the mountain like a great pine-tree, with a straight trunk that extended to an enormous height, and a crown of spreading branches. Vesuvius was erupting. For some days beforehand small earthquakes had been felt, but earthquakes were quite common in that part of Italy, and no one seems to have been alarmed or construed them as a warning. After all, Vesuvius had been quiet for a very long time, and there are no records of earlier eruptions, though both Diodorus Siculus in 45 B.C. and Strabo a little later were aware that the mountain had once "emitted fires". Seneca reports a damaging earthquake in A.D. 63, but whether the shock was a symptom of reviving activity, or merely another of the normal tectonic earthquakes of the region, no eruption was expected.

The Vesuvius of Pliny's days was a broad, flat-topped cone some 1,300 metres high. Its truncated summit was the rim of a depression to which access could be gained through a narrow cleft on the southern side of its symmetrical slopes. In 72 B.C. Spartacus and his gladiators had unsuccessfully tried to use it as a hiding-place. The top was covered with a deep layer of cinders, and barren except for wild and tangled vines, but the lower slopes were fertile and intensively cultivated, and villas and small settlements extended around the shores of the bay.

Pliny at once went up the nearby hill for a better look. There were great surges taking place within the cloud, and pieces of red-hot material were being carried upwards in the vertical column, which was lit by lightning flashes and appeared now bright, now dark and spotted. His curiosity was fully aroused and he decided to cross the bay, exercising his naval authority to have a light galley made ready.

Before he could leave, there was a change of plan. A message had arrived from Rectina, a lady living at the foot of the mountain. Her only possible escape was by sea, and she pleaded to be rescued. Realising that all the settlements were in danger he decided to mount a full-scale rescue and ordered the whole fleet to sea. The danger was very real, but he continued to record his impressions as his galley headed across the bay. The rain of cinders, pumice, and hot rock became thicker and thicker, and the sea was surging to and fro in a manner that threatened to strand them. They could see that the shore was littered with fragments from the slopes of the shattered mountain.

There was little more that could be done and the dark cloud above them was making it difficult to see. Pliny decided to rescue his friend Pompianus from Stabiae at the southern end of the bay. At this stage of the eruption, Stabiae was not in danger, but Pompianus had become alarmed and had already sent his valuables on ship-board. Meanwhile, a strong on-shore wind had sprung up, and the ships were unable to leave. Broad flames could now be seen. In an attempt to quieten the fears of his companions Pliny dismissed them, and went to bed.

Nobody slept. Frequent heavy earthquakes were going on, and they debated whether it would be better to shelter in the houses, which might collapse, or take to the fields where they would be exposed to falling stones and the rain of ash. In the end, they tied pillows to their heads with towels, and groped their way through the darkness to the beach. The wind was still strong, and there was no chance to leave. They were choking with sulphurous fumes. Pliny had a sail-cloth spread out, and collapsed on to it, twice calling for water, and shortly died. The rest of the party retreated on account of the fumes, and it was three days before it was light enough to identify and recover the body. Current medical fashion is to attribute the corpulent Pliny's demise to heart-failure, rather than to volcanic fumes. Since his companions were not overcome, it may well be right.

Back in Misenum the younger Pliny and his mother noted the increasing number of earthquakes. The shocks had become strong enough to throw things about the house, and in the morning they decided that it was time to flee. It had grown very dark, the ash was falling more heavily, and the chariots they were intending to use were being rocked back and forth by the earthquakes. When they finally set out it was nearly nightfall. Darkness became profound, and they were forced to leave the road to avoid screaming crowds of panicking refugees. Travel proved too much for Pliny's mother, who was old and stout, and it is not clear how far they got, but they were heartened by daybreak and decided to return to Misenum to await news from the head of the household.

Pliny's letters say nothing of the destruction of Pompeii and Herculaneum, and the account by Tacitus has not survived. There is reference to the event in an epigram by Martial, but that contributes little to volcanology and the earliest account we have is that of Dion Cassius, written a century and a half later and containing more legend than fact. We have learned most of what we know from the excavation of the buried cities.

After the eruption, Pompeii lay buried under six to eight metres of pumice and ash (Figure 3.4). It had been a busy commercial city of about twenty thousand people, and the skeletons of about two thousand of them have been recovered. In some cases the ash about the bodies had solidified into a mould, preserving (Figure 3.5) details of features and clothing that could be reproduced as a cast by filling the cavity with plaster. Many of the victims are holding cloths or pressing their hands to their mouths to fight the choking gases. Others were killed by falling buildings, or trapped inside them. The greatest loss of life came in the heaviest falls of ash, which Pliny's evidence shows to have come early, within the first few hours, but falls continued for about three days. The bodies of some who survived the initial stages of the eruption were found near the beach, and lie near the surface of the ash.

The burial of Herculaneum is a different story. Recent studies have overturned the traditional view that it fell victim to a flow of ash from the higher slopes of the mountain, triggered by the first rains,

Figure 3.4 The view over the excavated ruins shows the extent of devastated Pompeii.

Figure 3.5 Plaster cast of Pompeii victim in the Naples Archaeological Museum.

Figure 3.6 Vesuvius rises above the ruins of Pompeii, destroyed in the eruption of A.D. 79. Monte Somma, the peak on the right, is the product of later eruptions.

Figure 3.7 Vesuvius photographed from the International Space Station by Chris Hadfield (South to top).

which were perhaps induced by the eruption itself. Volcanologists now believe that the "mud" (which has hardened into volcanic tuff, a material very resistant to archaeologists) came from a kind of glowing cloud called a nuée ardente, of which we shall say much more in later chapters. In places the tuff is over twenty metres thick, and the small number of bodies recovered suggested that most of the inhabitants had had time to flee. It has since become clear that they got no farther than the beach. Unlike the buildings at Pompeii, those at Herculaneum have not collapsed. Erupted material penetrated into every nook and cranny, instead of becoming an insupportable load on the roofs.

The mountain that Pliny had known was no more, and in the coming centuries further eruptions transformed it completely (see also Figure 11.25). At first it was assumed that in its efforts to re-open the crater the eruption of A.D. 79 had blasted the mountain apart, but few fragments of the original cone were to be found in the surrounding countryside. It is now thought that the enormous volume of erupted material left a cavity into which most of the old crater rim collapsed, leaving only the segment now known as Monte Somma. Subsequent eruptions have now built a new cone about the re-opened vent (Figures 3.6 and 3.7).

Figure 3.8 Lakagígar from the air. The mountain in the foreground is Laki, a moberg. 'Lakagigar' means 'Craters of Laki', i.e. the fissure that opened on the W side of Laki, which itself last erupted when it was ice-covered long ago.

The great loss of life that resulted from the eruption of Vesuvius stands in contrast to the absence of deaths in Parícutin, though both eruptions destroyed buildings and crops. Fields buried under lava-flows are lost for a very long time – if not for ever – but those covered in ash can prove in the end to have had a beneficial top-dressing. Maize grows in the shadow of Parícutin, and the unexcavated parts of Pompeii are covered by trees and fields of grain. The problem is that recovery can be slow, and famine may intervene as it did in Iceland after the eruption of Laki in 1783, an event of a very different kind from those we have already described (Figure 3.8).

The first indication that Laki (Lakagigar) was to experience the greatest eruption of lava in historic times was the appearance of a bluish haze that hung about the headwaters of the Skaftá River, a glacier-fed stream that drained from the Vatnajökull, a great tract of permanent ice that covers nearly 9,000 sq. km of active volcanoes, and ever since Viking times eruptions of one kind or another have been reported every five years or so. People became wary, but were not at first alarmed.

After a week of earthquakes the eruption proper began with the opening of a fissure running south-west from the W flank of Mount Laki. From it great floods of a very fluid lava began to pour, and along sixteen kilometres of its length more than a score of vents hurled enormous fountains of the lava into the air. As it rose and cooled the dissolved gasses blew it apart to form a cloud of ash and a material known as Pele's hair (Figure 12.3). It is rather like the rock wool or fibreglass used for the thermal insulation of buildings, and its name honours the Hawaiian goddess of volcanoes. Soon all Iceland was covered with the ash, and the winds carried it eastward as far as Scotland and Norway. All that summer the blue haze persisted, giving off unpleasant acid fumes, and reducing visibility so greatly that the fishing fleets were unable to operate.

In 1783 the population of Iceland was about fifty thousand, and nearly a fifth of them were to lose their lives, not as direct victims of the advancing lava, but from the lingering effects of environmental damage – for after eruption came famine. Crops and grazing lands had been destroyed, and catches of fish were greatly reduced. Many sheep and cattle were poisoned as a result of eating the ash-covered grass, and the teeth of the survivors were so severely abraded that they failed to thrive. It has been estimated that 190,000 sheep, 28,000 horses, and 11,500 cattle were lost.

The effects of the lava that poured from the Laki fissure were no less calamitous than those due to the ash. It ran down the seventy-metre wide course of the Skaftá filling gorges two hundred metres deep and spilling from the shallower valleys on to the surrounding fields. Three days later, when it arrived at the coast eighty kilometres away, it spread out into a fan twenty kilometres wide. The Icelandic volcanologist Th. Thorarinsson has estimated that the volume of the average flow during the eruption was twice that of the river Rhine, and that the maximum was ten times the average!

On July 29 flow from this fissure ceased, but it was merely the onset of a new phase. A second fissure opened on the opposite side of the moberg Mount Laki, a modest cone that rises only a couple of hundred metres above its surroundings. This time, it was the valley of the Hverfisfljot that claimed the lava. When the eruption finally ended in November, 370 sq. km had been covered. The problems set by the melting of the glaciers and the permanent blocking of the watercourses had still to be faced in the spring (Figure 3.9).

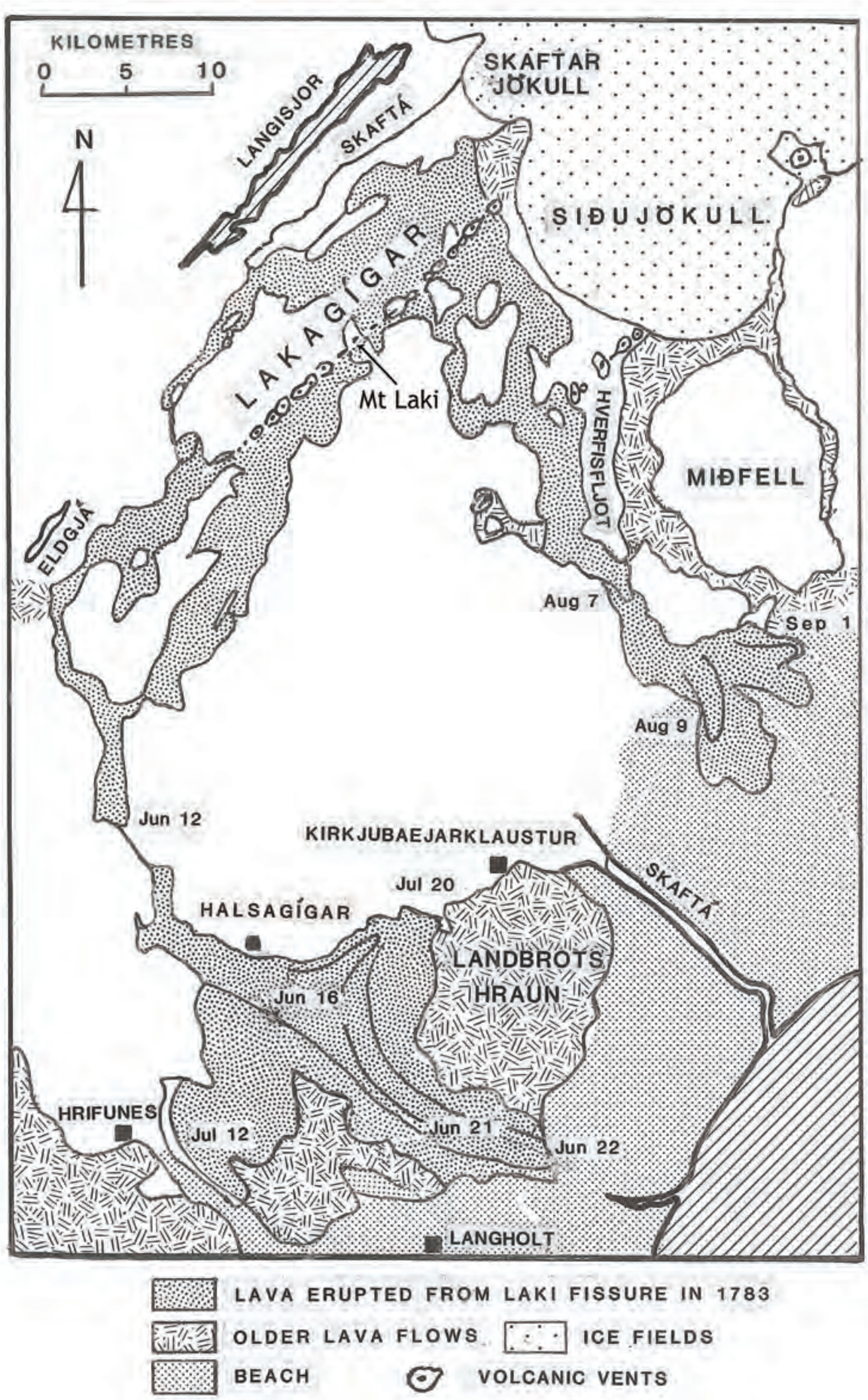


Figure 3.9 Progress of lava-flows from the Laki fissure during the eruption of 1783.

4—In the Beginning

"Where shall I begin, please your Majesty?" he asked. "Begin at the beginning," the King said, gravely, "and go on until you come to the end; then stop."

LEWIS CARROL: Alice in Wonderland

The three eruptions we have described are very different from one another, and if we were to consider several eruptions of the same volcano we should find differences that are just as striking as those from volcano to volcano. What comes out can vary from the finest dust to blocks the size of a house; it may be jets of steam under high pressure, or floods of liquid lava; its chemical composition can be quite as varied. One thing, however, is certain. Either it is hot, or it has been hot very recently indeed.

It is not difficult to establish that it is hot in the Earth's interior. Even in non-volcanic regions the temperature in mines and bore-holes rises quite rapidly with increase in depth – about 25°C for every kilometre, a value called the geothermal gradient – but getting reliable information about the Earth's internal heat turns out to be one of the most difficult problems in geophysics, both practically and theoretically.

The first thing that becomes clear is that the Earth cannot go on getting hotter at the same rate all the way to the centre, six and a half thousand kilometres down. Long before that it would become hot enough to turn everything to vapour. But we have little direct information. Our deepest drill-holes reach down only about fifteen kilometres, and cover only a tiny fraction of its surface. To get any reasonable idea of where the heat comes from and how much there is, we shall have to consider the Earth's beginnings and its present structure.

Let us stand off in space and take a broad look at it. It is a slightly flattened sphere over 12,000 km in diameter. Judging from the outside it is made of rock. The surface is slightly rough, and the hollows contain substantial quantities of brackish water, which covers 71 per cent of the surface. Wrapped around it is a cocoon of gas, consisting for the most part of nitrogen, oxygen, and water-vapour. The outer parts of this atmosphere are electrically charged, and the Earth as a whole behaves as if it is magnetised.

Most early conjectures about the interior were the fruit of a union between the little that was known of volcanoes and the teachings of theology. The first important constraints upon this speculation came with the formulation of Newton's laws of motion and the theory of gravitation, which led him to suggest that the Earth would be found to be flattened at the poles. The trouble was that when Dominique Cassini, the director of the Paris Observatory, and his son Jacques collected the survey measurements of the day they revealed an Earth that was more like a lemon than an orange.

The controversy that followed had little directly to do with volcanoes, but it began a chain of events that completely changed our views about the Earth's interior. King Louis XV of France sent out two expeditions with orders to clear up the argument about polar flattening. One was to go to Lapland, and the other to Peru. De Maupertuis, who made the shorter journey to Lapland, was the first to get back and to claim that he had proved Newton right. Voltaire accordingly bestowed upon him the title of "l'Aplatisseur" (the Flattener). It is really a pity that there were mistakes in his sums, but he did get the right answer.

Meanwhile Pierre Bouguer was in Peru (or rather, if you go by today's maps, in Ecuador) and having trouble with his measurements, for the massive gravitational pull of the Andes prevented the plumb-bobs in his instruments from hanging vertically. Bouguer realised that the amount of the deflection depended upon the relative attractions of the mountains and of the Earth as a whole. If he could find out a way to work out the mass of a mountain, he could calculate the mass of the Earth. Since he knew its size, he could also find its mean density, a most important clue to what might be inside.

The mountain he chose for a trial experiment was Chimborazo. He proceeded to survey it carefully, sampling the rocks and measuring their density so that he could work out its weight. He knew Chimborazo was a bad choice, but it was the only shapely mountain handy. It was also over six thousand metres high and then thought to be the world's highest peak. Being a volcano, it seemed likely to have a most complicated inside. The weather proved so treacherous that he nearly froze to death; but he was able to show that his method would work, and in 1772 Neville Maskelyne, the Astronomer Royal, repeated the experiment successfully with the aid of Ben Schiehallion, a smaller and more tractable peak in the highlands of Scotland.

By the end of the century John Michell and Henry Cavendish had realised that mountains were not necessary. Provided you could measure small deflections accurately, large lead balls would do just as well. You could work in comfort, and get better results. In 1798 Cavendish performed his experiment in a room at Cambridge, and showed that the Earth was a little more than five and a half times as massive as the same bulk of water, which is very close to the accepted value today. Expressed in modern language, the Earth's mean density is 5.517 Megagrams (or 5,517 kg) per cubic metre.

This is very much greater than the density of any rock that has been found at the surface. The heaviest ones do not go much above 3, and the average is somewhere about 2 ½ Mg/m^3. Whatever is inside the Earth is heavy. The next question is: Does it just get gradually denser all the way to the centre, or is there a lump of something very heavy indeed right in the middle?

Astronomers were the first to come up with an answer. As the Earth spins on its axis and moves around its orbit, the Sun and the Moon and the other planets tug it first one way and then the other by their changing gravitational pulls on its equatorial-bulge. As a result it develops a wobble called nutation (from the Latin nutare, to totter, or to nod). Terrestrial observatories can time and measure the nutation by watching the apparent displacements of distant stars. The amount of wobble that develops depends upon the Earth's efficiency as a flywheel, a factor known as its moment of inertia, which depends both upon its weight and upon the way the weight is distributed. If you want to make a good flywheel and have only a limited amount of metal, it is better to make a wheel with thin spokes and a thick rim than to put all the weight near the axle.

It turns out that the Earth is not at all a good flywheel. About a third of its mass is concentrated in a central core that makes up only a sixth of its volume. When this became known at the end of last century it led Emil Wiechert and others to suggest that the core consisted of heavy metals. One argument in favour of this depends upon the composition of meteorites, which fall into two groups – the stones, which are rather like ordinary rocks; and the irons, which are metallic. Since meteorites are generally thought to be either the remnants of a disrupted planet or material left over when the planets were built, it is not unreasonable to expect them to parallel the composition of the Earth. The irons are material like that of the core, and the stones are like that of the surrounding mantle. Their densities are about right, but it is harder to be sure about the proportions we have of each. The material that lands on the Earth may not be a representative sample, and once it has landed the stones weather more quickly than the irons, and become hard to distinguish from terrestrial rocks.

In 1886, when Henri Becquerel accidentally fogged a photographic plate and in consequence discovered radio-activity, no one seriously doubted that the Earth had once been hot, and was at present cooling by radiating heat into space. By about 1883 the Scottish physicist Lord Kelvin (William Thomson) had realised that if he started by assuming that the Earth was originally molten, and at a temperature round about that of the Sun, he could work out how old it was. "We must," he wrote, "allow very wide limits in such an estimate… : but I think we may with much probability say that consolidation can not have taken place less than 20 million years ago, or we should have more underground heat than we actually have; nor more than 400 million years ago, or we should have less underground heat than we actually have."

Geologists were uneasy. Even Kelvin's upper limit allowed barely enough time to lay down the great thicknesses of sediment that they knew existed; yet Kelvin had the support of Hermann von Helmholtz who had made similar investigations into the heat of the Sun, and concluded that the energy available could not have kept it going for more than a few million years. In 1897, when Kelvin announced that new knowledge of the thermal properties of rocks enabled him to reduce his upper limit to "less than 40 million years ago, and probably much nearer 20 than 40" they became openly incredulous. If that was what physics had to say, physics was clearly nonsense.

In fact, the geologists were closer to the correct answer, but there was nothing wrong with Kelvin's work. Given his carefully stated assumptions – which no one attempted to question – there was only one conclusion that could validly be reached. One of those assumptions was that the Earth contained no undiscovered sources of heat; but it did. Kelvin and his critics knew nothing of radioactivity.

Most scientists now agree that the history of the Earth's existence as a separate body began a little less than 5,000 million years ago. They are less agreed about what it was that happened then.

Before the seventeenth century there was little scientific speculation about the Earth's beginnings, and it was not until its closing years that Pierre-Simon Laplace was able to produce a theory with sufficient mathematical substance to gain support in a world still intoxicated with the successes of Newtonian mechanics. The germ of Laplace's "nebular hypothesis" as the theory is called can be found in the writings of Emmanuel Kant, but Laplace

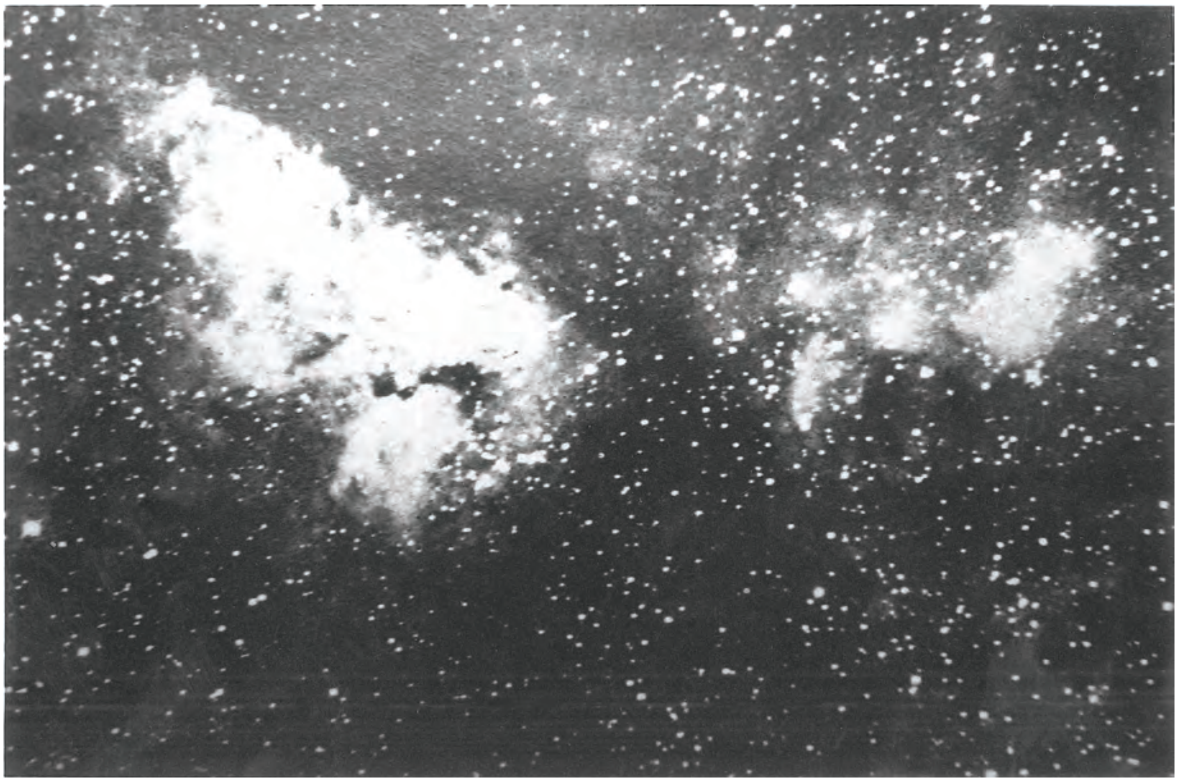


Figure 4.1 The Keyhole Nebula and surrounding regions of the southern Milky Way preserve remnants of the cloud of gas and dust from which stars and planets were originally formed.

knew nothing of them. He takes as his starting-point a cloud of hot gas that surrounds the Sun, and rotates with it. As the cloud cools it will contract and, since no mechanical energy has been lost, it will begin to spin more and more rapidly, in obedience to the physical principle known as the conservation of angular momentum.

As the cloud rotates, it first becomes disk-shaped and then, when it is moving fast enough, will throw off a ring of material from its outer edge. As the process continues a whole series of rings is thrown off, each of which provides the material to form a planet. So the Earth was born.

Laplace did not explain how the rings became transformed into planets, and unfortunately for his theory later analysis shows that there would be little tendency for them to be transformed into large bodies. The most that could be expected would be a swarm of tiny asteroids. Nevertheless, most recent theories owe something to Laplace; but before we look at them it would be as well to look at some of the alternatives that dominated astronomical and geophysical thinking well into the first few decades of the 20th Century.

While Laplace's system was one of steady evolution, most of his rivals began with a cosmic catastrophe. The idea first appeared as a suggestion by the naturalist Buffon that material could be struck from the Sun by a passing comet – though he clearly had in mind a more massive body than anything we would now regard as a comet.

One of the earliest of the modern theories was put forward by the New Zealand Professor A.W. Bickerton, whose colliding stars became involved in a whirling coalescence from which a filament of planetary material was drawn out as the wounded stars escaped. He emphasised a number of important matters that had previously been neglected – the heat that would be generated when the stars collided, the tidal deformation that they would undergo before they met, and the fact that nothing smaller than a star would have sufficient mass to separate the material from the Sun. Later theories differed mainly on the emphasis they placed on one or another of these factors. The most widely advocated views were those of Chamberlain and Moulton, in which tides played the major role; of Sir James Jeans, in which a cigar-shaped body was erupted from the Sun, resulting in a neatly-sized sequence of planets; and that of Sir Harold Jeffreys, which returned to a more straight-forward collision aided by heavier mathematics.

It would be more accurate to say that the older theories went out of fashion than to say that they have been disproved, though all of them were known at the outset to present difficulties. Growing knowledge of the atomic processes going on inside stars and increasing emphasis on the role of interstellar matter in cosmic processes left theories that involved little more than classical mechanics without much appeal to those trained in more recent cosmology.

Spectacular photographs from the world's great observatories have made the existence of widespread and heterogeneous clouds of interstellar dust and gas a familiar commonplace (Figure 4.1).

Since the 1940's C.F. von Weizsäcker and other cosmologists have explored the processes by which the material within these clouds can concentrate itself into stars and their associated planetary systems. Like Laplace, von Weizsäcker starts with a flattened envelope of material surrounding the Sun. In it, vortices are formed within which the nuclei of future planets can condense. Very similar views were developed by O. Yu. Schmidt and his colleagues at the Institute of Physics of the Earth in Moscow. He pictured the Sun's gravitation accreting a cloud of dust and gas as it travels through space. Friction between the gas and the dust particles shapes it into a thin disk, and collisions and encounters between nuclei within it finally create the nine major and minor planets, leaving the debris in the form of asteroids and meteoritic particles.

In these theories both the solar and the planetary material is cold to begin with, but at a later stage it must become hot. It can do this in two ways – as a result of gravitational collapse, and by the concentration of radioactive elements. In the case of the Sun, which eventually became hot enough to start and maintain its own thermo-nuclear reaction, gravitational collapse is the more important. In a smaller body like the Earth the temperature could never become great enough to initiate an internal reaction, and the accreted radioactive elements and solar radiation therefore play the major roles.

Knowledge obtained indirectly is not necessarily inexact. Nearly all of the most exact information we have about the Earth's interior comes from seismology, the study of earthquakes. The speeds and other characteristics of earthquake waves depend upon the densities, rigidities and compressibilities of the rocks they pass through. Earthquake records therefore enable us to locate the boundaries between different materials, and to make very good guesses at their identity. Thus they are a very powerful tool not only for investigating the central regions of the Earth, but for exploring small-scale features near the surface, such as individual volcanoes.

To understand how this is done we must learn a little more about earthquake-waves. There are two main types: body-waves and surface-waves. Since the main property of surface-waves is that they are guided round the Earth's surface and do not penetrate very deeply, we shall concentrate upon the body-waves.

Seismologists can recognise two kinds of body-wave, and since they refer to them a great deal they have developed a kind of shorthand for describing their behaviour. Their speeds vary in different materials, but one kind is always faster than the other. The faster ones are called P-waves, and the slower ones S-waves. A P-wave is really a sound-wave through the Earth. Physicists would call it a longitudinal wave, because it depends upon the particles of the material in which it travels moving to-and-fro along the line of travel, setting up a series of compressions and rarefactions. The S-wave is a transverse wave, in which the particles move sideways at right angles to the direction of travel, like a wave sent along a rope (Figure 4.2).

The letters P and S originally stood for "primary" and "secondary", and referred to their order of arrival. It will be easier to remember which is which if you think of them as "push" and "shake" or "shear".

In order to start a wave of any kind, you must do work against some force that resists your changes, and will do its best to put things back to normal the moment you leave off. In the case of waves on the

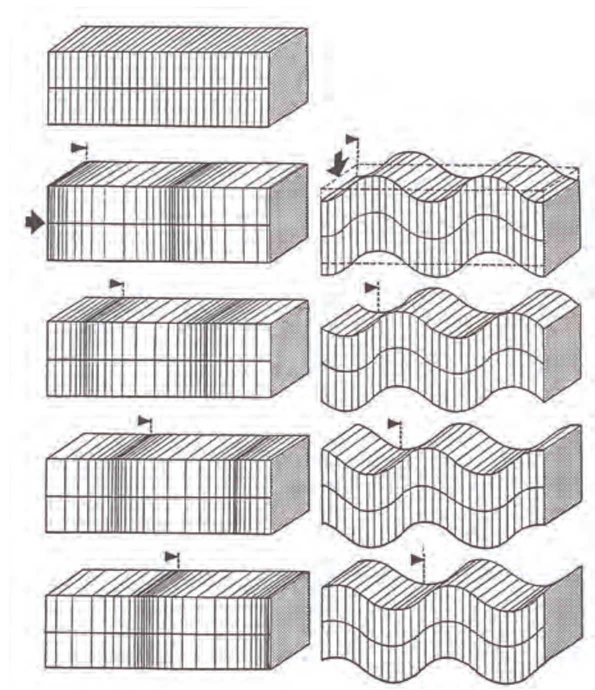


Figure 4.2 (from Earthquakes, G.A. Eiby, Fig. 18). Longitudinal and transverse waves. If the bar shown at the top left is given a sharp blow on the left-hand end, a compressional wave will travel along it to the right. A downward blow will start a transverse wave, like the one in a rope shaken at one end. Volcanic explosions can send both types of wave through the ground and, as the longitudinal waves travel more rapidly than the transverse ones, the difference in their times of arrival provides a measure of the distance they have come.

sea, the restoring force is gravity. Earthquake waves are elastic waves, and molecular forces between the particles provide the restoring force. A solid will transmit both P- and S-waves. No matter how you deform it, the particles will tend to come back to their original positions. It is quite different with liquids,which have no resistance to shear, and will assume any shape their container forces upon them. On the other hand, they have considerable resistance to pressure. The consequence of this is that while a liquid is happy enough to transmit a P-wave, there is no way you can make it accept an S-wave. Refusal to transmit an S-wave is therefore an indication that a substance is a liquid. When a solid is heated it goes through a stage in which it becomes plastic and can be slowly deformed under pressure, but substances in this condition still retain some rigidity and continue to transmit S-waves. This is the condition of a great part of the Earth's interior, and of many magmas and lavas.

In 1889 Dr E. von Rebeur-Paschwitz was studying the Earth's gravity at Potsdam in Germany, and noticed that the pendulums he was using were disturbed by large earthquakes in distant Japan. About the same time, the first satisfactory seismographs were invented, and it was found that they could record waves that had passed right through the central parts of the earth. The existence of the core was confirmed by R.D. Oldham, and shown to be liquid. When an S-wave reaches the Earth's core, part of it is reflected, and the rest is transformed into a longitudinal wave, and travels on as P. In 1913 Beno Gutenberg accurately measured the depth of the core boundary, which has become known as the Gutenberg Discontinuity. In 1909 another important boundary had been found by Andrija Mohorovičić, who located the base of the crust. The last of the major divisions of the Earth's interior was not discovered until 1936, when the Danish seismologist Inge Lehmann showed that the liquid core contained a solid nucleus known as the Inner core (Figure 4.3).

Until seismology was brought to bear on the question, it was widely assumed that the Earth possessed a comparatively thin outer crust resting upon a molten interior that was the source of the lava that issued from volcanoes. This simple view overlooked the fact that pressure is as important as temperature in determining whether a substance will exist in a solid, liquid, or gaseous state. It seems likely, for instance, that the outer and inner sections of the core are made of the same material, the difference in condition being the result of the difference in pressure.

We shall not follow the seismologist through all the detail of his ingenious explorations, but we shall need to use his results, and it will be helpful to glance briefly at the way in which he gets them. The purpose of a seismograph station is to record the movements of the Earth's surface at that particular place. Those movements are rather complicated, and it is usual to split the record into three separate parts – two horizontal components at right angles, and a vertical one.

Even a single component can tell us a great deal, however, and less elaborate stations sometimes have only one component, usually the vertical. Interpretation is a matter of comparing the records from a number of stations. To find the position of a shock and its depth a minimum of four stations is needed, and one of them must be as close to the origin of the earthquake as the depth of the structure it is hoped to measure. The shallower it is, the closer the recording stations need to be. For information about the central core, we need records from stations on the far side of the globe, while to explore the inside of a volcano a close network of stations no more than a few kilometres apart is used. When we have assembled our records we must identify waves that have travelled along adjacent paths, and measure their times of arrival. All stations have precision timing, and it is usual to work to a tenth of a second, but in volcanological work even higher accuracy is sometimes needed.

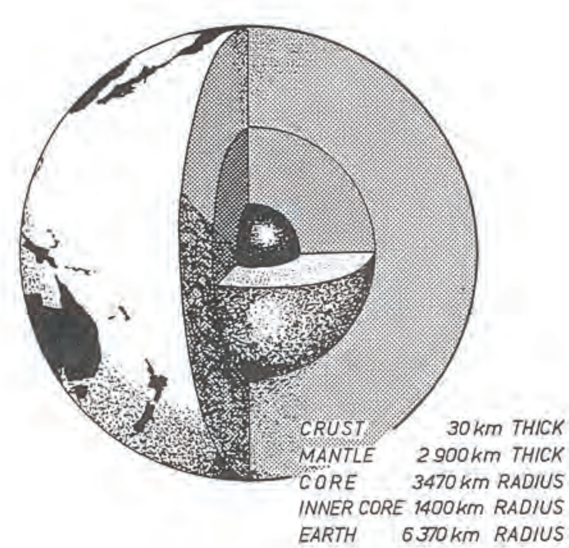


Figure 4.3 (from Earthquakes, G.A. Eiby Fig. 59).
The Earth's interior.

5—Finding a Volcano

Next morning, after breakfast a party of us set out for the country, to try if we could not get a nearer and better view of the volcano…After ascending another ridge, as thickly covered with wood as those we had come over, we saw yet other hills between us and the volcano, which seemed as far off as at our first setting out. This discouraged us from proceeding farther…

Capt. JAMES COOK: Journal, Aug. 14, 1774

A volcano that proclaims its presence by erupting is not hard to find, and some volcanoes obligingly remain in a state of more or less permanent eruption; but such behaviour is exceptional. Volcanoes spend most of their time sleeping, and in the end they die, but long periods of geological time must pass before it is safe to assume they are extinct. In the nature of things we cannot expect full marks for a map of the world's active volcanoes, however we decide to define "active". Nevertheless, Figure 5.1 reveals the heart of the matter.

Volcanoes lie in narrow belts, rather than in broad patches or lines of single craters. The belts differ in character, but they can be classified into a few major types. The two most important are those that follow the submarine ridges that cross the floors of the great oceans, sometimes showing their heads as small islands, (for example Easter Island, Figure 5.3, the small dot on the main map in Figure 5.1 just north of the 90 W on the Antarctic inset), and those that outline the margins of the ocean basins. This pattern is very similar to that of the world's earthquakes (Figure 5.2) and this is no accident, for both earthquakes and volcanoes are products of the same fundamental geological processes. Let us look at these more closely.

The first problem that we face is that seventy per cent of the earth's surface is covered with water. It is not easy to study rocks that lie beneath several kilometres of ocean, or even to dredge up samples of the bottom for study, and until recently we have had to do the best we could with what we knew to be a badly distorted picture. Within the last few decades advances in instrumentation have greatly improved matters. Not only can we make continuous records of depth, gravity, and magnetism from a moving ship, but we can determine the ship's position accurately. In the past, when the stated position of a ship could be out by several kilometres, the value of precise measurements made on a bottom-sample was greatly reduced.

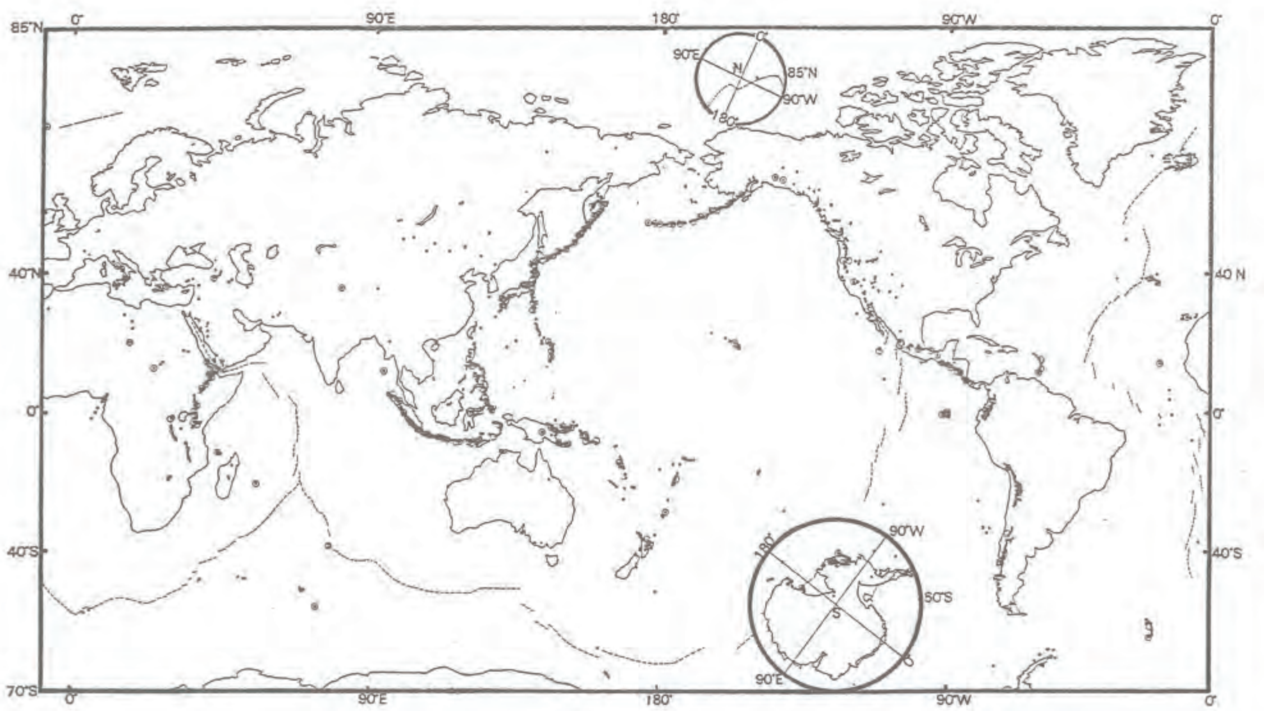


Figure 5.1 Distribution of volcanoes known to have been active in the last 10,000 years. The broken lines show the position of the mid-oceanic ridges.

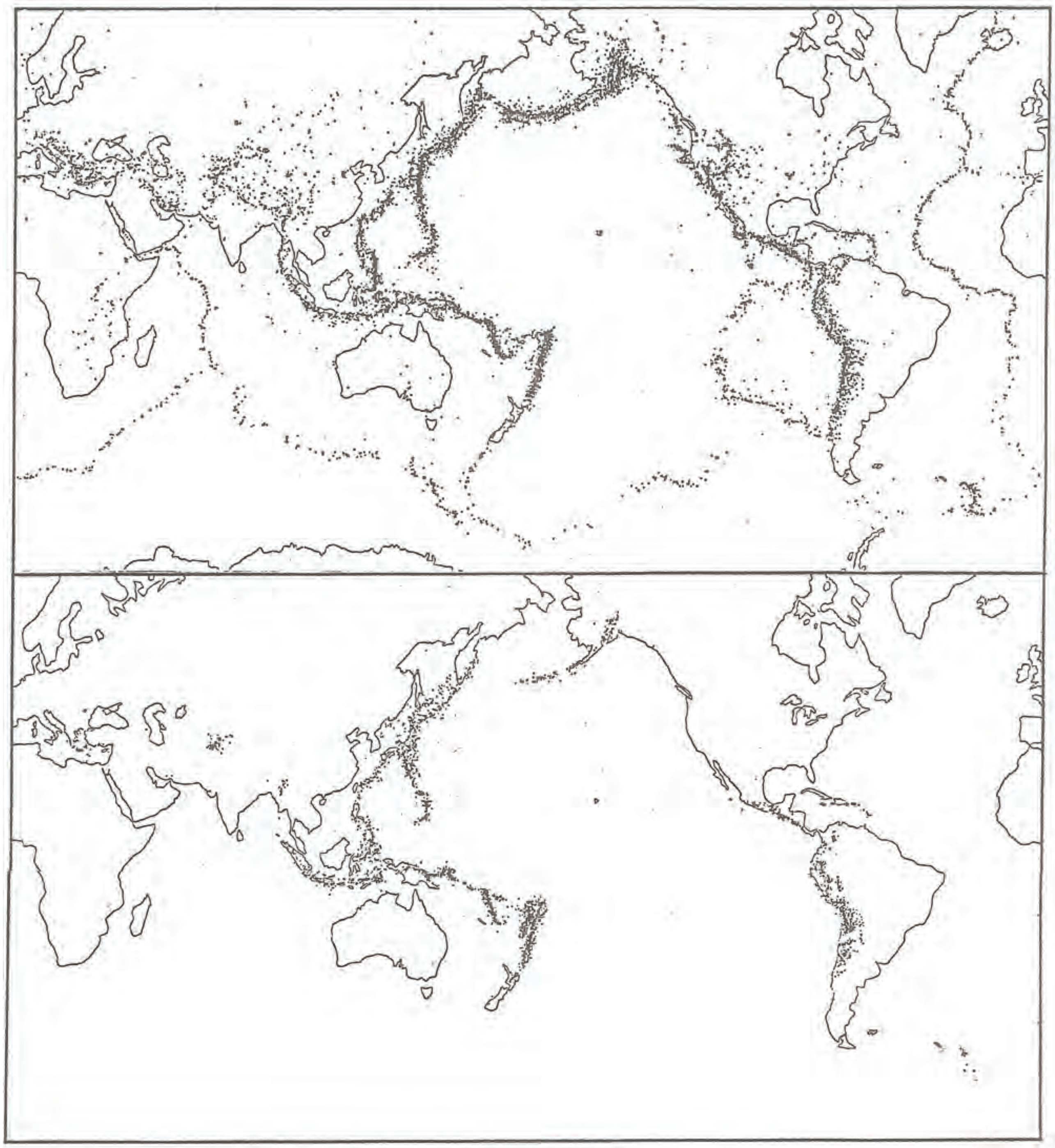


Figure 5.2 (from Earthquakes, G.A. Eiby, Fig. 82). Shallow and Deep earthquakes. These maps show the seismically active regions and the position of the mid-oceanic ridges very clearly, but do not show the relative seismicity of different parts of the globe very exactly, as not all countries have good recording networks. The upper map shows shallow earthquakes recorded between 1962 and 1967, and the lower one those with depths of more than 100 km in the same period (after Barazangi and Domain).

These technical advances began to bear scientific fruit in about 1950, when it became apparent that the mid-oceanic ridges formed a connected network that enmeshed the globe, and that the submarine mountain-chains were usually divided longitudinally by a central rift. At the same time, more and more accurately-located bottom-samples were being obtained from the really deep parts of the oceans. Previously it had been natural to assume that the ocean floors had lain undisturbed for a long time, that they would be covered by thick deposits of sediment, and that the bottom layers of sediment would be very old. Instead, they turned out to be thin, and the oldest ones that were found had been laid down a mere 135 million years ago, in the Cretaceous period. Two American oceanographers, R.S. Dietz and H.S. Hess, suggested that this was because the ocean floors were continually moving outwards from the ridges and carrying the older material to the ocean margins.

This was not a new idea. Many geologists considered that sea floor spreading produced the forces that had

Figure 5.3 Easter Island, a Holocene complex structure of basaltic shields: one of the world's most isolated volcanoes.

folded the chains of young mountains that paralleled the ocean margins, and others invoked something of the kind to back up their conviction that the continents were slowly drifting about and changing their relative positions. So far all attempts to measure these movements had failed. Most physicists argued that they failed because the viscous condition of the material in the outer hundred kilometres of the Earth would make movements of the kind the geologists suggested quite impossible. It was a physical measurement that proved them wrong, and to understand how we must digress to consider the Earth's magnetism.

Any boy scout who has used a compass knows that the Earth is magnetised, and that there is a difference between the "magnetic" north the compass shows and the "true" north he can find from the stars. By the sixteenth century it had been realised that the difference was slowly changing, and that the magnetism of the Earth must be rather different from that of a piece of lodestone or a bar of iron. The Earth's magnetic field turns out to have two parts. The weaker part arises from the interaction between streams of electrically-charged particles coming from the sun and those in the ionosphere, the layer in the upper atmosphere that helpfully reflects radio-waves round the globe. For our purposes it is less important than the internal field that originates in the Earth's core.

The core is fluid, and a good conductor of electricity. The movements of the fluid and the electrical currents that circulate within it combine to form a kind of dynamo that generates the main field. Those who understand exactly how the circulation behaves hide it from the profane in a thicket of fearsome mathematics, which conceal the important conclusion that the arrangement is unstable. The Earth's rotation ensures that the magnetic poles remain somewhere near the geographic ones, but every so often a small upset in the internal currents produces a magnetic reversal. The dynamo slowly rearranges itself and over the next thousand years or so the north and south magnetic poles change places. The end of the compass-needle that had been pointing to the north now seeks the south with equal persistence.

There has been no magnetic reversal in historic times, but magnetised rocks preserve evidence that there have been many in the quite recent past. The study of this record is called palaeomagnetism (Greek palaios, ancient). When rocks are heated above about 600°C, a temperature called the Curie point (after Pierre, not Marie), they lose their magnetism; but on cooling once more they become re-magnetised in whatever direction the Earth's field has at the time.

One of the first detailed studies of the magnetism of the rocks of the sea floor was made on the Reykjanes Ridge, which extends south-westwards from Iceland (Figure 5.4). As the ship made its way to and fro across the Ridge the direction of magnetisation was found to change every few kilometres. Alternately magnetised stripes lay parallel to the axis of the Ridge, and on either side of it the patterns were almost exact mirror-images. Before long similar data had been gathered from the Indian Ocean and the Antarctic Ridge, and in 1963 F.J. Vine and D.H. Matthews of Cambridge University realised that here was observational proof that the sea floors were in fact moving.

Below a thin layer of watery ooze and soft sediments the deep ocean floors are made of a dense basalt that has come from the submarine volcanoes of the mid-ocean ridges, and is similar to that erupted from the volcanoes of Iceland and Hawaii. The rising lava accumulates, cools, and solidifies and is then steadily thrust outwards as the continuing activity adds more and more material to what has become a spreading ridge. The rate of outward movement depends upon the vigour of the activity. In most cases, it amounts to a few centimetres per year. As the lavas cool and the temperature falls below the Curie point the rocks

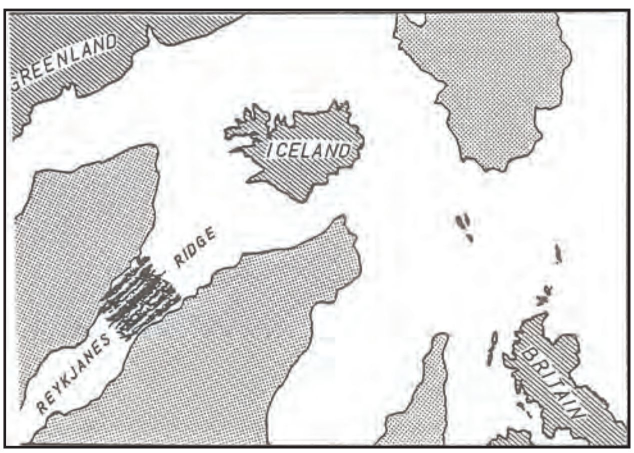


Figure 5.4 (from Earthquake, G.A. Eiby, Fig. 65). Magnetic striping of the sea floor on opposite sides of the Reykjanes Ridge, south of Iceland. Black and white regions are oppositely magnetised, and the patterns on opposite sides of the Ridge are mirror-images.

become magnetised. Because the spreading outwards from the ridge proceeds in both directions, rocks of the same age will be found at equal distances on either side of it, and will be magnetised in the same direction. The reversals account for the stripes, and the regularity of the movement for the symmetry.

Piece by piece, these ideas developed into a new way of looking at the outer parts of the Earth, which has come to be called <u>plate tectonics</u>. The word tectonics was already part of the geologist's vocabulary. It comes from the Greek <u>tekton</u>, a builder, and has been defined as "the architecture of the Earth's crust", but most modern geologists use it in a more dynamic sense to cover the processes of folding, faulting, mountain building, and the rise and fall of crustal blocks. According to the plate tectonic hypothesis the outermost layers of the Earth are divided into a number of rigid plates that fit it like loose caps, free to move about on the surface of a zone of weaker material at a depth of 150 or 200 km. This zone is known as the <u>asthenosphere</u> (Greek <u>a</u>, without, and <u>sthenos</u>, strength).

There are six main plates and an ever-growing number of minor platelets resulting from the efforts of geologists to improve the fit of the global jig-saw (Figure 5.5) In the main the boundaries of the plates follow surface features that can be recognised as structurally important on other grounds, such as the boundaries between continent and ocean. Nearly all the active volcanoes lie close to one of these plate boundaries, but there are some exceptions accounted for by fractures within the plates and other "hot spots" that we shall describe later.

Volcanoes differ greatly from one another, but there are family resemblances to be found between those that lie along the same plate boundary, and between those where the conditions at the boundaries are similar. One important generalisation is that the volcanoes of the spreading ridges usually erupt dense basaltic lavas that are chemically basic, while those that ring the ocean basins produce more acid and lighter andesitic ones. As with most generalisations it is not hard to find exceptions. "Andesitic" volcanoes can readily erupt basalt, and those on the ocean ridges can produce rhyolite. To understand both the rule and the exceptions we must consider the structure of the Earth and the details of plate tectonics more closely.

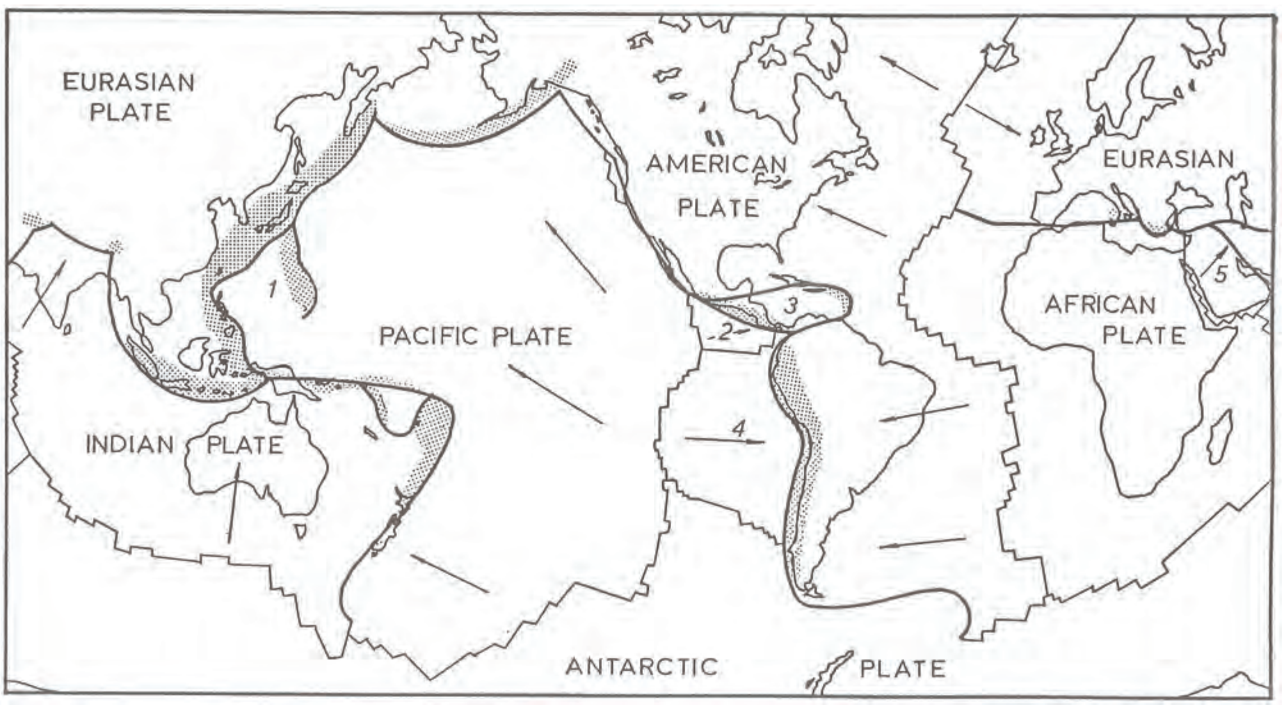


Figure 5.5 (from Earthquakes, G.A. Eiby, Fig. 65). Boundaries of the lithospheric plates. The names of the major plates are shown, and minor platelets are identified by numbers: 1 Philippines Plate, 2 Cocos Plate, 3 Caribbean Plate, 4 Nasca Plate, 5 Arabian Plate. The main zones of deep earthquakes are shaded, and the arrows show the directions in which the plates are believed to be moving.

6—Inside and Out

Well, my deliberate opinion is – it's a jolly strange world!

ARNOLD BENNETT: The Title

Basically the Earth is a rather simple structure. A thin rocky crust and a solid mantle surround a liquid core that probably has a solid nucleus. On the human scale the outer surface is rough and varied, but this impression is deceptive. The Earth is 12,742 km in diameter, but the difference in level between the summit of Mount Everest and the bottom of the greatest ocean deep is only about twenty kilometres, and the average difference between continent and ocean floor a mere five – yet we cannot ignore the variety of the surface rocks and their complex pattern. This is the traditional province of geology.

Most of the rocks accessible to the geologist belong to the upper layers of the crust, though there are some deeper ones that have been brought to the surface by volcanism or the processes of folding and fracturing, and have been exposed by erosion. Even the deepest of these have come from no greater depth than the uppermost part of the mantle, and the great bulk of the Earth must be studied indirectly.

The inside of the Earth is hot, but we cannot be sure how hot. Since metals are good conductors of heat, the core is probably at the same temperature right through. The temperature must be high enough to melt it, but not so high that it could also melt the rocks of the solid mantle above. Allowing for the pressure of the material on top, that puts it at about 2,500°C, which is far less than the temperature gradients we measure at the surface would lead us to expect.

The core is the only large reservoir of molten material inside the Earth, but it cannot be the source of the lava that issues from volcanoes. The pressure behind anything that came from a depth of 2,990 km would probably hurl it straight into space. We must therefore look for a source comparatively close to the surface, in the form of material that is normally solid, but can under certain conditions melt and erupt. This parent material from which lavas are derived is called magma, a term coming from a Greek root meaning "to knead". When magma reaches the surface and the confining pressure is released it quickly gives up its dissolved gases, either becoming fragmented in the process, or becoming more fluid and emerging as lava. Lava is just magma that has lost its gas, while the fragmented materials are known as pyroclastics (Greek pyr, fire, and klastos, broken in pieces). For convenience lava, pumice, ash, and anything else that comes out of a volcano are lumped together under the term ejecta, which is just Latin for "things thrown out" – though one might hesitate to apply the word to the kind of copious lava-flow that emerged at Laki.

Whether a substance is solid, liquid, or gas depends upon both the pressure and the temperature, and when these differ greatly from those we meet daily, common substances can develop surprising physical properties. One property that is often affected is the time the material takes to respond to a change, and the response to slow and rapid changes can be quite different. If you take an ordinary lump of pitch and hit it hard with a hammer, it will shatter into fragments, and you will be quite justified in calling it a brittle solid – but if you had left the same lump of pitch overnight on the laboratory bench you would find that by morning it had assumed the shape of a puddle and provided clear evidence that it was a viscous liquid. The Earth's mantle behaves much like pitch. Seismic waves show it to be a solid – but give it time, and it can flow.

Except for the metals, solids are very poor conductors of heat, and it takes a long time for changes of temperature at one place in the Earth's crust to become

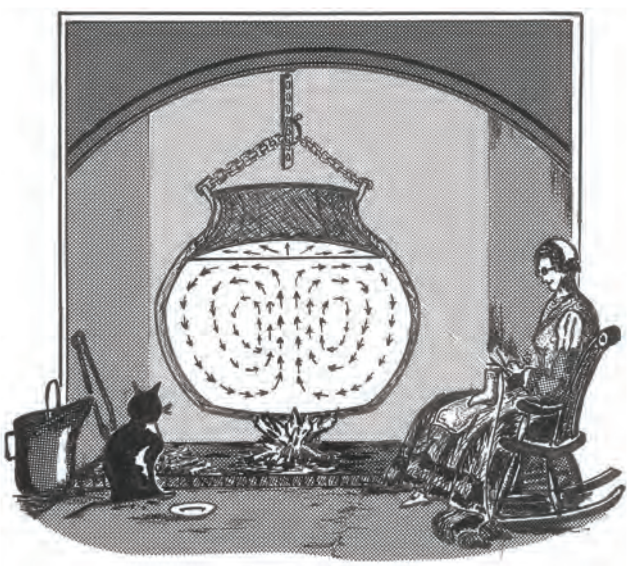


Figure 6.1 Convective circulation in the kitchen.

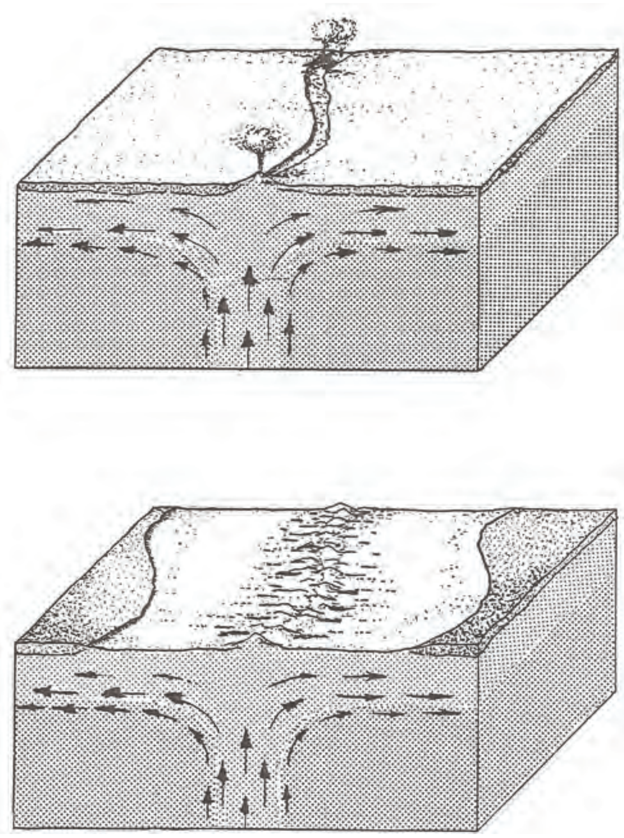


Figure 6.2 (from Earthquakes, G.A. Eiby, Fig. 84). Rising convection currents beneath the mid-oceanic ridges produce volcanic activity that adds material to the edges of the lithospheric plates and drives them apart.

apparent in another, even a short distance away. A thermometer buried a metre or so in the garden will not respond to daily changes at the surface, and one buried two or three metres deep will not even respond to differences in the seasons. When heat must be moved in a hurry it is best to carry hot material from one place to another. If conditions are right, it will move of its own accord. The process is called convection (Latin, convehere, to carry together).

If heat is applied to some part of a liquid it expands, becomes less dense than its surroundings, and rises. On reaching the surface it cools, becomes more dense than its surroundings, and sinks again, creating a circulation. The process can be seen in any cooking-pot (Figure 6.1). The rocks of the mantle are liquid enough to allow a slow circulation of this kind, and the convection currents in the mantle act as major distributors of the Earth's internal heat. In broad terms, there are rising currents beneath the mid ocean ridges, and descending ones at the continental margins (Figure 6.2).

Convection currents are an important part of the mechanism of plate tectonics. Rising currents beneath the mid-ocean ridges supply the material that is intruded along the ridge axis, and erupted from the volcanoes, and adds all this to the edges of the plates, forcing them apart as it cools and becomes part of the sea floor. The outward circulation of the current beneath the plate provides a kind of natural conveyor-belt to assist its movement towards the ocean margin. At the margin, the oceanic plate comes into collision with the surrounding continent, but before we consider what happens to the colliding plates we shall look once again at the crust.

The upper surface of the crust is accessible and familiar. We live on top of it, and dig and drill our way into it in our search for oil and other minerals. The greatest depth we have reached is about 15 km – which is impressive until we remind ourselves that it is over six thousand kilometres to the Earth's centre. The variety of the upper surface is not characteristic of the crust as a whole, and continental and oceanic crusts are different. The continental crust is typically about 35 km thick, and is divided into two roughly equal layers. Seismologists, who tend to concentrate upon physical properties and to ignore the niceties of chemical composition and petrological nomenclature, call the uppermost layer granitic and the lower one basaltic, and it is broadly true that the rocks of the granitic layer are less dense and more acidic in composition. The oceanic crust is much thinner, usually about 5 km thick, and the granitic layer is missing.

The base of the crust is known as the Mohorovičić discontinuity, after the seismologist who first detected it in about 1910. The habit of calling it the Moho is widespread but disrespectful. Below it are the ultra-basic rocks of the upper mantle, and no more sharp boundaries are found until we reach the core.

The Mohorovičić discontinuity does not mark the bottom of the plates. Plates only 30 km thick would not be nearly strong and rigid enough to behave as they do. In the upper mantle two opposing forces are at work on the rocks. The increasing heat tries to weaken them, and the increasing pressure to make them more rigid. For the first hundred kilometres or so the heat wins, and the rocks become weaker and weaker, but at greater depths the pressure finally dominates. The result is a zone of weakness through which earthquake waves pass less readily than they can through the more rigid material above and below. They become trapped in it, and seismologists refer to it as the low-velocity channel. It is of course the same thing as the asthenosphere upon which the plates can move, and marks the somewhat diffuse boundary between the upper and lower mantle, and between rocks with the familiar properties of those at the surface and those transformed by high temperatures and pressures. The region lying above the asthenosphere is called the lithosphere (Greek lithos, stone), and the plates are often described as lithospheric plates.

Let us surface once more and see what happens when two plates collide. If two similar plates come together the result can be a chain of fold mountains as spectacular as the Himalayas, which lie along the boundary of the Indian and Eurasian plates. A more oblique collision may allow the plates to slide sideways past one another, as they do along the great San Andreas Fault in California. The contact of a plate boundary like this is rough, and from time to time the roughnesses succeed in holding up the movement, which normally shows itself as a gradual creep. When the plates get stuck the rocks begin to deform, and elastic strain builds up until it finally becomes great enough to overcome the resistance by fracturing the rocks and releasing the strain as earthquake waves. This will either free the plates and start another period of creep, or they will stick again until there is enough strain to produce another earthquake.

Direct collisions between an oceanic and a continental plate are more complicated, as there is usually a descending convection current involved as well. The ocean floor is pulled or sinks downwards, and the lighter continental rocks are thrust over the top.

Geophysicists still argue about the relation between the movement of the plates, the convection currents, the forces exerted by the addition of material at the ridges, and by the gravitational pull of the down-going plate. The basalts of the plate are denser than the heated materials of the upper mantle, and may be heavy enough to sink under their own weight without much help from convection currents.

As the down-going plate is gradually bent over and is sucked or thrust or sinks downwards several things happen. The bending strains cause sudden fractures which come to our notice as earthquakes. They are concentrated in the upper part of the plate and enable us to follow its downward path. At a depth of about 700 km they cease, either because what was left of the plate has completely melted and been absorbed into the mantle, or because it is now too soft to support enough strain to cause an earthquake.

We have not forgotten the volcanoes. By the time a plate has sunk to the level of the asthenosphere, softening of the outer surfaces is well advanced, and it melts. If the nose of the upper plate is fractured – which, after an eventful history that involves a collision is more likely than not – molten material can work its way to the surface, and volcanoes appear. This is not just a simple matter of forcing its way through cracks, as we shall see in Chapter 9, but involves melting of the material encountered along the route to the surface. Particularly in their youth, these volcanoes erupt stiff lavas rich in silica, and build up the lofty cones that most of us picture as the typical form of a volcano. It is

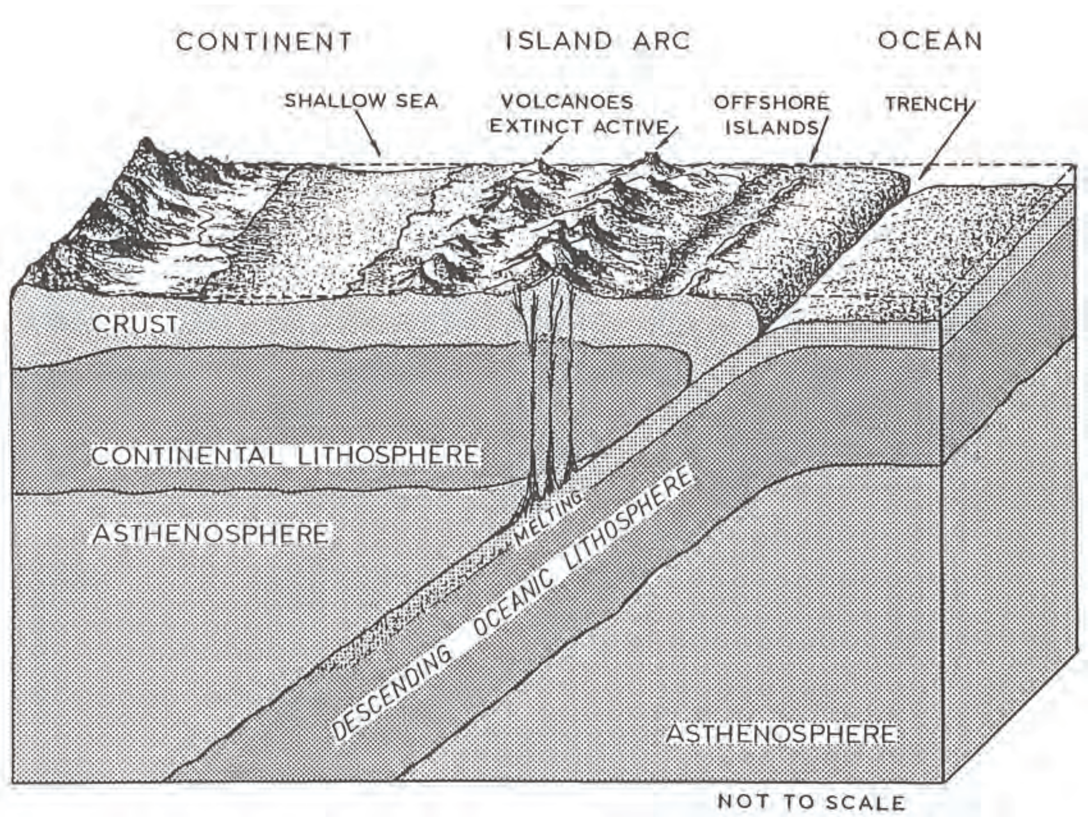


Figure 6.3 (from Earthquakes, G.A. Eiby, Fig. 86). Subduction beneath an island arc. Not all the features shown are to be found in every arc, but when they are present their relative positions are maintained. Shallow earthquakes occur over the whole breadth of the zone, but deeper shocks are confined to the descending plate, the pattern at active continental margins is essentially similar.

usual therefore to call them acidic, although they will probably produce basalt at some stage in their history. The region where these processes are occurring are known as subduction zones (Latin sub, under, ducere, to lead); or as convergent or destructive margins because of the consumption of the oceanic floor.

The various features of a subduction zone are arranged in an orderly way that was recognised long before plate tectonics had been thought of, and many earlier terms and concepts remain in valid use. The arrangement is to be found both in island arcs and at active continental margins. The Aleutians are perhaps the most striking example of an island arc, but there are many others to be found around the Pacific, and Indonesia provides fine examples.

Figure 6.3 shows some of the typical features of a subduction zone. A deep and narrow ocean trench marks the boundary between the colliding plates. The contact between them and the flexure of the down-going plate create stresses that are relieved as shallow earthquakes, which have been missing during the steady progress of the plate across the deep ocean. They may be large. Sometimes the leading edge of the continental plate is forced upwards to form a ridge, and a few small islands, like the Mentawai Islands off the south coast of Sumatra, may make their appearance. Beneath the main islands of the arc the earthquakes become progressively deeper, following the upper surface of the plunging plate. Active volcanoes appear above where the earthquakes are at a depth of one to two hundred kilometres. Unless the arc is very young, older volcanoes will be found behind them, and extinct volcanoes may extend to the coast of a shallow sea lying between the islands and the continental mainland. The belt of shallow earthquakes does not as a rule extend far beyond the volcanoes, and shocks on the inner side of the arc tend to be less violent. In a well-developed system the activity may continue beneath the continent itself until the maximum depth of about 700 km is reached. Not every island arc exhibits all the features described, but when they are present the relative positions are maintained. Active continental margins, like the western coast of South America, are not essentially different.

7—Eruptions Classified

And from this chasm, with ceaseless turmoil seething,
As if this Earth in fast thick pants were breathing,
A mighty fountain momently was forced,
Amidst whose swift half-intermitted burst
Huge fragments vaulted, like resounding hail.

SAMUEL TAYLOR COLERIDGE: Kubla Khan

What happens when a rising column of magma reaches the surface depends upon its composition, its temperature, and what it meets when it arrives – fissure, cone, ocean bottom, or ice-sheet. The beginnings of some kinds of outbreak, such as the re-opening of old fissures in small Hawaiian eruptions and in the crater of Vesuvius, have been well observed on many occasions; but detailed descriptions of the opening of completely new vents, or of very large fissures as at Laki in 1783, are rare.

The earliest stages of an eruption do not seem to be violent. Rather, the ascent of the magma is a steady but accelerating process that becomes explosive only after a breach has been made. Neither the nuclear processes that now leap to mind at the mention of explosions nor the long-familiar chemical reactions of gunpowder and dynamite have much relevance to volcanoes, except that in all of them the sudden release of gas under pressure plays a large part.

Of all volcanic gases steam is the most abundant and the one most often involved in violent explosions; but it is not the only gas present, and it often becomes involved only at a comparatively late stage. In spite of their importance in volcanology and the major contributions they have made to the composition of the air and the oceans, we are still very ignorant of the sources of magmatic gases.

Water is the one volcanic constituent that clearly originates near the surface. Most other gases almost certainly come from the mantle, as even those magmas that have formed from crustal rocks containing little volatile material are quite rich in gas. If they do come from deeper levels, the relationship between the gases and the lava in a particular eruption could have been largely determined by chance. Present ideas about the origin of the Earth and the part that gases rising from the interior played in its early history favour a deep origin.

Although volcanic explosions depend upon the gas content of the magma the process is not quite straightforward. Explosiveness is linked to the viscosity of the magma involved, and viscosity falls with rising temperature. Since andesitic rocks melt at a temperature 400°C lower than that needed to melt basalt, they reach the surface at a lower temperature and a higher viscosity. Viscous lavas have difficulty in passing through small fissures, so they slow down, solidify, and plug the vent. If gas continues to accumulate beneath the plug an explosion becomes inevitable. The stronger the plug, the longer it holds, and the bigger the eventual bang. A basalt rich in gas on the other hand may either emerge gently in the form of a froth, or throw up spectacular fire-fountains.

The gas content of a magma reduces its density, especially when bubbles are formed, and this enhances its ability to rise. It also determines how long a lava will remain able to flow. If there is sufficient gas it may remain fluid even when the temperature has fallen to 600°C or 700°C. During the final steps of cooling, chemical reactions between the magmatic gases and the oxygen of the air can generate additional heat and further delay cooling. In Hawaii instances of lava-flows becoming hotter are known.

No two eruptions are exactly alike, and the ones we have so far described were chosen to illustrate the diversity. When Vesuvius erupted in A.D. 79 it was already an impressive mountain, though it had been dormant for a long time. The erupted material contained much gas, and Pompeii was buried under pumice. Eruptions of this kind from a single vent are known as central eruptions. Parícutin has become the standard example of a "new" volcano, but it would be better to regard it as a new vent rather than as a new volcano, as it probably shares its magma-chamber with nearby cones, and the field as a whole can be considered dormant. The term areal eruption is sometimes applied to regions like Parícutin and Auckland, but volcanic field is the better term.

It is probable that Goropu, in Papua, is a much better example of a new volcano. In 1943 it appeared in a place where the only other known volcano had last erupted in the Pleistocene, two or three million years ago. Unfortunately its story is not known in the same detail.

Laki was different indeed, and belongs to the class of fissure eruptions. Vast quantities of basalt issued from a crack that became some 30 km long. Being liquid, it did not build up around the crack but flowed across the country-side and down the river-channels. Only in the final stages, when the crack was largely filled with cooling material, did a line of about a hundred tiny conelets build up to mark its position.

Just as there is more than one way to arrange a stamp-collection, there are a number of ways to classify volcanoes and eruptions (which are not at all the same thing, for volcanoes can change their habits). The character of an eruption depends both upon the supply of magma and its composition. It also depends upon the way the vent is blocked, for a volcano must clear its throat before it performs.

One common classification depends upon comparisons with a series of historical eruptions that typify the different ways in which volcanoes can behave. We will look at them in growing order of violence, or what amounts to the same thing, in the order of increasing chemical acidity and increasing viscosity of the magma (Figure 7.1).

In Icelandic eruptions enormous floods of liquid basalt pour from a fissure. In historic times only one has been on the scale of Laki, though the eruption of Eldgjá in A.D. 934 is a possible rival. In the geological past there were many more, which have left a record in the form of plateau basalts, which cover large areas in many parts of the world. About 150 million years ago, in Jurassic times, they appeared in Africa,

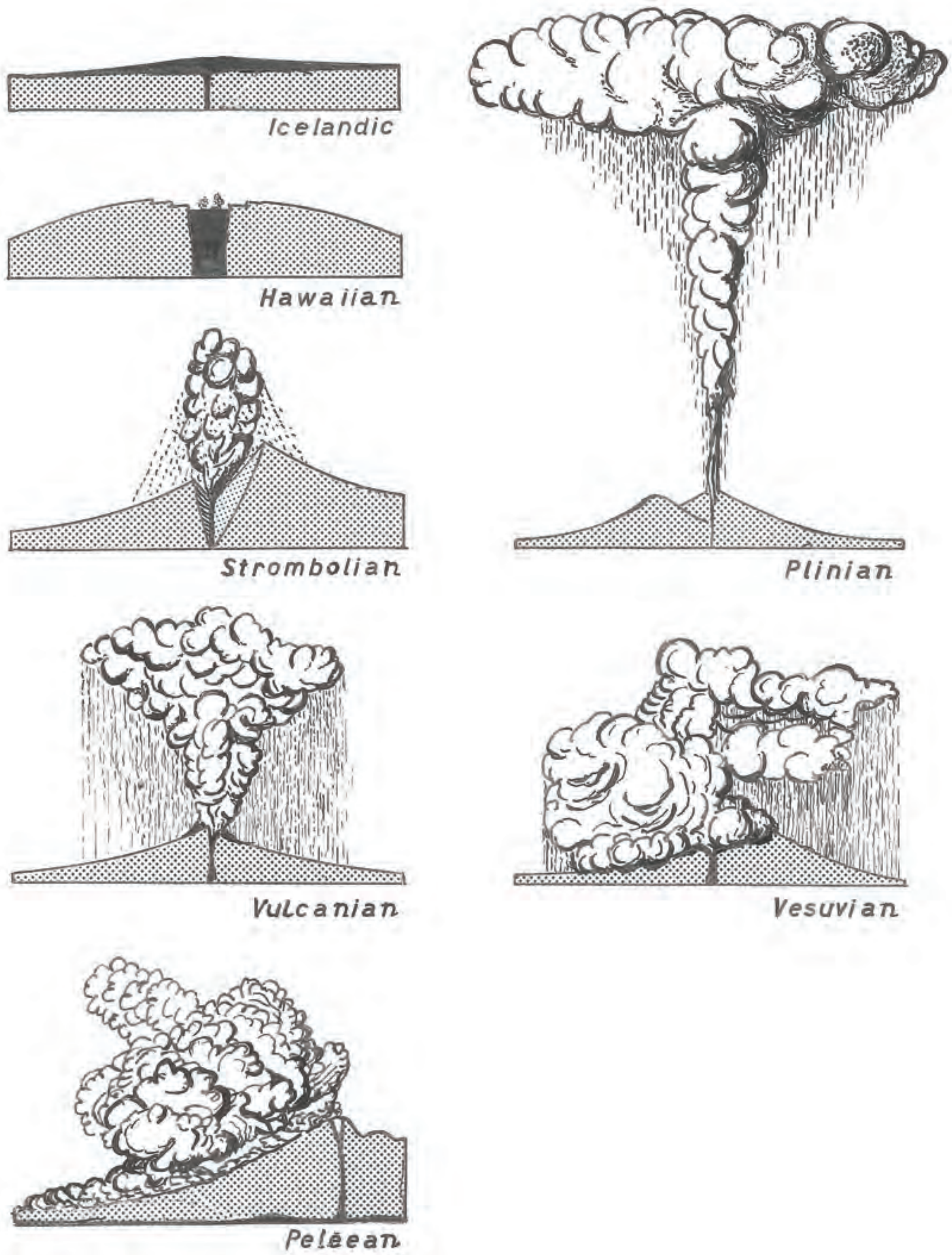


Figure 7.1 Eruptions classified. The sizes of the volcanoes and the eruption clouds are roughly to scale.

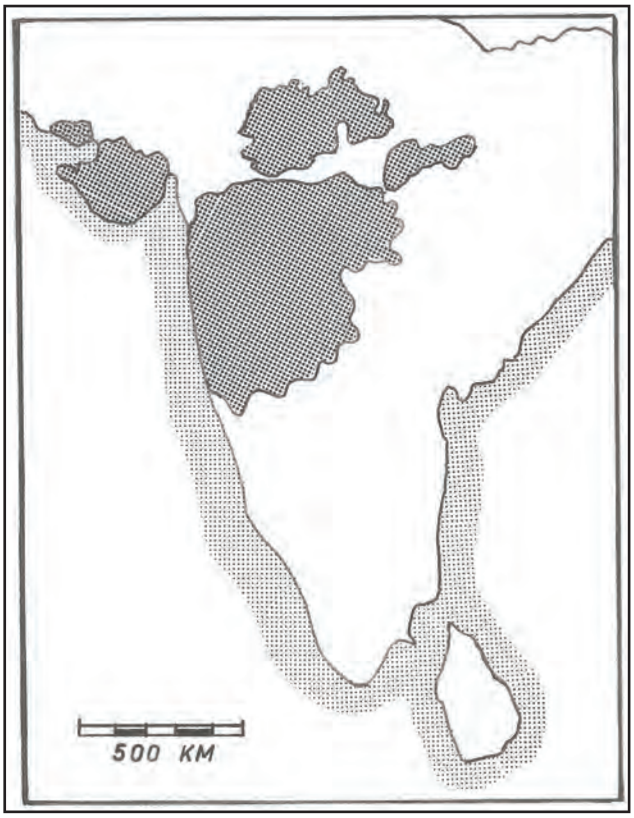


Figure 7.2 The Deccan Traps, which cover an area of 250,000 sq. km, exemplify the extent of plateau basalts. Ancient eruptions produced the repeated floods of basalt lava that have since been eroded to produce the stepped layers of the Deccan Traps.

Figure 7.3 View of the Deccan Traps.

Siberia, and south-eastern Australia. More are to be found stretching from the western isles of Scotland to Greenland, but they are much younger, and were part of the activity that persists in Iceland today.

One of the most impressive of these outpourings occurred about 20 million years ago in the Columbia River area of the western United States of America, and covered 130,000 sq. km of Oregon, Washington, and Idaho. The individual flows are seldom more than a few metres thick, but repeated eruptions finally succeeded in drowning hills 1,500 metres high.

An even bigger area of plateau basalt can be found in India (Figures 7.2 and 7.3). It covers 250,000 sq. km, and is known as the Deccan traps. In spite of its size, it seems to be no more than the eroded remnant of the original plateau, displaying a characteristic stepped formation that gave it its name, which is derived from the old Swedish word trappa, a stair.

Before we leave Icelandic eruptions we should note that violence and destructiveness are not the same thing. Basaltic eruptions take place quietly, but few explosions have had such disastrous consequences as the events at Laki. Finally, we must observe that not all eruptions in Iceland are Icelandic!

The volcanoes of Hawaii are exceptionally well-behaved, and can usually be trusted to perform a range of spectacular antics for the amusement of tourists, without sudden and unpredictable lapses into dangerous displays of ill manners. Like the Icelandic fissures they emit large quantities of fluid basalt, and if we concede the right to be called Icelandic to the smaller as well as to the larger eruptions in Iceland it is possible that Hawaiian eruptions do not deserve a special classification. One characteristic shared by the volcanoes of Hawaii and Iceland is the production of spectacular lava-fountains when gas is being given off (Figure 7.4) – but some writers insist that when there are fountains we should call the eruption Hawaiian!

Because of their fluidity, the Hawaiian magmas can readily give off their gas without producing violent explosions, and the lava flows easily from the vent, building up a dome-like structure with sides that slope at no more than about six or eight degrees. The volcanoes of Samoa and the Galapagos Islands also erupt in this way. The true size of these structures is not at once apparent, for although Mauna Loa and Mauna Kea rise an impressive 4,000 metres from the sea it is easy to overlook that their bases stand on the Pacific floor, 5,000 metres below. Structures of this kind are called shield volcanoes, by reason of their shape (Figures 7.5 and 7.6).

Strombolian eruptions are modelled upon the behaviour of Stromboli in the Aeolian Islands, which has earned itself the title of “lighthouse of the Mediterranean” by producing flashes of light at brief and regular intervals that have varied down the years from a few minutes to an hour or more. Although there have been interruptions marked by more violent outbreaks, this rhythmic behaviour has continued for at least two thousand years. Other volcanoes may exhibit Strombolian behaviour only intermittently, or as a brief episode in their active life; but a few of them, like Yasour in Vanuatu (formerly the New Hebrides) are about as constantly active as Stromboli itself (Figures 7.7, 7.8 and 18.2).

Figure 7.4 Fire fountain from Eldfell on Heimaey in 1973.

Figure 7.5 Banks Peninsula, New Zealand is the eroded remnant of two shield volcanoes.

Figure 7.7 Stromboli, whose rhythmic eruptions have earned it the title "lighthouse of the Mediterranean".

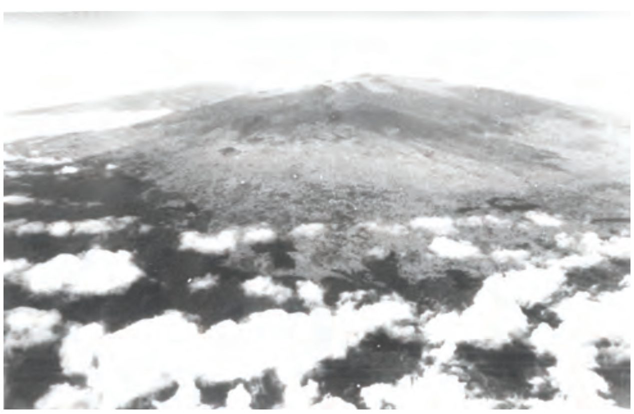


Figure 7.6 The great Hawaiian shield volcanoes Mauna Kea, and behind it, Mauna Loa.

Figure 7.8 A strombolian eruption of Etua.

The lava of the volcanoes that display this kind of activity can differ greatly in chemical composition. Its essential quality is that it should be less fluid than the Icelandic and Hawaiian basalts. This allows its surface to cool and form a crust that prevents the dissolved gases from escaping until they can accumulate sufficient pressure to burst it. Since the composition of the lava and the rate of cooling change only slowly, the interval between explosions remains fairly constant for long periods. Individual explosions can be quite violent, hurling lava "bombs" and lumps of glowing scoria in a rain that can cause heavy casualties and deaths. A particularly violent eruption of Stromboli in 1930 decided fishermen from Ginostra to emigrate to New Zealand, and they now work the waters of Cook Strait from the Wellington suburb of Island Bay.

During periods of intense activity, Strombolian ejecta may form a greyish cloud above the crater, but its height is seldom more than a few hundred metres. Lava flows may continue for months, or even years, but the volume of material expelled is nowhere near as great as that of the fissure basalts, and the vents of Strombolian volcanoes eventually become surrounded by cinder-cones made up of the exploded material. Other volcanoes of this type are Mihara in Japan, Capelinhos in the Azores, and Izalco in El Salvador.

Although Vulcano (Figures 3.2 and 3.3) lies only forty kilometres to the south-west of Stromboli, its lava is much more pasty and viscous. This enables it to form a thicker and more lasting crust than its neighbour can. This is a very effective trap for the rising magmatic gases, and when the eventual Vulcanian eruption takes place it is a more violent and spectacular affair, usually sending a dark "cauliflower" cloud heavily charged with ash to several times the height of the cone (Figure 7.9). Since every volcano must clear its vent before it can begin a new eruptive cycle, most of them start with an eruption of Vulcanian type. The type of lava that will be involved at a later stage is much less significant. Vulcanian characteristics can also reappear at the end of a cycle, when the waning strength of the eruption remains just sufficient to clear the vent of material that has fallen from the crater walls. Ngauruhoe, in the centre of New Zealand's North Island, has provided many good examples of Vulcanian eruptions (Figure 7.10).

There are few volcanoes whose history has been recorded in such detail as that of Vesuvius, yet many volcanologists class its outbursts only as more violent examples of Vulcanian eruptions. Those who do regard Vesuvian eruptions as a distinct variety emphasise the vastly increased amount of gas in the magma. A period of quiescence often ends with preliminary explosions that clear material from old vents and fissures and reduce the pressure confining the underlying magma.

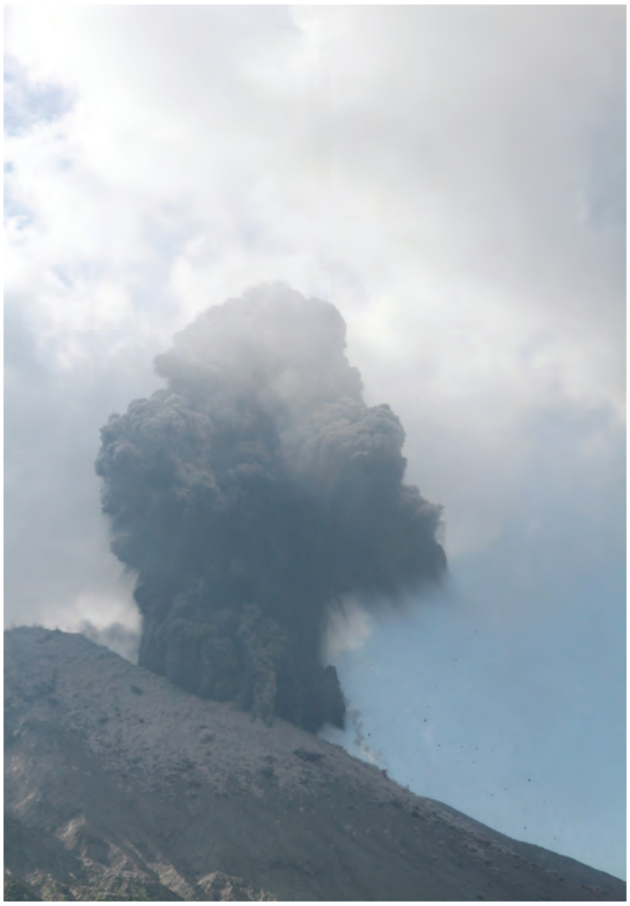


Figure 7.9 Commencement of a Vulcanian eruption from Sakurajima, Japan.

When it falls sufficiently, a cloud of frothy material from which the bubbles of gas have had no time to escape shoots to an enormous height, and deposits ash over a wide area. The extreme form of an event of this kind is a Plinian eruption like the one in A.D. 79. In such an eruption the "cauliflower" cloud becomes a pino (Italian, pine-tree) several kilometres high. It is luminous by night and pervaded by internal lightning flashes (Figure 7.11).

The eruption in 1902 of Mont Pelée, at the northern end of the West Indian island of Martinique exemplifies still greater explosiveness. Volcanoes of this type have extremely viscous acid or intermediate lavas which block the vent so effectively that the rising magma is obliged to force its way out through lateral fissures below the plug, producing the nuées ardentes that are the most characteristic feature of a Peléean eruption (Figure 7.12). A nuée ardente (French for "scorching cloud", plural nuées ardentes) is an avalanche of incandescent ashes and fragments of lava, each particle of which is surrounded by a cushion of gas that practically eliminates internal friction, and enables the cloud to sweep down the slope at a very great speed and to gain enormous destructive power. Strictly speaking the nuée is the cloud that forms above a flow of denser material whose course is controlled by the contours of the ground, while the cloud sweeps

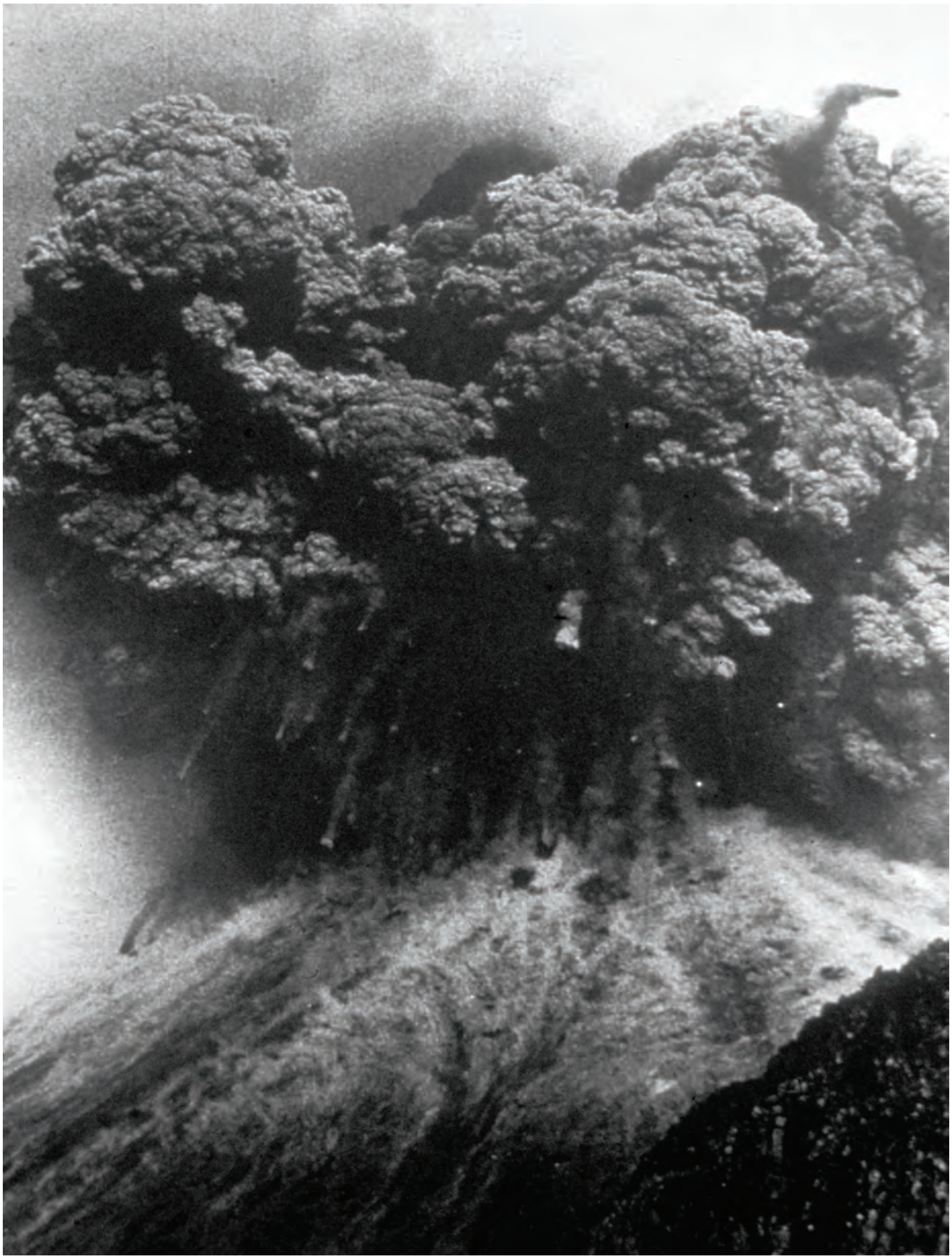


Figure 7.10 Vulcanian eruption of Ngauruhoe in 1975.

over intervening obstacles. We shall return to the subject of nuées in Chapter 12. Even when the lava is viscous enough to form an effective plug to the main vent, the pressure beneath is sometimes able to extrude it like toothpaste from a tube, forming a spine (Figure 7.13). The spine of Mont Pelée became an impressive column several hundred metres high but the material was rather soft, and soon weathered away.

The very largest eruptions are called Katmaian, after an Alaskan volcano that erupted in 1912. Their most characteristic feature (apart from their great size) is the production of a material called ignimbrite, first identified in New Zealand where ignimbrite layers form a volcanic plateau covering some 26,000 sq. km in the central North Island. Recent deposits of pumice and ash cover much of its surface, but beneath it lies

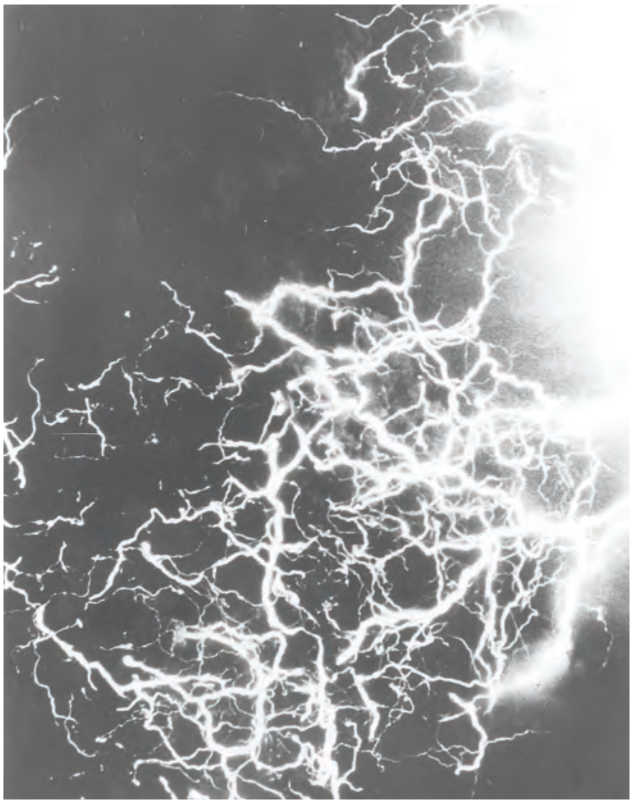


Figure 7.11 Lightning discharge, Galunggung during an eruption in 1982.

Figure 7.12 Mont Pelée. The nuée ardente of 16 December 1902 reaching the sea.

a thick layer of rhyolite tuff. Patrick Marshall, who gave it its name (Latin ignis, fire and imber, a shower of rain), considered that it originated as a dense fall of glowing particles that had been welded into a glassy material by their heat and pressure. Few geologists now share Marshall's apocalyptic vision of a fiery rain, preferring to invoke many nuées ardentes, and they no longer restrict the term to welded material. His apocalyptic vision was of a series of nuées ardentes, each falling on the preceding ones so quickly that they had no time to cool, and therefore welding together. It is now recognised that unwelded layers also commonly occur in an ignimbrite deposit.

The production of ignimbrites has rarely been witnessed, and none of the witnesses have been geologists. These examples were all on a comparatively small scale. The eruption of Katmai seems to have been the only large one of its kind in historic times, yet ignimbrites are to be found in almost every volcanic region. Both in the Yellowstone National Park in the U.S.A. and in New Zealand there have been repeated eruptions, but the intervals between them have been as long as a quarter of a million years. There is every reason to expect more Katmaian eruptions.

The explosive power of all these eruptions depends upon the magmatic gases and the physical properties of the lavas involved. There is another important class of eruption that falls outside the scheme we have so far outlined. These are known as phreatic eruptions (Greek phrear, a well or cistern), and derive their force from the steam generated when water comes into contact with magma or hot rock. The most violent eruptions of this kind that have been observed are submarine eruptions like that of the Icelandic volcano Surtsey. Not only does the contact of liquid basalt with the ocean generate enormous volumes of steam, but portions of the rising magma are detached and erupted with them. Events of this kind are called phreato-magmatic eruptions (Figures 7.14–17 and Figure 7.18).

Less violent eruptions of this kind occur in regions of thermal springs where ground-water or lake water can encounter hot rock. The conditions in such regions are often very finely balanced, and small changes of the

Figure 7.13 Ruins of St Pierre. Mont Pelée in the distance showing the spine.

Figure 7.14

Figure 7.15

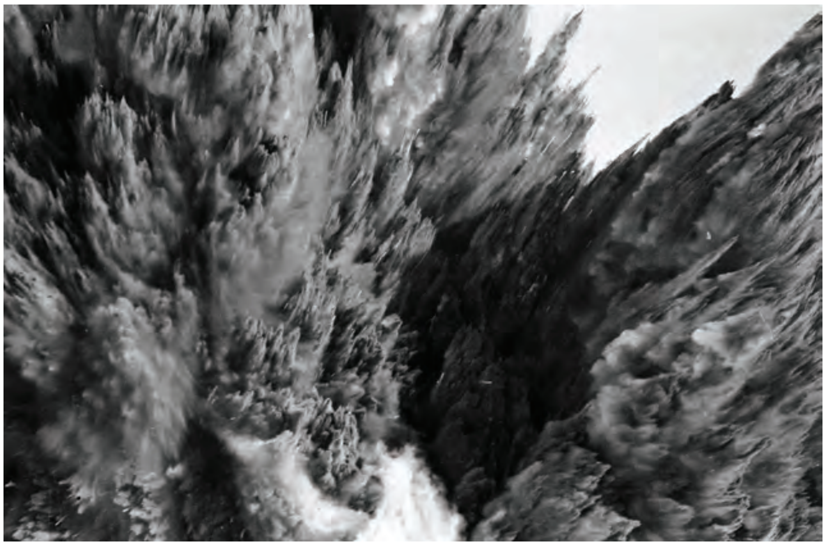


Figure 7.16 Three stages of a phreato-magmatic eruption through the Crater Lake of Ruapehu. The third image shows the 'cypress tree' appearance typical of large Surtseyan submarine explosions.

Figure 7.17 A surge in Ruapehu Crater Lake that followed the eruption shown in Figures 7.14–7.16.

water level or new intrusions of magma can trigger sudden explosions. Ground-water may reach boiling point at depths of a few hundred metres and generate sufficient pressure to lift the overburden. Many such eruptions have occurred in the New Zealand thermal regions, where they are usually referred to as hydrothermal eruptions (Figure 7.19 is the crater left by such an eruption in the Philippines).

Sudden hydrothermal eruptions have occurred in regions without active volcanoes, and where the more usual forms of eruption are unknown. In 1934 the area of previously well behaved hot springs and gas-vents at Suoh in southern Sumatra was suddenly convulsed by a hydrothermal outbreak. It lasted less than three months, but in that time more than a hundred vents opened up and covered an area of about 32 sq. km with ejecta to a depth of 6 metres. The vents were scattered over a belt 5 kilometres long, and about a kilometre and a half wide. Trees were felled by the blasts, which were heard 650 kilometres away.

Although phreatic explosions can be violent, and may be a prelude to magmatic eruptions of other types, contact between lava and water does not necessarily result in an explosion. Its surface may be so rapidly cooled that an insulating skin is formed limiting the supply of heat and the production of steam, or conditions may allow the steam to escape readily. The lava island in the St Vincent crater lake grew quite peacefully, as did that in the Ruapehu crater lake in 1945.

An important point to stress about these classifications is that they apply to eruptions rather than to volcanoes, and even, if we are being careful, only to phases of an eruption. Take the 1971 eruption of Etna. Etna has two summit craters, and early in 1967 the north-eastern one, which had been more or less active for some years, began spattering lava to heights of up to 200 metres, with mild "Strombolian" explosions (Figure 7.8). This activity was fed by lava from a fissure at the base of a flanking cone.

The Strombolian phase continued for about four years until March 1971, when the activity stopped. About the same time snow near the main crater began to melt, and on April 6 four radial fissures opened on the southern and eastern sides of the cone and began pouring out lava. Soon regular explosions were occurring, and the eruption had once again entered a Strombolian phase (Figure 7.8). On May 13 a new phase began. A fissure in the Valle del Bove, an ancient depression on the eastern side of the mountain, opened at a height of about 1,800 metres. There had been previous outpourings of lava in the Valle in 1928 and in 1950-51. At first only sulphurous fumes were emitted, but quantities of lava followed, and flowed sufficiently far to cause extensive damage to vineyards, roads, and bridges, and threatened three of the higher villages. About three-quarters of a cubic kilometre of fluid lava quietly covered seven and a half sq. km of land. This can be called a Hawaiian phase. Finally, on May 18 a new crater opened on the eastern slope of the cone. No lava was erupted, but great cauliflower explosion-clouds poured out, depositing ash down wind. By the time the eruption ended in June about a third of a cubic kilometre of pyroclastics had been ejected in a typical Vulcanian manner.

Before leaving the subject of eruptions we must look at a common feature of phreato-magmatic eruptions that was not generally recognised until the world became preoccupied with nuclear explosions, though it had often been the cause of deaths. It is so natural to think of a volcano shooting a vertical column of gas and ashes out of the top like water from a hose or bullets from a gun that it was easy to overlook the powerful horizontal movement called base surge (Figure 7.20).

When the surroundings are level and a column of compressed gas is suddenly expelled from a crater, a ring-shaped cloud moves outwards from the rim. Exactly how it is generated is not fully understood, for if the bomb people have done the necessary sums, they have not told peaceful volcanologists their answers. The outward surge begins at a speed of about 50 metres per second and is powerful enough not only to carry mud and ash, but to move large blocks, knock down trees and houses in its path, and sand-blast walls and trees. The base surge often carries material to much greater distances than any of the ejecta that falls from the main cloud. It is presumably a pressure rather than a heat phenomenon, for it does not char wood, and the temperature could even be less than 100°C (Figures 7.21 and 7.22). Underwater blasts, or the eruption of an island crater like the one in Taal Lake in the Philippines present suitable conditions for setting up a surge. The deposits can be recognised from a characteristic cross-bedding.

Figure 7.18 Phreato-magmatic eruption, Surtsey.

Figure 7.19 Hydrothermal eruptions, Bao, Philippines.

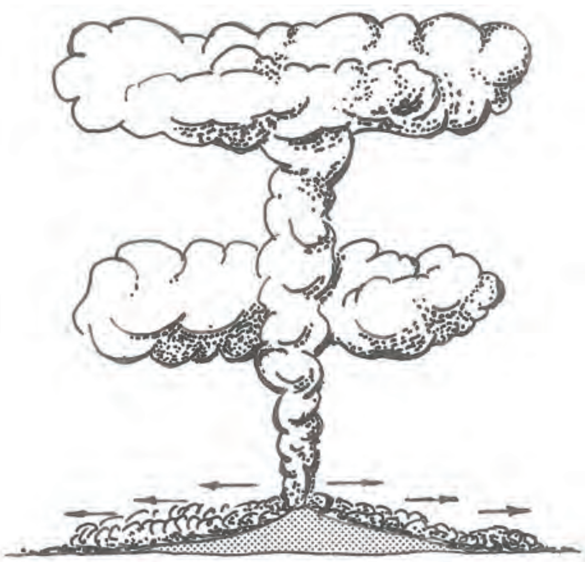


Figure 7.20 Base Surge. When a column of compressed gas is expelled from a crater there is often a powerful outward horizontal surge at its base.

Figure 7.21 The devastated forest, Mt St Helens.

Figure 7.22 Tree destroyed by base surge.

8—Magmas and Lavas

Confused, commingled, mutually inflamed, Molten together…

WILLIAM WORDSWORTH: The Excursion

On the whole, lavas succeed in getting out of volcanoes and magmas don't – but this is not the essential difference between them. It is much better to define lava as magma from which most of the gas has escaped. Both are forms of molten or potentially molten rock and can flow under pressure or, on emerging, rather less readily downhill under gravity. We shall leave consideration of how rock becomes magma and how it finds its way to the surface for the next chapter. Much more often it fails to escape, and cools and solidifies underground, and it is not until long afterwards that erosion of the surroundings exposes it and reveals that it was once molten. Such bodies of igneous rock are said to be intrusive. If magma succeeds in reaching the surface, an eruption marks the spot.

Intrusive rocks provide an opportunity to study the composition of magma before it has lost its gas and become contaminated by contact with its surroundings. They can appear in a number of different forms. Sills have forced their way along the boundaries between strata and forced them apart, while dikes fill cracks that cross them (Figures 8.1, 8.2 and 8.3). They are usually parallel-sided, but lens-shaped bodies are also found. Laccoliths (Greek laccos, a cistern, lithos, stone) have been arched up into a dome by pressure, while lopoliths (Greek lopas, a shallow basin) are spoon-shaped. They can be very large. One at Duluth, near Lake Superior in Canada, is nearly 200 km long and is estimated to have a volume of nearly 200,000 cubic km. Although the Whin Sill in Britain and some of the dikes of the South African Bushveld can approach this size, sills and dikes are usually on a much smaller scale. In California, Peru, and many other parts of the world huge blocks of igneous rock extend for hundreds of kilometres. These formations are called batholiths (Greek bathos, depth) and smaller and more circular examples are known as stocks or bosses. Most of them are so thick that no bottom is apparent, but recent geophysical studies in Britain suggest that 10 km is a typical value.

Although batholiths are the exposed remnants of magma-chambers, we cannot just knock a piece off with a geological hammer, take it to the laboratory, analyse it, and assume that we have established the chemical composition of magma. On its way to the surface, the hot magma probably dislodged pieces of the walls and roof and incorporated them in the

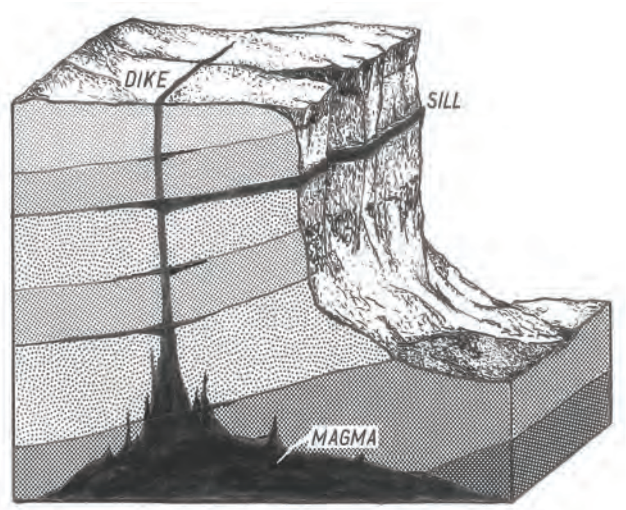


Figure 8.1 Sills and dikes. Magma that has been intruded along the boundary between strata can be exposed by erosion after it has cooled, thus forming a sill, while dykes have filled cracks that cross the strata.

Figure 8.2 Basalt dike, cutting Eocene shale. Near Dargaville, Northland, New Zealand.

melt, or carried them along as xenoliths (Greek xenos, foreign). These are common in the upper parts of a batholith, but become scarcer at greater depths. We have also to consider how much of the batholith was ever in the molten condition that entitles it to be regarded as magma, for the volume of a batholith is many times greater than the amount of material that surfaces in even the most enormous eruptions known.

There is another reason for doubting whether either the top or the bottom of a batholith provides a good sample of magma. They are largely granitic, whereas the commonest volcanic rock is basalt. If the batholiths were typical we might expect the most common to be rhyolite. (We shall discuss the composition of rocks in Chapter 10.)

The release of gas that converts magma to lava results in both chemical and physical changes. Magmas are not simple substances. They both hold gases in solution, and generate them as a product of chemical reaction between their constituents. How much dissolved gas a magma can hold depends upon pressure and temperature. As it moves towards the surface both of these fall, it becomes saturated, and eventually bubbles form. They at once begin to expand at a rate that depends upon the viscosity and rate of ascent of the magma or, what amounts to the same thing, upon how rapidly the confining pressure is falling. A very fluid magma rises rapidly and can produce spectacular fire-fountains, but if the gas has a chance to expand freely there may be no more than shreds and droplets of volcanic glass and a copious flow of liquid lava. A viscous magma usually explodes violently into fragments of ash or pumice and no actual lava emerges.

It has been estimated that in the last 500 years less than 70 cubic kilometres of lava have come from volcanoes on land. Most of it has been basalt, and has come from a few island volcanoes on the mid-oceanic ridges. How much more the submarine volcanoes have produced is hard to tell, but it is likely to be about the same amount. A few of the largest historic flows have amounted to about 4 cubic km, but in many eruptions the total volume reaches no more than a few hundredths of a cubic kilometre.

Figure 8.3 Dolerite sill, Antarctica.

Since the transition from magma to lava is a matter of losing gas, let us see what gases are involved. By far the commonest volcanic gas is water, or rather steam; but not all of it is juvenile water (Latin juvenis, young) that has come from the magma and is reaching the surface for the first time. Much of it is circulating ground-water or water from lakes and streams that has come into contact with hot rock. In order to ensure that their gas-samples are truly representative of the magma and uncontaminated by contact with the atmosphere, volcanologists collect them from cracks and blisters in lava-flows and from gas-fountains in lava lakes – a hazardous procedure. On the whole, the hotter the gas the less likely it is to be contaminated, and ingenious methods (discussed later in Section 37) are needed to collect the samples safely.

One method, popular with Hawaiian volcanologists, is to evacuate a glass tube and provide it with a tip that can be broken off in the gas-stream and then resealed by holding it against the hot lava before it is withdrawn. Other workers have donned asbestos armour and sallied forth with tubes and funnels (Figure 37.9). An indirect and safer method is to examine the flames with a spectroscope, but only a few elements can be detected in this way, and results have been disappointing. The degree to which a sample is contaminated can be estimated by comparing the proportion of the isotopes it contains with that in the surrounding rocks and surface-waters, but reliable sampling and analysis remains difficult. Chemical reactions between the different constituents of the sample as it cools is another problem. It can be minimised by absorbing the gases in silica-gel at the time of collection, but speed is essential.

The amount of water in samples that have been collected ranges from 60 to over 90 per cent, so that quite large volumes of gas are needed in order to study the other gases present. The commonest are carbon dioxide, nitrogen, and sulphur dioxide. Hydrogen, carbon monoxide, sulphur, and chlorine, in a variety of compounds like sulphuretted hydrogen and hydrochloric acid are present in smaller amounts, along with fluorine and the volatile chlorides of iron, potassium, and other metals.

Most of the standard methods of measuring high temperatures can be applied to lava-flows, but the temperature of magma deep in the Earth can only be inferred and not directly measured. The deeper it is, the higher the pressure, and the higher the temperature needed to bring it to a molten state, but when lavas emerge they are seldom found to be much above their melting-point. This varies greatly with their composition and the amount of gas they contain. Basaltic lavas, which are the hottest, may reach 1,200°C, but lavas are still able to flow at only half that temperature. The physical and chemical changes that accompany the process of cooling and losing gas usually have the effect of raising the melting point. This has its importance in determining the course of a new eruption, for the temperature of the rising magma may be insufficient to melt the plug of old solidified lava that blocks the vent. The eruption will therefore be delayed until rising pressure has built up sufficiently to remove it explosively. While lava remains molten, there can be chemical reactions that generate heat, increasing its mobility and delaying its cooling. Factors of this kind make it very difficult to generalise about the behaviour of erupting volcanoes.

The final length and thickness of a lava-flow, assuming the volumes involved to be of the same order, depends mainly upon its composition, while the character of its surface is a product of its temperature and gas content. Basaltic lavas, being not only very fluid but emerging at high temperatures, travel far and spread thinly, while lavas rich in silica congeal into short thick tongues without getting far from their vents. On large andesitic composite volcanoes, the flows have thicknesses up to about 30 metres, but the individual basaltic flows that make up the Icelandic shield volcanoes are frequently less than a metre thick, and some of those in Hawaii measure no more than a few centimetres. Iceland seems to hold the distance records. The Laki flows in 1783 travelled 88km, a prehistoric flow from Trolladyngja reached 105 km, and one at Veidivatnahraun went no less than 150 km. An Australian challenger from Undara crater in northern Queensland claims to have broken this record by 10 km.

Figure 8.6 Aa lava, Taal.

Figure 8.4 Lava levées on Etna.

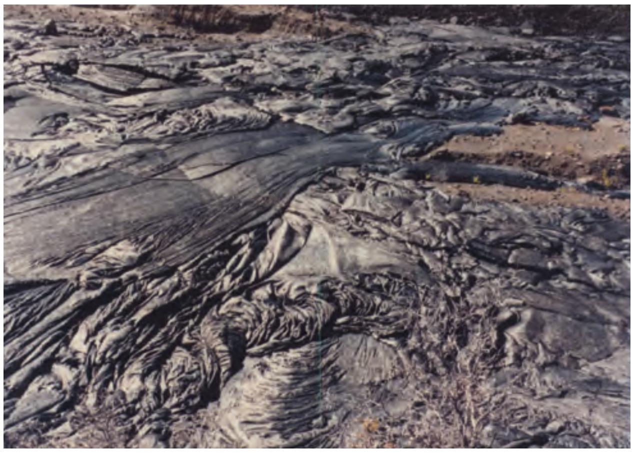


Figure 8.5 Pahoehoe.

Figure 8.7 Columnar Basalt. The Organ Pipes, Mt Cargill, Dunedin Volcano.

Very viscous lavas have the strength to push walls and buildings over bodily, but are less likely than fluid ones to travel far from the vent. Fluid lavas are readily channelled by quite minor depressions, and surface cooling builds levées (French, embankments) that keep them in the paths they originally selected (Figure 8.4). Instances are known of buildings whose lower stories have filled with basalt without disturbing the upper ones, which remained standing above the solidified flow. In other cases, lava has entered buildings through the doors and left by the windows.

The surface of a high temperature lava from which the gas can escape in tiny bubbles usually forms a smooth skin like cooling pitch, which puckers into wrinkles before the flow solidifies and gives it a ropy or corded appearance. British geologists are happy to call this ropy lava, but their colleagues in other lands seem to prefer the Hawaiian term pahoehoe (pronounced pa hoy hoy) (Figure 8.5). The other form is also known by a Hawaiian term, aa (pronounced ah ah), or blocky lava. This is formed when the violently-escaping gas breaks the crystallising mass into a slag-like pile of rough and jagged chunks, which form a most effective barrier to progress on foot (Figure 8.6). Shallow intrusions and the lower parts of thick, homogeneous, basalt lava-flows that have been able to cool slowly and evenly without exposure to the air are often divided into regular hexagonal columns (Figure 8.7). Although pillow lavas have been described as "probably the most abundant volcanic rocks on Earth", the details of their birth remained a matter of controversy until 1971, when J.G. Moore and his Hawaiian colleagues succeeded in taking underwater motion pictures of the process in action. When they are first formed, the skins of the pillows remain flexible, so that their weight causes their bottoms to flatten, and they become even more pillow-shaped than before (Figure 8.8).

This seems a suitable place to mention lava tubes or tunnels. When a stream of lava issues from a vent, it continues on its way for some distance as a liquid stream; but before long the surface cools and a skin forms. The skin, being a poor conductor of heat, slows the cooling of the material below the surface. This continues on its way, forming a continuous protective cover as it goes. If the supply of lava is now cut off, the still molten material beneath the skin will drain away, leaving an empty tube or tunnel with an arched roof (Figures 8.9 and 8.10). The diameter of these tubes varies greatly from a few centimetres up to as much as 30 metres, and there is frequently a bewildering network of interconnected channels, which may extend for several kilometres. One at Hambone, in northern California, is said to be 22 km long, but is apparently in several sections. Some well-formed examples can be found in Western Samoa. As with rivers, swift flows are straight and gentle ones meander. Tubes are common in pahoehoe lava, but the conditions for their formation are not present in aa.

Figure 8.8 Pillow lavas.

The ability to drain away and leave a tunnel implies a fluid lava that can move quite quickly. Quite a number of factors determine the speed of a flow. They range from the slope and character of the ground to the density and viscosity of the lava, and the volume and speed of ejection from the volcano. A liquid basaltic lava pouring like molten steel from a furnace may dash down the mountainside in a fiery stream, splashing against rocks and cascading over obstacles,

Figure 8.9 Lava tube, Red Crater, Mount Tongariro.

but the more it leaps and splashes, the more rapidly it cools and acquires the consistency of treacle. On steep slopes Hawaiian lavas attain a top speed of about 65 km per hour, and even on more gentle ones they can reach thirty or forty, but they cannot maintain these speeds for long. Haroun Tazieff reported that when the lava-lake at Nyiragongo erupted and overflowed down the volcano's flanks in 1977, its initial speed was about 100km/hour, slowing to 30km/hour. This eruption killed many people. Cooling slows it down, and lateral spreading and ponding delay the advance. The front of the record-breaking flow just quoted took a week to advance a kilometre and a half. This is a figure of much greater practical importance. At the other extreme, the lava that poured from the Laki fissure in 1783 moved nearly 15 km down the valley of the Skaftá River in one day. Sluggish behaviour is most usual.

It should be remembered that just as with rivers, which flow more rapidly in mid-stream than near the banks, lava-flows are retarded by the sides of the channels through which they move and, unlike rivers, by the cooling layer that forms on their surface. Solidified lumps of lava tend to pile up at the sides and confine the flow, forming levees that can remain standing like parallel walls when the level of the fluid lava drops. This is a modified version of the process that produces tunnels.

At any given instant the temperature and rate of movement in a cooling lava-flow varies markedly within a short distance. The structure of a solidified flow is therefore rather complex. The blocky surface of aa comes to form a layer of jagged angular rubble overlying the more uniform and massive rock formed by the slower cooling of the liquid beneath; but it is also possible for a layer of the rubble to accumulate underneath the flow, having been carried over the toe of the flow and buried. For this to happen, the upper part of the flow must be moving more rapidly than the part in contact with the ground, so that the front folds over, and the advance of the lava becomes more like that of a caterpillar tractor than like the flow of water along a gutter.

D.R. Gregg describes a close-up view of a slowly-moving aa lava-flow during an eruption of Ngauruhoe in 1954:

> The most rapidly moving parts of the flow were moving forward bodily. Boulders were tumbling from the face and exposing the red-hot interior of the flow as it slowly advanced over the fallen debris. As the blocks fell off, incandescent dust tumbled out. The finer dust particles remained suspended in the air, producing a reddish-brown smoke most irritating to the eyes. As the flow moved forward it produced continual grating and clanking noises. There was no strong smell apart from a typical "foundry" odour.

This flow was about 20 metres thick, and moving ponderously forward at some 20 to 25 centimetres a minute.

Geologists have described the features of lava-flows in what may fairly be described as tiresome detail, and developed an elaborate terminology to describe their observations. Some occurrences are sufficiently widespread to deserve a mention. Perhaps the most

Figure 8.11 Vesicles in lava.

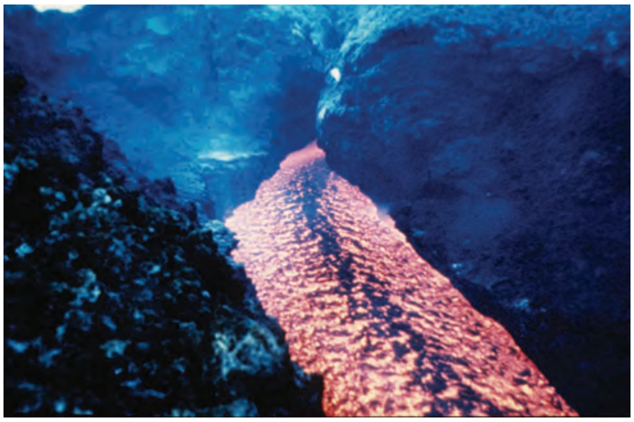


Figure 8.10 Glowing lava exiting lava tube, Etna.

Figure 8.12 Lava entering the sea, Surtsey, December 1985.

important group are those that involve water. A lava that moves on to a swamp, for example, may generate enough steam to rupture the flow like the side of an exploding boiler, or in milder cases produce bubbles and blisters. Water or gas released from chemical reactions in the lava can also cause bubbles. When the lava cools, the bubbles leave holes called vesicles ((Figure 8.11), Latin vesicula, a blister), which are very common. The Cornish mining term vug has been applied to large vesicles, but the miners use it for all kinds of holes in rocks, up to and including caves.

While magma is underground, the pressure keeps the gas in solution, like the gas in unopened soda-water, but the instant it is released bubbles form in great quantity. Opened soda-water soon goes flat, and so does lava with the result that vesicles become smaller and scarcer with increasing distance from the vent, and finally disappear altogether. Later, vesicles may become filled with percolating fluids which crystallise into a wide variety of minerals, including gem-stones such as amethyst.

Bubbles have a habit of mating to become larger bubbles, and the escaping gas may finally reach the surface through a limited number of small vents, emerging in a stream under continuous pressure, and carrying blobs and shreds of liquid lava with it. These blobs are known as spatter. On landing they flatten out and cool and may build up a small cone around the vent, like a succession of tiny lava-flows. The number and position of the vents is greatly influenced by the extent of the cracks that have formed on the surface of the flow. In the case of a fissure eruption a line of cones may develop, as it did at Laki.

The falling clots of lava usually land close to the vent, so that the resulting structure is often more chimney-like than cone-like, and may become several metres high. These chimneys are called hornitos (Spanish, little furnaces), and the gas escaping through them can reach very high speeds. Supersonic speeds have been recorded by sacrificing anemometers to the high temperatures involved.

Rather surprisingly, there is comparatively little fuss when a lava-flow reaches the sea or a lake (Figure 8.12). Steam is formed on the surface in large amounts, but it at once builds up a protective blanket that shields the flow from further rapid cooling, and the result is the formation of a kind of skin not unlike that formed in the case of pillow lavas.

The other class of feature has little to do with water or gas, but depends upon the physical character of the lava and the stresses that act on it. When molten or plastic lava is compressed, or if material is injected beneath it, the surface of an otherwise flat flow can be forced up into a hump or a ridge. Humps of this kind are called tumuli (Latin, mounds or hillocks, singular tumulus). Typically they are elongated like the burial-mounds upon which archeologists have bestowed the same name, and are up to 3 metres high. A limit is set to the height by fracturing of the skin, which becomes filled with molten material from beneath. In this condition they are known as squeeze-ups. Near Sunset Crater in Arizona there are ridges 20 metres wide and two kilometres long that have been so described.

The features we have just discussed are typical of pahoehoe lavas. When a squeeze-up occurs beneath an aa surface, the result is the extrusion of a spine, and heights of 30 metres have been reported. These spines have something in common with the much larger spines and domes described in Chapter 7, including the grooved sides caused by projections on the edge of the hole through which they were extruded. When the surfaces are smooth, friction may produce the polished surfaces called slicken-sides. The word is derived from a Middle English root meaning sleek or glossy which persisted in the dialect of Derbyshire miners. Slickensides also occur on the faces of faults.

9—The Rise of Magma

The greatest and most accomplisht Wits for these many ages have labour'd and sweat in these Inquiries, and yet have not been able to bring forth any greater Effects than Probabilities.

ROBERT HOOKE: The Present State of Natural Philosophy

It is much easier to describe a volcanic eruption than to explain it. Neither the physical condition of the material at the depths where we think the activity starts, nor the processes by which it becomes transformed into magma can be inferred with anything like certainty. The best we can do is to limit the possibilities.

The occurrence of earthquakes is one indication that "things are going on" in the depths; but there are earthquakes in places far from volcanoes, and few great earthquakes have been accompanied by much in the way of volcanic eruption. Igneous rocks can be found where there are no volcanoes. Yet we have already noted some important generalisations. In subduction zones earthquakes as deep as 700 km can occur, but directly beneath the andesitic volcanoes the typical depth is 100–150 km. Under the basaltic volcanoes of the mid-oceanic ridges, on the other hand, the earthquakes are shallow – though just what is meant by "shallow" in this context is arguable. During eruptions of all kinds small shocks take place at depths of less than 10 kilometres, and larger ones at depths up to 30 or 40 km may precede or follow the eruption. The biggest shocks usually mark the climax.

We have seen that there are unlikely to be permanent reservoirs of molten rock at these depths, and that although the asthenosphere on which lithospheric plates are moving is weak, the behaviour of earthquake waves shows that in physicists' terms it is not molten. We have therefore to explain the comparatively sudden transformation of rock to magma, and its accumulation in significant quantities.

The familiar substances of our world exist in three forms – solid, liquid, and gaseous. By heating or cooling them, or changing the surrounding pressure, we can change them from one form to another, though not all substances do this as readily as ice, water, and steam. Seismology can establish the pressures deep in the Earth within fairly narrow limits, but there is no comparable way of finding temperatures. We can be reasonably certain that they increase with depth, but it is most unlikely that they increase at anything like the rate that they do near the surface, where the usually accepted figure is 25°C per kilometre. In the deepest mines and drill-holes the rate of increase falls to no more than 6°C per kilometre, which reinforces the belief that the major radioactive heat sources are concentrated at shallow depths. The difficulty of estimating temperature is further complicated by the convective movements in the mantle, which transport heat from deeper levels to the surface. Bearing all this in mind, the temperature at a depth of 100 km could be about 1,400°C, which is about the melting point of peridotite and eclogite, the most likely constituents of the upper mantle.

Let us see what happens when a substance melts. In a solid the molecules, the tiny individual packages of atoms that determine its chemical identity, are held together by electrical forces, and tend to arrange themselves in a regular pattern known as a space lattice, which can repeat itself to produce the regular and symmetrical forms of crystals. The individual molecules vibrate to and fro about their average positions in the lattice, but as long as the body stays solid the attraction between them remains strong enough to ensure that it retains a definite size and shape. If the body is heated, the energy of the vibration increases, the bonds of the lattice are weakened, and the molecules become free to change their fixed positions, though the average distances between them remain much the same. The substance has become liquid, and can readily change its shape. With further heating the molecules gain sufficient energy to break their bonds entirely, and the liquid becomes a gas. The molecules are no longer constrained, but move in straight lines until collision with another molecule, either of the gas or its container, diverts them from their linear paths.

Man has found it difficult to understand the nature of heat and its relation to temperature. The problem seems to have been that heat is not a substance, but a property substances have; and that while the human body is sensitive to differences in temperature, our senses tell us nothing directly about heat. Robert Hooke had the matter sorted out in 1665: "Heat is a property of a body arising from the motion or agitation of its parts; and therefore whatever body is thereby toucht must necessarily receive some part of that motion." Yet the nineteenth century was well advanced before James Prescott Joule established the exact relationship between the amount of work done and the heat it produces that has become known as the First Law of Thermodynamics.

The energy of a moving molecule – or any other moving body for that matter – is called kinetic energy (Greek kinein, to move) and depends upon its mass and its speed. It follows that since the molecules of different substances have different masses the same amount of heat energy will cause them to move at different speeds.

If two dissimilar bodies are placed in contact so that their molecules can interact, they will begin to share their energy, and the sharing will go on until every molecule has an equal share. The bodies are then said to be in thermal equilibrium or, in other words, at the same temperature; but they will not possess the same amount of heat. The amount of heat is the total kinetic energy of the molecules, while the temperature depends upon the average energy of an individual molecule, and it is upon the temperature that the direction of any transfer of heat depends. Heat flows from hot bodies to cold ones, and not the other way round. This is known as the Second Law of Thermodynamics, and the writer C.P. Snow has proposed that a proper understanding of it should be made the basic test of scientific literacy. It is certainly part of the basic knowledge of every volcanologist.

Before we can get back to the formation of magma, we need to know a little more about the energy-sharing process, which will ultimately bring the Universe to a stop. Suppose we heat a bar of metal at one end, the other end will also get hot, but not instantaneously. It takes time for the heat to travel; that is, for the molecules to share their energy. How long it takes depends upon the sorts of molecules we are dealing with. Metals conduct heat well, but non-metals like rocks are poor conductors, and as we saw earlier, it takes a surprisingly long time for a change of temperature to travel a short distance through the ground.

How can a rock somewhere within the Earth's upper mantle be induced to melt? There are three possibilities: to supply more heat, to reduce the pressure, or in some way to change its composition. Suppose that we have raised the temperature or lowered the melting-point in one or other of these ways. It does not immediately follow either that quantities of magma will be produced, or that any kind of chain reaction will induce the surrounding rocks to become magma as well.

Heating a solid raises the temperature until the melting point is reached, but if we go on heating it there is no further rise in temperature until the melting process is quite complete. All the available energy is being used in weakening the molecular bonds. The energy needed to bring this about is called the latent heat of fusion, and unless it can be supplied melting cannot continue.

Within the Earth we are not dealing with a simple situation like heating an ice-cube in a pot, but with the differences in the conditions from point to point within an extended body. There is plenty of heat available, but it is not necessarily where it is wanted, and not easy to move it about rapidly. Further complications arise because most rocks are complex mixtures, and not simple chemical compounds. Adjacent crystals within them consist of molecules of widely differing mass, constrained by bonds of widely differing strength.

Let us return to our three ways of producing melting. Whether the Earth as a whole is at present heating or cooling remains an open question, but there are almost certainly local concentrations of radioactive material generating heat. Many geological processes can lead to changes in pressure or temperature at depth. Rapid sedimentation may depress deeper rocks to a level where the surrounding temperatures are above their melting-points; folding and faulting may relieve pressure; and subduction may involve friction that generates heat. The role of chemical reactions is less certain. The presence of quite a small amount of water or carbon dioxide appreciably lowers the melting-point of peridotite, and small quantities of these and other volatiles are rising from deeper parts of the mantle, but unless they have already saturated the levels at which magma is generated, it is not clear how important they are.

Having accumulated a quantity of magma, the next problem is to bring it to the surface. Since it is less dense than its surroundings gravity will play a part, but it is not correct to picture magma as a simple liquid that can readily force itself through a network of cracks and fissures, combining to form larger tributaries and ultimately reaching a single vent. Given the initial difficulty in producing a melt and the presence in the parent rock of a variety of crystals having different melting-points, it may at this stage be a mixture of crystals and liquid best described by the Americanism "mush". It has been argued that a magma that became too liquid at depth might be unable to overcome the pressures that sealed the cracks and boundaries between strata, or that if it could its ability to do so would result in its arriving everywhere but at the surface – but then, intrusive rocks are commoner than volcanic ones. Once again there is a lack of plausible figures to which we can appeal for a verdict.

In 1903 R.A. Daly suggested that magma could reach the surface by mechanical removal of material from the roof followed by an advance to fill the space. To this he applied the miners' term stoping. In 1925 John Joly placed the idea on a sounder physical basis by pointing out that conditions at the top and bottom of a column of magma would be very different, and that pressure would play a principal role. Much higher temperatures would be needed to melt rocks at the bottom than at the top, and while convection would quickly bring the magma to a uniform temperature, the temperature of the surrounding rock could change only more slowly by conduction. The result would be that while the roof of the magma-chamber was dissolving, crystals would be forming on the floor. The net effect would be an upward movement of the chamber. Once a rising chamber reaches a level within the crust at which the pores of the rock contain water, its conversion to steam will aid the stoping process by shattering the rock and creating fractures that extend ahead of the intrusion.

A more recent suggestion invokes diapiric rise (Greek diapirein, to pierce through). This has been the subject of many laboratory experiments, but they have yielded

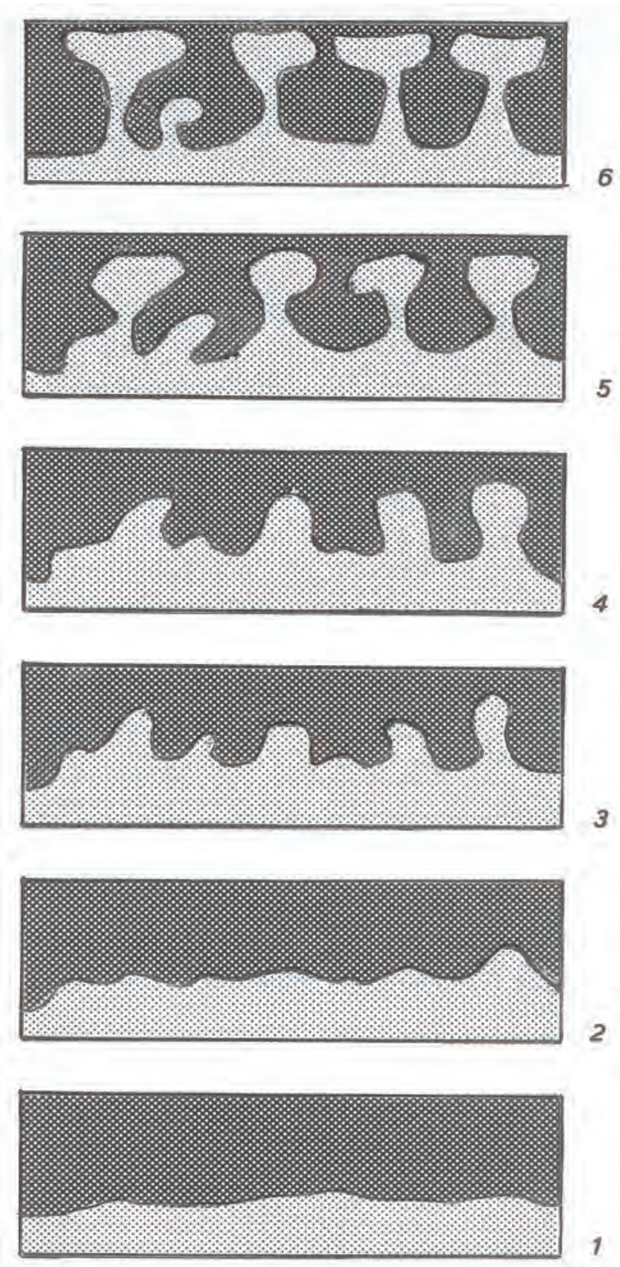


Figure 9.1 Growth of mantle plumes. Successive stages of a laboratory experiment in which gradual heating creates an instability at the boundary, and induces columns of light oil to penetrate a layer of denser oil resting upon it.

few of the figures needed to link them to conditions in the Earth. For the process to work there must be a dense material overlying a lighter one, a condition that exists at the top of the asthenosphere. Such an arrangement is unstable, and even a slight thermal or mechanical disturbance will start the development of irregular ripples along the boundary (Figure 9.1). These grow into localised bulges in the lower layer. Gradually the bulges become plumes or diapirs that move upwards with increasing speed, depending upon the viscosity of the surrounding material. Localised regions of abnormally high heat-flow or particularly vigorous vulcanism have been attributed to the presence of these mantle plumes.

Geologists have always been much readier than geophysicists to accept the presence of underground reservoirs of liquid magma. The swarms of dykes to be found in such places as western Scotland and Iceland, extending for tens of kilometres, are a strong (though not decisive) argument for the existence of large and laterally extensive reservoirs at some level between the top of the asthenosphere and the base of the crust. Certainly, the rate and volume of the discharge in a large fissure eruption are far too great to be supplied from magma generated in the course of the eruption. The failure of seismologists to detect these reservoirs is probably due at least in part to their partly molten and partly crystalline character, so that they remain able to transmit shear-waves. The different constituents of a magma crystallise at widely differing temperatures, and the behaviour of partial melts is a subject of great importance to volcanology. Both their physics and their chemistry are complex and controversial, and we must be content to leave the subject there.

The Mohorovičić discontinuity marks the boundary between the essentially brittle material of the crust and increasingly plastic material that can support convective circulation at greater depths. Although it would not be impossible for some magmas to originate within the crust, and the basalts of the Hawaiian shield volcanoes have often been considered to originate just below it, the small thickness of the oceanic crust makes this unlikely. In the thicker continental crust, it is possible that rhyolite magmas reaching the surface have been melted by basalts coming from a greater depth, but there is little doubt that the primary origin is deep. The transition to the crust is a major change in physical surroundings that inevitably influences the final character of the magma.

None of the processes by which magma rises proceed rapidly, and the predominance of plutonic rocks shows that most intrusions cool and solidify before they can get out. How quickly a rising body cools depends greatly upon its shape. The material of a sill or a laccolith has a much greater cooling surface than a more compact body, whose upward progress is aided by internal convection, which brings heat from lower levels to replace that lost by cooling at the top. The usual pattern of circulation involves a hot rising central column surrounded by cooler descending currents. Cross-sections of volcanic pipes disclose that rock fragments in the outer parts have come from above, while those in the central core have come from below.

The impressive ash-clouds that rise above an erupting volcano are propelled by liberated gas with some help from rising currents in the atmosphere, and tell us little about the conditions at depth. The behaviour of lava, on the other hand, reflects pressure conditions in the system of pipes that feeds the volcano. How far above sea level magma can rise depends upon the pressure, and this depends upon the weight of the overlying rocks.

The highest basaltic volcanoes reach about 5,000 metres. By making reasonable assumptions about the composition of the crust and upper mantle and the density of liquid basalt, it is easy to calculate that the principal magma-chamber (but not the depth at which the magma originated) must lie at a depth of about 30 to 35 kilometres, which is close to the base of the crust. Mount Etna, which is 3273 metres high, is probably an example of a volcano that has reached its maximum height. Most of its eruptions now come from vents below the level of the crater rim.

Calculations of this kind are necessarily simplified, but they can be carried a little further. We would expect, for example, that in a given volcanic region all the volcanoes would reach much the same height, even if the level of the surrounding land varies quite widely. This seems to be the case in East Africa, and also in the Auvergne region of France, where it has also been noted that volcanoes on low ground tend to be larger and more productive than those at higher levels.

One limit to these arguments is set by the fact that we are dealing with fluids in motion, and that we have ignored their viscosity. Additional pressure is needed to drive viscous liquids through long pipes. There are also some observations that do not easily fit the simple story. In Hawaii, magma has erupted from the summit of Mauna Loa while the lava lake of Kilauea, 3,000 metres below, remained undisturbed; arguing, if not for independent magma-chambers, at least for very different conditions in the rising columns.

These considerations reinforce the older conclusion that volcanoes are not fed from some world-wide layer of liquid lava. A source of that kind would ensure that a basaltic fissure eruption once started, would continue until all the material was either erupted, or transformed into sills and dikes on the way up. There is also another factor that limits the extent of magma-chambers. As the depth increases so does the pressure at the bottom of the magma column; but the strength of the rocks forming the walls decreases, and a depth can be reached at which the magma will prefer to force its way sideways and form a sill, rather than force its way out at the top. These conditions are reached at about 45 km, but we have once again neglected the effects of viscosity and the fact that conditions are not static.

If the simple static arguments applied to rising magma columns there could not be many volcanoes, for the upper parts of most volcanic vents must pass through rocks of much lower density than the rising magma. The volcanoes of the Mono Basin and Imperial Valley in California, for example, have erupted through thousands of metres of light alluvium. Sills can be found at all levels in thick sedimentary sequences, though seldom at the base, where the most important change in the strength of the rock could be expected. It is unlikely that the strength of the walls of the intrusion is as low as that of the rocks forming the surrounding country. Once the level at which they contain much water is reached it can cool the surface of the magma and cause it to seal itself in a kind of glassy casing, though the result is more likely to be phreatic explosions.

Every real volcano is different, because of the enormous number of possible combinations of rock properties and magma composition involved. The volcanologist has therefore to study the whole range of physical processes that could be taking place, to consider how far the local conditions impose limits upon them, and to establish their relative importance. It is not a simple demand, and we have so far learned more about the trees than about the wood.

10—On the Rocks

Die Steine selbst, so schwer sie sind,
Die Steine!

WILHELM MÜLLER: Die schöne Müllerin

In everyday speech the term rock almost always implies a degree of hardness. The geologist, having observed that sands and muds grade imperceptibly into harder material, uses the word in a wider sense. It will readily be agreed that the atmosphere and the oceans are not rock, and that molten lava will not become rock until it cools. Broken fragments and pebbles may be pieces of rock, but it is better to call them stones, along with diamonds and gold nuggets. It may be unwise to venture on a definition, but any piece of the solid Earth that is reasonably permanent, extensive, and uniform in composition and texture may fairly be described as rock.

Rocks can be classified in many different ways – by the way in which they were formed, by their age, by their chemical or mineralogical composition, or by any one of a wide range of physical properties. Petrology is a very specialised subject, and failure to absorb the detail of this chapter will not be found a hindrance to understanding the rest of the book. In spite of their apparent diversity, the range of composition of rocks is surprisingly limited. Ninety-eight elements occur in nature, but there are only twelve that make up more than 0.1 per cent of the crustal rocks, and two of them, oxygen and silicon, account for no less than 74 per cent between them. They are usually found in chemical combination as silica (oxide of silicon, SiO_2), and the principal differences between volcanic rocks lies in the amount of silica they contain.

If a rock is less than half silica it is described as basic, or if there is less than 45 per cent as ultra-basic. At the other extreme, rocks that are more than two-thirds silica are acid. The rest, with unusual respect for ordinary language, are intermediate. Acid and basic are in fact chemical terms used to describe the relative concentration of hydrogen and hydroxyl ions when a substance goes into solution, but the geological rules-of-thumb will serve our purposes adequately.

A few rocks, like deposits of sulphur or graphite, are almost pure chemical elements; and others, like silica and rock-salt, are simple compounds; but most are aggregates of small particles of varied composition. These particles are called minerals, and can best be seen if the rock is cut and ground into a thin transparent slice and examined through a microscope. As in the case of rocks, some minerals are elements or simple compounds, but many are crystals of definite (but usually rather complex) chemical composition. They may have separated out during cooling, have been selectively deposited from solution, or have been mechanically sorted during transportation. Rocks fall into three main classes – igneous, sedimentary, and metamorphic.

Igneous rocks (Latin ignis, fire) have cooled to their present condition from a molten state. Since the whole Earth was once molten, they are in a sense more fundamental than the other kinds of rock, which have been derived from them. Volcanic rocks were molten when they reached the Earth's surface, but most igneous rocks are intrusive, and cooled and solidified underground before they could find a way out. Intrusive rocks are at least ten and possibly a hundred times more common than volcanic extrusive ones, and appear on the surface only when the original cover has been eroded away.

Some petrologists distinguish between rocks that have come from comparatively thin and shallow intrusions, and those from the remains of magma-chambers that have cooled at great depth. The shallower ones are confusingly called hypabyssal (Greek hypo, beneath, and abyssos, bottomless. The deepest parts of the sea-bottom were once referred to as abyssal, but the usage is now obsolete). The rocks of deeper origin are called plutonic, after Pluto, the Roman god of the underworld.

Figure 10.1 Sedimentary rocks. The uppermost and youngest of the layers of sediment exposed on the flanks of the 681 m high Teufelsschloss, in eastern Greenland, were deposited about 400 million years ago, while the rocks at its base are more than 100 million years older.

Figure 10.2 *Monotis* fossil.

Most of the rocks that now make up the Earth's surface are sedimentary (Figure 10.1). Once a rock becomes exposed to wind and weather, water and ice and alternating heat and cold begin to break it up, and the fragments are carried away by river, glacier, and ocean current. Strength of attack and power to resist both vary greatly, but the process is relentless. Each year the Mississippi River alone moves 340 million tons of suspended silt, and another 136 million tons of material in solution.

These vast amounts of eroded material eventually come to rest at the bottom of seas and lakes. In time, the accumulated deposits can become many kilometres thick, and the pressure of the superimposed material great enough to harden the sediments into solid rock. From time to time the texture or composition of the sediment being laid down in any particular place can change, sometimes abruptly. The behaviour of rivers and coastal currents alters continually. Violent floods can move great boulders, while fine particles can settle only in calm waters. Progressive erosion can expose a completely different source of sediment.

Because of the way in which they are formed, sedimentary rocks lie in a series of superimposed layers or strata, with roughly parallel surfaces. They vary in thickness with the rate of deposition, and how long it went on. Sandstones and mudstones are common examples of sedimentary rocks; but sea-shells and the skeletons of dead marine creatures accumulate to form chalk or limestone, and vegetable matter turns to coal. These too are sedimentary rocks.

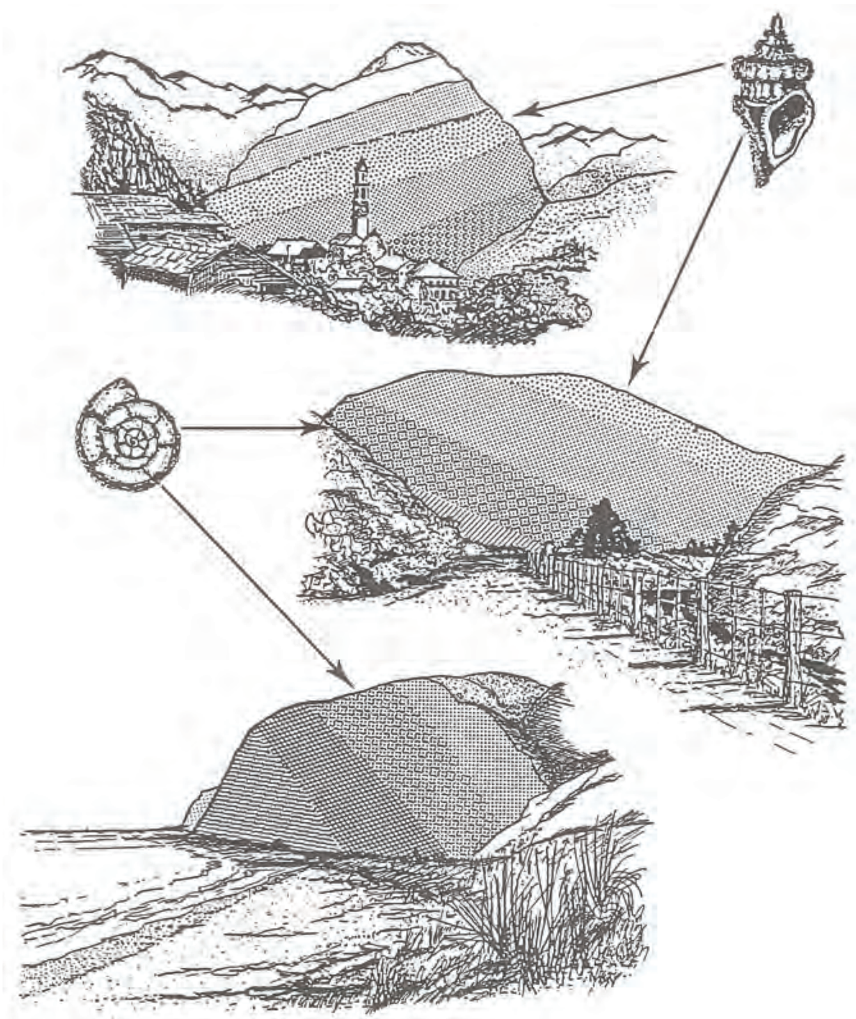


Figure 10.3 (from Earthquakes, G.A. Eiby, Fig. 51) The complete geological column has to be pieced together by comparing the sequence of fossils in the strata of many different localities. The fossils determine the age of their rocks, not their composition.

In a sequence of undisturbed strata the oldest rocks are to be found at the bottom and the youngest at the top. The variety and confusion of the rocks that now appear at the Earth's surface is evidence that most of them have been anything but undisturbed. They have been so folded, fractured and disrupted that the only uninterrupted sequences of strata we can find extend over comparatively short periods of geological time. We can never hope to find a complete sequence, for no such thing ever was.

In order to piece this fragmented history into a continuous chronicle that extends from rocks laid down over 500 million years ago to mud brought down in last season's floods we need the help of some other method of finding the date of a rock. That is why geologists have become so interested in fossils. Fossils are the remains of dead plants and animals that have become imbedded and preserved in accumulating sediments (Figure 10.2). Since the kinds of plants that flourish and creatures that rove the Earth are continuously changing, we can assume that rocks containing similar sets of fossils were formed at the same time. By comparing their fossil content, we can fit the rocks of the short sequences together into one grand series called the geological column (Figure 10.3).

It must be stressed that fossils indicate the ages of rocks, and not their nature. Rocks formed in different places at the same time can be very different in character and yet contain the same fossils, but the situation is complicated by the influence of climate and environment. Even if a sandstone from a shallow sea and a coal-seam from a swamp were formed at the same time, we could not expect them to contain the same set of fossils. No field geologist is likely to find a fossil penguin lying alongside a fossil hippopotamus.

Although the concept of the geological column is invaluable for placing events in the right order, it can tell us little about the age of a rock in years. A geologist will say that a rock is of Eocene or Jurassic age much as a historian will say that something happened during the reign of Charles II or George III; but while it is easy to confirm that Charles came to the throne in 1660 and that George died in 1820 we cannot assign exact dates to the beginnings and endings of the geological periods. The thicknesses and probable rates of deposition of sediments can be used to get a rough idea, but there is a better method that depends upon an analysis of the radioactive constituents of the rocks.

Radioactive elements spontaneously emit atomic particles, and in consequence become transformed into lighter elements. Uranium, for example, eventually becomes lead. The rates at which different elements decay differ greatly, but the time that a given quantity of an element takes to fall to half the original amount is constant, and unaffected by heat, pressure, or any other external influence. Measurements of the relative amounts of a suitably chosen element and its decay-products in a sample will therefore allow its age to be calculated. The particular elements chosen are discussed in Chapter 18. There are many practical difficulties. The amounts of the decay-products are often very small, and some may be gases, or readily soluble, so that we cannot be certain that we have collected all that were produced. Nevertheless, many rocks have now been assigned dates to within useful limits, and it is possible to place some reasonable

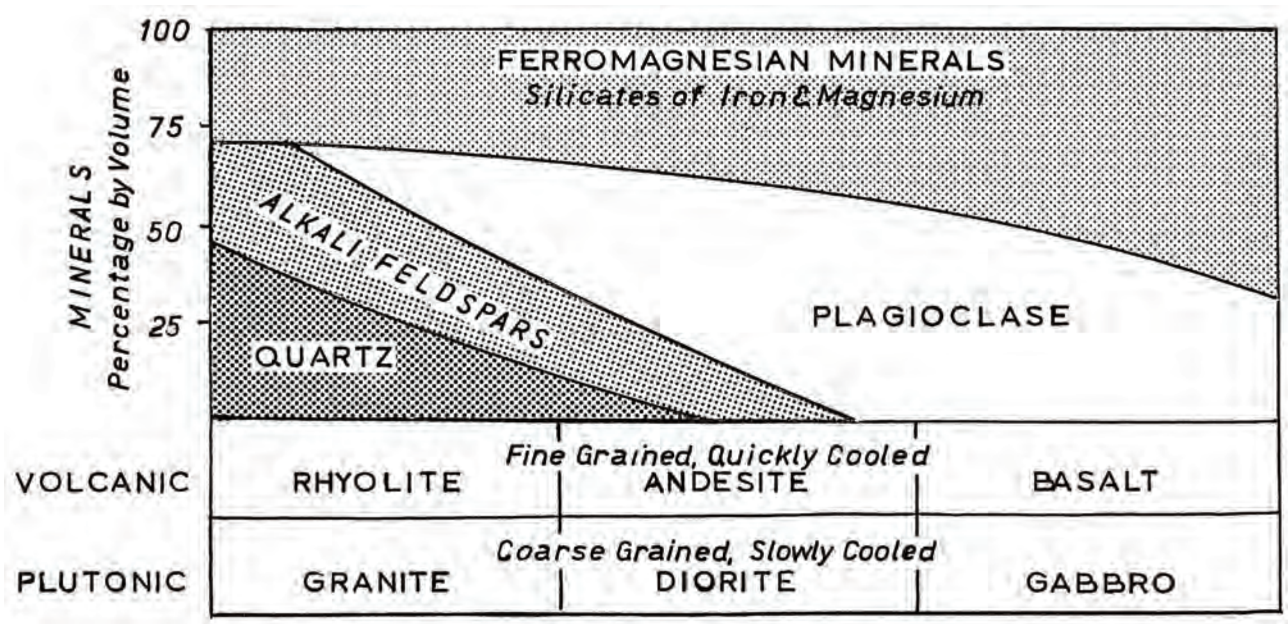


Figure 10.4 Composition of the six most plentiful igneous rocks to be found at the Earth's surface. Other families of rocks are produced by intermediate rates of cooling, or from magmas in which the proportion of ferro-magnesian minerals is increased.

figures against the names of the periods that make up the geological column. These are listed in the Appendix.

Places in the column are not reserved just for sedimentary rocks, but care is needed in dealing with igneous rocks that do not contain fossils. It is safe to assume that a lava-flow or a deposit of ash is younger than the rocks that lie beneath it; but intrusive rocks can thrust themselves between existing layers, and can look deceptively like lava-flows.

We have still to introduce the third main class of rocks. Once molten rock has cooled or sediments have compacted and hardened, the rock that has formed is not necessarily in its final state. Deformations of the crust may bury it once more and subject it to further heat and pressure, or the heat from an igneous intrusion nearby may cause it to melt and re-crystallise, so that it becomes a new kind of rock. Rocks that have gone through transformations of this kind are called metamorphic (Greek metamorphe, change of form). One result of metamorphism is to obliterate original differences, and rocks that were once very unlike can end up almost indistinguishable.

To the horror of petrologists, seismologists have long divided the Earth's crust into two layers, which they term granitic and basaltic. They will offer the further generalisation that granites are light, acid, and viscous, while basalts are heavy, basic, and fluid. It must be declared that this is an inadequate summary of igneous petrology, and if pressed further becomes seriously misleading. The problem is to say more without entering a thicket of fine distinctions.

Many rocks have familiar names, but when names were bestowed on the minerals it was customary for scientists to display their classical learning. Today, when Greek and clarity are widely thought to be incompatible, we shall include only major landmarks in our text, and relegate detail to the Appendix for reference if needed.

Igneous rocks, like sedimentary ones, are composed of a variety of minerals; but while the sediments are loosely-controlled mechanical assemblages, the constituents of an igneous rock have crystallised from a complex melt in a way that depends upon differences in melting-point and crystal form. The first crystals to form can attain their natural size and shape, but latecomers are forced to fill the interstices in whatever way they can. In general plutonic rocks, which cool slowly and give crystals time to grow, are coarse-grained, while volcanic rocks and shallow intrusions that have been rapidly chilled are fine-grained, and may even become a glass, like obsidian.

We have already noted that the silica content of volcanic rocks greatly influences their viscosity, and consequently their behaviour when erupted. Varying silica content produces a similar range of physical properties in hypabyssal and plutonic rocks, but we cannot reduce the bewildering variety of igneous rocks to order merely by considering their silica content and the rate at which they have cooled. We must also consider their mineral composition, which involves us in further complication.

It is probably best to consider the minerals as building blocks. If we lay bricks in a particular pattern, we can produce the same pattern with bricks of a different colour. When minerals can be fitted together to make a particular kind of rock, there is almost certain to be a similar rock in which one of the minerals has been replaced by another that has crystals the same shape. Such crystals are said to be isomorphous (Greek iso, the same, and morphe, shape). When each unit of a pattern contains several building-blocks of the same kind, the number of possible substitutions becomes very great, and perhaps it is as well that not every possibility occurs in nature.

Silica is the overwhelmingly predominant constituent of crustal rocks. In acid and intermediate rocks it is usually present as quartz, which typically occurs as transparent six-sided crystals that end in pyramids. It can combine with oxides of other compatible elements, the chief of which are sodium, potassium, and calcium, to form a group of minerals called silicates. The commonest of these are the feldspars.

Feldspar is an old German mining term, as are most of the common mineral names that are not Greek. The spars were a group of more or less transparent crystalline minerals that could easily be split, and feld just means field. They are complex silicates of aluminium, termed orthoclase if potassium is present with the aluminium, and plagioclase when either sodium or calcium is there instead (Greek orthos, straight, plagios, oblique, and clasis, a fracture). When feldspars are decomposed by weathering they combine with water to form clays or mica.

Quartz, feldspar, and mica are the essential constituents of granite, whose usefulness as a building-stone has made it perhaps the most familiar of all rocks to non-geologists. Most granites have cooled slowly and the crystals of the constituent minerals are well-developed. It is by far the most abundant of the intrusive rocks. When an essentially similar magma is cooled rapidly, the products are very dissimilar, and include the vitreous rhyolite, the glassy obsidian, and pumice, which owes its open texture to gas bubbles. Porphyry, the deep purple stone so prized for architectural decoration in classical Rome, lies between these two groups, and when polished displays a characteristic texture, with large shining crystals of orthoclase standing out from the ground-mass. Such crystals (not only the ones in porphyry) are called phenocrysts (Greek phaino, to make appear).

Let us begin once more with granite, and confining ourselves to coarse-grained rocks that have cooled slowly, look for ones that are increasingly basic. As we turn to rocks with less and less silica content we find instead more plagioclase and more minerals rich in oxides of iron, calcium, and magnesium. We pass first to the intermediate diorite (Greek diorizein, to distinguish) which contains hornblende. This is another old German mining term. Blenden means "to deceive", and the name was given because it turned out not to be an ore of lead. It is in fact a complex alumino-silicate rich in iron, magnesium, and calcium. Still more basic is a gabbro, a Florentine word once applied to a variety of rocks, fortunately including gabbro.

The fine-grained and rapidly cooled volcanic equivalents to the plutonic gabbro, diorite, and granite are basalt, andesite, and rhyolite. These six rocks with a few closely-related neighbours make up well in excess of ninety per cent by volume of all igneous rocks that occur at the Earth's surface. Figure 10.4 shows the broad relationships between their composition and properties.

As the granites dominate the intrusive rocks, so do the basalts dominate the volcanics. They are dark in colour, and their constituent minerals are most easily distinguished with a microscope. When basalts weather, a rusty-looking deposit appears on the surface. This is due to the presence of the iron oxide magnetite, the ancient mariner's lodestone. The denser basalts also contain augite or olivine. Augite (Greek auge, lustre) occurs also in the other basic igneous rocks and is a member of a group of minerals called – or rather mis-called – pyroxenes (Greek pyr, fire; xenon, a stranger) because early geologists did not consider them to be igneous. They are silicates of magnesium, calcium, and iron. Olivine, a complex silicate of iron and magnesium, forms transparent olive-green crystals that can be cut into gems called peridots. The word is of mysterious eastern origin, first applied to olivine by French jewellers in the eighteenth century, and has given rise to the name peridotite for the most important of the ultra-basic rocks which are the main constituents of the mantle.

Between basalt and gabbro lies dolerite (Greek doleros, deceptive), perhaps the commonest member of the basalt family, and so-called because its rather fine grain makes the constituent minerals hard to distinguish. American geologists call it diabase (Greek diabasis, transition). Most sills and dikes consist of dolerite, but very sudden cooling can surround them with a transitional layer of basalt, and an outer skin of the comparatively rare tachylite (Greek tachos, swift, lytos, soluble). This is a misnomer, for it is not soluble, but readily fusible, which is not at all the same thing. It represents the glassy extreme of the basalt family.

Andesite is the fine-grained equivalent of diorite, and an intermediate rather than an acid rock, though andesitic volcanoes have often been loosely described as acidic, in opposition to basaltic ones. It issues from the volcanoes of the Andes, and indeed from almost every volcano in a subduction zone, but Andean volcanoes do not limit themselves to the eruption of andesite. More acid than andesite, but less so than rhyolite, is dacite, named after Dacia, a Roman word for a region now part of Romania.

Diorite and andesite are paralleled by two other intermediate rocks of alkaline composition, the plutonic syenite (from Syene, in Egypt (Figure 10.5)) and the volcanic trachyte (Greek trachus, rough). They are composed of alkali feldspar in which orthoclase predominates. If plagioclase is present it takes the form of albite (Latin albus, white), the silicate of sodium and aluminium.

A rather more complete classification of igneous rocks and some chemical analyses are listed in the Appendix.

Figure 10.5 An intrusion of the dark plutonic rock syenite, Cape Syenite, King Oscar's Fiord, East Greenland.

11—Hills and Holes

The convulsions and revolutions of the geological world, like those of the political, are sad confounders of place and station, and bring into close fellowship the high and the low.

HUGH MILLER: The Old Red Sandstone

Hokusai, Hiroshige, and a host of less talented artists have made the symmetrical beauty of Mount Fuji a universally recognised symbol of Japan, and at the same time the archetypal volcano by which we judge the perfection of the rest. In fact, there are many tall volcanic cones like Fuji – El Misti in the Andes, Mayon in the Philippines, Shishaldin in the Aleutians, and Klyuchevskaya in Kamchatka, to make a random selection. All of them prove to lie in subduction zones. Not that it is impossible to find cones near a spreading ridge, like the 3,713-metre Pico de Tiede in Tenerife and Fayal in the Azores, but they tend to be less steep and not so high. In Iceland and Hawaii the volcanoes are quite a different shape, reflecting differences in their composition and behaviour.

Volcanoes, like any other protruding feature of the Earth's crust, are no sooner built than the forces of erosion mount their attack, while they assist in their own destruction by blowing themselves apart, or by pouring out so much lava that there is a collapse that leaves a hole rather than a hill. Growing neighbours can cover them in ash, or pile debris alongside until they are overwhelmed. Physicists are apt to see all this activity as a side issue that diverts attention from the primary source of energy that lies underground. Volcanic cones are at best beautified rubbish-heaps – yet archeologists have learned much from middens, and it is well to approach volcanoes in the same spirit.

The shape of a volcano depends upon the shape of the vent that feeds it, on what comes up the vent, and upon whatever erosion and other destructive forces subsequently do to it. Most vents are either cylindrical, or elongated fissures. To produce a cone there must be a cylindrical vent that will remain more or less circular in spite of the hazards that attend plugging and unplugging in successive eruptions and the explosions that take place in the crater, and there must not be any outbreaks through the side wall because the plug has proved too effective.

Arguments about the beauty of volcanoes usually dwell upon symmetry, and by this criterion Mayon (Figure 11.1), in spite of a gully on its south side, must be considered to outclass Fuji, which has an unbecoming bulge on its northern flank. Shishaldin in the eastern Aleutians comes nearer to perfection, but few volcanoes appear equally shapely from all directions. Egmont has a parasitic cone (or could it be too close a neighbour?) to the south, prominent enough to have been given the name Fantham's Peak (Figure 11.2). The rather derogatory term parasitic is applied to a smaller cone built around a lateral vent through the wall of an existing cone (Figure 11.3). If blockage of the main vent persists or the new path proves easier, it is possible for the parasite to overwhelm the host, growing higher and becoming more frequently active than the original outlet, as was the case with Ngauruhoe and the older Tongariro (Figure 11.4). It is more usual for the new cone to remain small, and for the presence of blemishes to be regarded as an indication of old age.

Figure 11.1 Mayon volcano, in southern Luzon, is a typical symmetrical cone. Note the formation of orographic cloud in the lee of the mountain. The church in the foreground was destroyed by lahars (Chapter 12) in 1814, killing several hundred people seeking shelter inside.

Figure 11.2 A parasitic cone. The symmetry of Mount Egmont is marred by the presence of Fantham's Peak, a parasitic cone on its southern flank.

The material that issues from a vent often changes in character and composition during the course of an eruption, and from outbreak to outbreak. Nearly all large volcanoes in island arcs and at continental margins prove to be complex structures of old lava-flows, falls of ash, blocks, and fragments of rock blown from the vent, and of lahar and landslide debris (Figure 11.5). Volcanoes of this kind have traditionally been called strato-volcanoes (Latin stratum, a layer), but the term is out of favour with modern volcanologists, both because the material is seldom disposed in orderly layers, and because basaltic domes (which are not strato-volcanoes) have an equal or stronger logical claim to the name. We shall follow the up-to-date trend and call them composite, a name to which both their varied composition, and the fact that they are built up in a series of eruptions, entitles them.

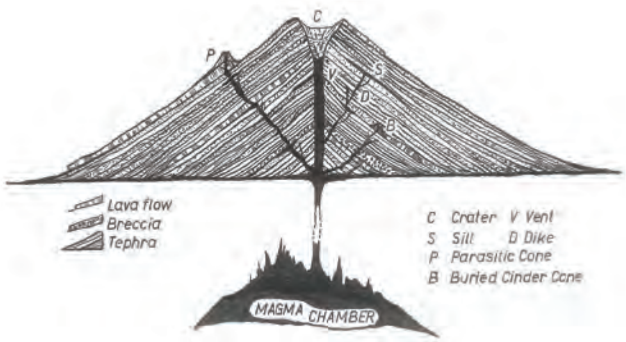


Figure 11.3 A composite volcano with a parasitic cone.

Figure 11.4 Ngauruhoe on the right, which began as a parasitic cone, has now outgrown the parent Tongariro.

Figure 11.5 Structure of a composite cone. In this close view of Mount Egmont the scale of the massive lava-flows is established by the chalet buildings, lower left.

The size of the best-known composite cones is impressive. Fuji rises 3,700 metres above a base 30 km in diameter, giving it a volume of about 870 cubic kilometres, and it is not hard to find others to equal it – Mount Rainier and Mount Shasta in California, and Popocatépetl in Mexico. Egmont, in New Zealand, is broader at the base than Fuji, but only 2,978 metres high, while Etna, Europe's largest volcano, is 3,210 metres high and 40 km across. Several of the Andean volcanoes are higher, rising to more than five thousand metres, but they have the advantage of starting fully half that distance above sea level, and none of them compares in volume with Fuji and its peers.

Perfection of form is not usual among giants. To find it we must go to a class of formations variously known as scoria cones, pumice cones, and ash rings (Figures 11.6 and 11.7). All of these are heaps of loosely piled fragments, usually produced in the course of a single eruption, and seldom exceeding a few hundred metres in height. Many of them are indeed quite small and reach only tens of metres. Being composed of loose material they are rapidly eroded. They do, however, afford the best opportunity for looking more closely at the shape of a cone.

If you try to heap up coal or gravel, the dirt you have dug from a hole, or your last year's turnip crop, there is a limit to the angle at which you can make the sides of your pile stay up. It depends upon the friction between the particles of the material you are trying to stack, and is called the angle of repose. For a pile of scoria it is 33 degrees, and all scoria cones turn out to have this slope. The values for other kinds of rock fragments are not very different, though fine particles tend to have smaller angles than coarse ones. Composite cones tend to have gentler slopes than scoria cones, as the inclusion of fluid lava-flows tends to lower the average coefficient of friction.

Figure 11.6 Mangere Mountain or Te Pane-o-Maaoho in the Auckland Volcanic Field is a scoria cone that is still close to its original condition.

Most people instinctively feel this angle to be too low, and nearly all artists improve on nature in this respect (Figures 11.8 and 11.9). Hokusai draws Fuji with an average slope of 40 to 50 degrees in different pictures. Hiroshige limits himself to a more realistic 35 or 40. This tendency to exaggerate is not limited to Japanese artists. Charles Heaphy, who produced his popular view of Egmont in 1840 when realism was the fashion, starts off at the right angle, but gradually steepens his curve until just below the peak he reaches an impossible 62 degrees. At the very summit there is a steep-sided dome, but much of the upper part of the mountain is covered with loose scoria, and anyone who has climbed it will agree that 30 degrees is plenty.

The artists have some justification for increasing the slope towards the top, for once erosion begins the profile of a volcano gradually assumes a graceful hyperbolic curve. Falling rain and melting snow form streams that become larger and swifter as they descend the slopes. Landslides and collapses are started, and material washed away is deposited again at the bottom. Gradually a wide skirt is built up, while the upper slopes are steepened. Most material is removed from the middle part of the course, where the streams flow deepest and swiftest.

Composite cones are not so successful in retaining their figure as scoria ones. Heaps of scoria are porous, rain readily soaks in, large streams cannot form, and erosion is delayed; but not for ever. Sooner or later, weathering breaks up the surface, small particles are

Figure 11.7 The inner and outer slopes of a young cinder cone are equal, both lying at the angle of repose. Vulcan, near Rabaul, Papua New Guinea.

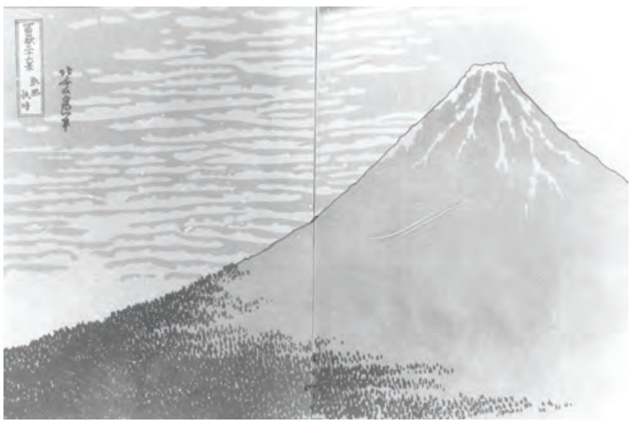


Figure 11.8 Most artists exaggerate the slope of a volcanic cone, as in this illustration from Hokusai's "Thirty-six Views of Fuji".

Figure 11.9 Like Hokusai, Hiroshige exaggerates the steepness of Fuji in the print "Hara" from his "Fifty-three Stages of the Tokaido", but not to the same degree as most western artists would do.

Figure 11.10 Parasol ribbing. Bromo, Java.

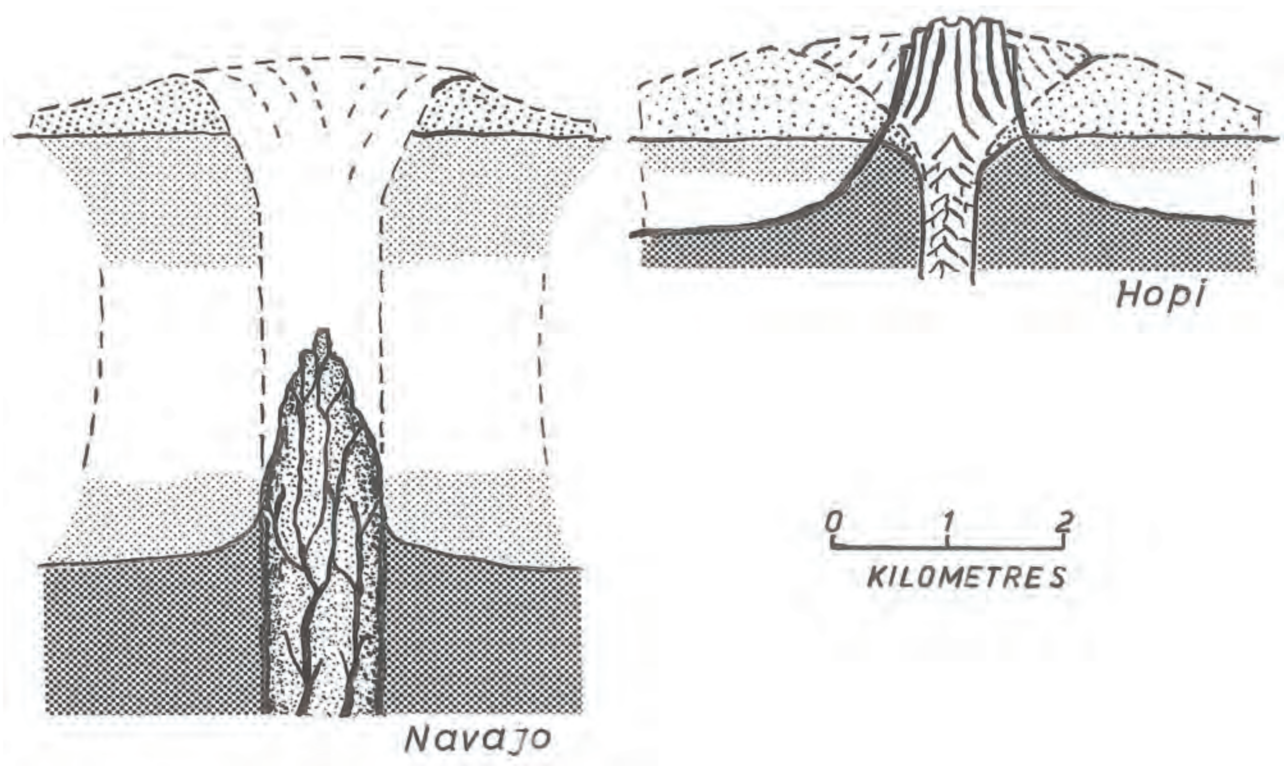


Figure 11.11 The form of a volcanic neck depends upon the extent to which both the neck and its surroundings have been eroded. These two characteristic forms have been given the names of North American Indian tribes.

Figure 11.12 Tokatoka volcanic neck Northland N.Z.

Figure 11.13 A stock or boss, Issoire, Auvergne, France.

washed into the spaces between the lumps of scoria, and the surface becomes sealed. Once that happens, streams can form, and re-shaping of the cone begins.

When seen from a distance at high noon the sides of a cone appear smooth, particularly when they carry a coating of snow, but the slanting rays of the setting sun cast shadows into the deep gullies cut by the streams, and wrinkles appear, arranged radially in a regular pattern, like the ribs of a partially opened sun-shade. As the streams cut deeper and deeper the spaces between them become narrowed to sharp ridges, producing the effect known as parasol ribbing (Figure 11.10).

Rates of erosion depend greatly upon climate and covering vegetation, and active volcanoes often succeed in supplying new material as fast as the old is removed, or there may be cycles of destruction and re-building. In the last quarter of a million years both Egmont and Ruapehu have been through several such cycles, and it can be 15 or 20 million years before a tall cone is finally reduced to a low rounded hill. Nevertheless, every mountain and hill is fated to be laid low.

Figure 11.14 The shield volcano, Skjaldbreidhur in Iceland.

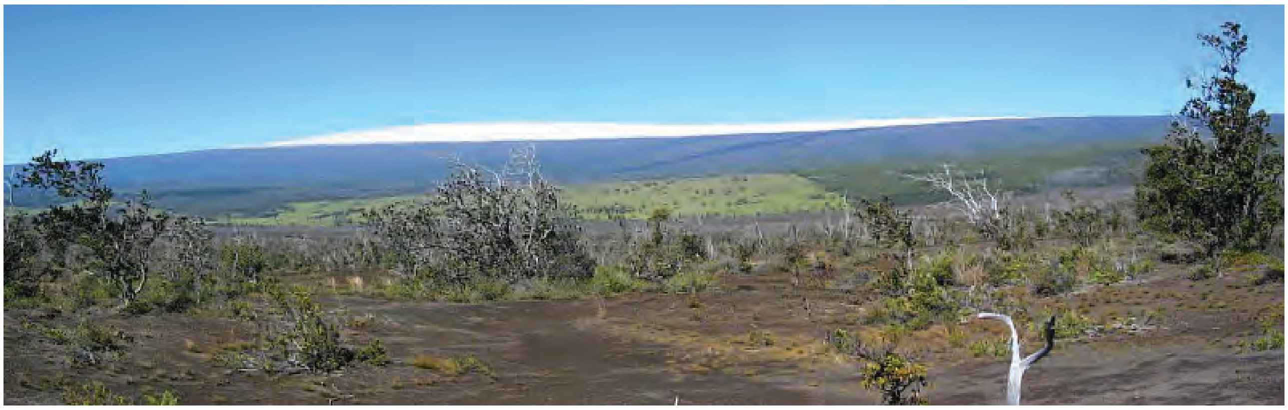


Figure 11.15 This view of snow on Mauna Loa, on Hawaii Island, emphasises how gentle are its slopes.

Eroded volcanic remnants assume a number of characteristic landforms. Softer material is removed first, and the lava of the central pipe and the harder intrusions may remain as a volcanic skeleton. Plugs and material filling the central vent are usually the last to disappear, and can remain standing as isolated crags or pinnacles known as necks (Figures 11.11, and 11.12). The larger and more regular examples may be regarded as stocks or bosses (Figure 11.13).

The building of cones is typical of volcanoes that emit fragmented material – scoria, pumice, ash and lapilli – either alone, or in the case of composite cones alternating with the emission of lava. Volcanoes that emit fluid basaltic lavas, like those of Iceland and Hawaii, build shields rather than cones, as liquids do not consist of separate particles that can be piled into heaps. Liquids do, however, possess viscosity. We can think of this as a kind of internal friction that delays their efforts to find their own level. Viscosity depends upon temperature, and lavas become more viscous as they cool. The shield-like shape of many basaltic volcanoes therefore depends not only upon the composition of the lava, but upon how rapidly it issues from the vent, and how large a cooling-surface it offers once it gets out. Basalt flows may have a slope of as little as half a degree or as much as ten, though two to seven degrees is a more typical range (Figure 11.15).

The type example of a shield volcano is the 1060-metre high Skjaldbreidhur in Iceland (Figure 11.14). It has a slope of seven degrees, is about 7 km in diameter, and has a volume of about 15 cubic kilometres. The resemblance to the traditional shields of the Vikings is striking, and its form is as regular as that of any cone.

Figure 11.16 The dome of Showa-Shinzen, Hokkaido, Japan was formed by an eruption between 1943 and 1945.

Figure 11.17 A cumulo-dome in the Chaîne des Puys, Auvergne, France.

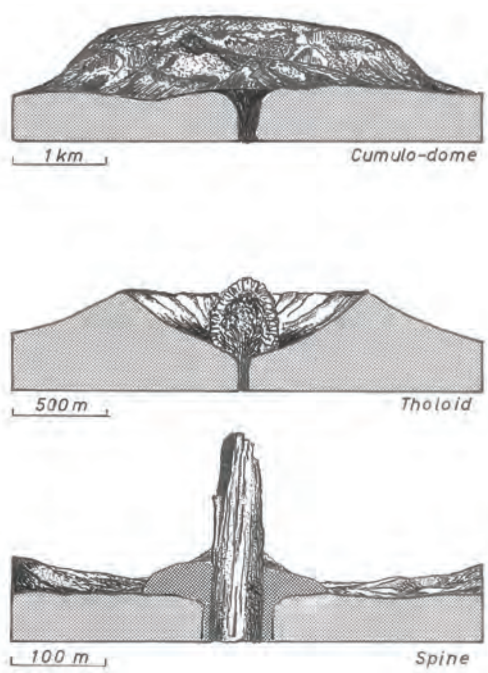


Figure 11.18 Domes, Tholoids, and Spines.

Figure 11.19 The spine of Mont Pelée, from Alfred Lacroix's classic study of the 1902 eruption.

Compared with the Hawaiian shields, Skjaldbreidhur is perhaps a pigmy. Mauna Loa is no less than 120 km in diameter and rises 4169 metres above sea level. If we were to measure from its true base on the sea floor it would add another 6,000 metres, and easily outclass the 8,848 metres of Mount Everest. Its volume has been put at 40,000 cubic kilometres, and it is no surprise to find that it is the largest shield.

We have seen that viscosity is the main factor determining the profile of a shield. If a lava becomes solid before it has moved far from the vent, the result is not a flattened shield, but a dome. While cones and shields are large composite structures built up in layers in the course of many eruptions, basalt domes are often, though not always, the product of a single eruption, and more or less uniform in composition. The smaller specimens, bounded by the crater of an old volcano, may be short-lived, and destined to be blasted to pieces by the first explosion of a subsequent eruption.

The domes of rhyolitic or andesitic lava formed by acidic volcanoes are usually extruded at a late stage of an eruption, when the magma has lost most of its gas. While the gas content remained high, the lava was light and brittle, and easily blown away by quite small explosions. Although any accumulation of material over and around a vent may be called a dome, acid lavas are viscous enough to assume and retain a variety of shapes to many of which descriptive names have been given (Figures 11.16, 11.17 and 11.18).

The important feature uniting these structures is the absence of a crater. Their material is not thrown from an open vent, but extruded like toothpaste from a tube, and may either remain protruding to form a spine, or collapse and flow to form a cumulo-dome (Latin cumulus, a heap) or a tholoid (Greek tholos, a kind of circular tomb with a dome). In losing enormous volumes of dissolved gas, the material has often become soft and porous and can offer little resistance to erosion, so that it soon collapses and piles about the vent. Acidic domes may therefore be the product of successive episodes of collapse and re-building. Cumulo-domes are sometimes called mamelons (French, nipples), but the term is not restricted to domes of volcanic origin.

The most famous spine is the one extruded from Mont Pelée after the disastrous eruption that destroyed St. Pierre in 1902 (Figure 11.19). Its sides rose vertically for several hundred metres, and at one stage it grew at the rate of 13 metres per day. The cross-section of a spine depends upon the shape of the aperture, and as this is usually an old vent they are seldom circular. Spines may be considered an extreme form of piton

Figure 11.20 The one-year old Parícutin has the form typical of a young scoria cone, rising 350 metres above the valley floor, with sides sloping at an angle of 33 degrees.

Figure 11.21 Explosion pits and scoria cones abound in the Auckland Volcanic Field. The pit in the foreground has become cultivated farmland, and the terraces on the two cones are Māori defence works. The view is of north-east Tamaki.

Figure 11.22 The crater of Mayon is barely 200 metres in diameter. Single vents are seldom much bigger than this.

Figure 11.24 Panmure Basin, Auckland, a breached maar.

(French, a mountain peak or, in popular language, a large nose) or plug dome, which is the usual American term for a cumulo-dome. Like spines, pitons tend to be short-lived, though fairly numerous exceptions can be found in the West Indies. The Gros and Petit Pitons of St Lucia reach heights approaching 800 metres, and the great Puy Chopine, one of the more impressive of the Chaine des Puys in the French Massif Central, is considered by one school of geologists to be a piton. Mount Edgecumbe, an isolated 800-metre peak in the Bay of Plenty whose sides carry deep grooves scratched during the process of extrusion is sometimes cited as an example, but New Zealand geologists more often call it a lava-dome.

Occasionally, when the extruded material is too weak to stand vertically, it may be pushed along horizontally, and form an extended ridge. Extrusion is not always a smooth and steady affair. The moving column can become stuck until protuberances have been broken away, and remaining pockets of gas can explode and shatter the surface, sometimes piling up a skirt of talus-like material at the angle of repose, and even on occasion burying the dome.

Figure 11.23 Maar at Dieng Plateau, Java.

Just as pitons are a kind of spine, tholoids are cumulo-domes formed within a crater. The end of an eruption is often marked by the formation of a tholoid, but the appearance of a tholoid is by no means an indication that an eruption is about to end, for a whole series of tholoids may be formed and blown apart before it is finally over. There is a well-developed tholoid in the crater of Mount Egmont. It signalled the end of its last eruption two or three hundred years ago, but it would be surprising indeed if it proved to be a permanent feature of the mountain.

The look of a volcano frequently owes as much to destructive forces as it does to those that built it. They range from the comparatively gentle and regular sculpture of the slopes by running water to the violent and erratic hazards of explosion, and the chaotic results of collapse. Explosions usually form a crater, or clear a blockage in an existing one. Regular explosions in a vent, like those in Strombolian volcanoes, have the effect of enlarging it until it becomes conical in form, with an inner slope much like the outer one, as they both depend upon fragments that will assume the same angle of repose. This is very well seen in young scoria cones like Parícutin and those in Auckland, New Zealand (Figures 11.20 and 11.21). Such craters rarely become more than a kilometre or two in diameter. Many crater walls, however, are precipitous, for more violent eruptions can "clear the volcano's throat". Walls of solidified lava or material welded by past heating can stand almost vertically, so that the crater remains little larger than the vent, which is usually quite small. The crater of Mayon, for example, is only about 200 metres across, and it is rare to find vents that are more than a few times bigger than this (Figure 11.22).

One important kind of explosion crater need not involve a mountain at all. When percolating groundwater comes into contact with hot rock and is suddenly converted to steam, there is likely to be an explosion and a crater. The pits formed by these phreatic eruptions are nearly circular and may measure as much as a kilometre across, but they are seldom deep. The ejected material forms a rim, most marked on the down-wind side, and up to 50 metres high. Although shallow, they are usually deep enough to intersect the water-table and form lakes called maars, the name given to the ones in the Eifel district of Germany, where they are quite numerous (Figure 11.23 is an example from Java).

In some cases, the formation of a maar is followed by the building of a scoria cone, and at Mount Wellington, near Auckland, the cone has almost buried the maar. Lake Pupuke, north of the city, is one of a number that retain their circular form, though some, like the Panmure and Onepoto Basins, have been invaded by the sea (Figure 11.24). Maars are also to be found in the Auvergne, in Idaho, in Victoria, and in many other places.

The common fate of summit craters is for an explosion to open a breach in their wall. The explosion that clears a blocked vent is unlikely to be symmetrical, and zones of weakness in the wall influence the position of the breach. Old volcanoes seldom keep their youthful figures. The story of Vesuvius will serve to illustrate both the constructive and the destructive powers of vulcanism.

We must thank one of the great pioneers of volcanology, Sir William Hamilton, for the survival of so many early accounts of Vesuvius. He became British Ambassador to the court of Naples in 1764, and soon became an authority on the volcanoes and the antiquities of Italy, reporting his findings to the Royal Society in London, of which he became a Fellow in 1766. He commissioned competent artists to illustrate accounts of his travels, and in 1772 published his Campi Phlegraei containing the volcanological observations, adding a supplement in 1779. It is sad that he should be better remembered for the love affair between Horatio Nelson and Emma, his second wife, than for his contributions to science and the fine collection of ancient vases that he gave to the British Museum.

Vesuvius began as an island cone in the Bay of Naples about ten thousand years ago. It grew, and joined itself to the land. Successive eruptions truncated the cone, and enlarged the crater, and by the time of the Plinian eruption in A.D. 79 it had become a flat-topped mountain rather higher than the one we know today, with a great cleft on the seaward side. That eruption blasted away fully half of the crater rim, and started an internal collapse that engulfed much of the remnant. Within two days copious showers of ash and pumice had buried Pompeii and Herculaneum, and a new cone had begun to form about the vent (Figure 11.25).

No further eruptions are recorded for nearly two centuries, but it is unlikely that none occurred. After that accounts become quite numerous. In A.D. 472 ash

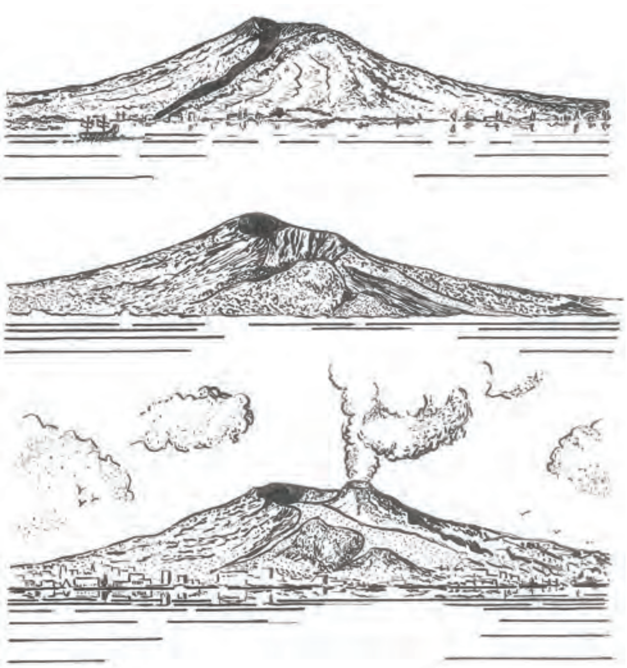


Figure 11.25 Changes in the shape of Vesuvius. The two upper pictures show the mountain before and after the Plinian eruption of A.D. 79, and the lower picture its appearance in the early nineteenth century. A modern photo appears in Chapter 3.

Figure 11.26 Santorin.

Figure 11.27 Taal Lake, a caldera in northern Luzon, is some 30 kilometres in diameter. Since this picture was taken in 1961 the shape of the island has been modified by subsequent eruptions.

from a major eruption caused alarm in Constantinople, 1,200 km away, and in 1036 an even larger one gave rise to the earliest accounts that refer to lava-flows.

The eruption of 1631 lowered the cone by 168 metres and doubled the size of the crater. Lava-flows from two lateral fissures reached the coast, and lahars destroyed nine towns. Later eruptions display a new and more regular pattern that continued until the eruption in 1944. Lava-flows became usual, and few parts of the southern slopes remained unaffected, but Monte Somma, the remains of the ancient crater rim, prevented flows from reaching the north.

In 1872, the north flank of the cone split from top to bottom, and a succession of cone-building episodes and lava-flows characterised the eruptions from then until 1906, when the cone within the central crater became large enough to fill it and become an effective continuation of the slopes. At this time Vesuvius reached a height of 1,322 metres, the greatest measured, but within a month an outrush of gas carried away a hundred metres of the top. A repetition of these events occurred in 1944.

Changes to the crater have been as extensive as those to the outer slopes. In the 1906 eruption it became an elliptical basin about 300 metres deep and 550 metres from east to west. By 1944 the cinder-cone had filled it and risen high enough above the rim of the main crater to be visible from Naples, but in 1952 there was a hole once again, over 200 metres deep.

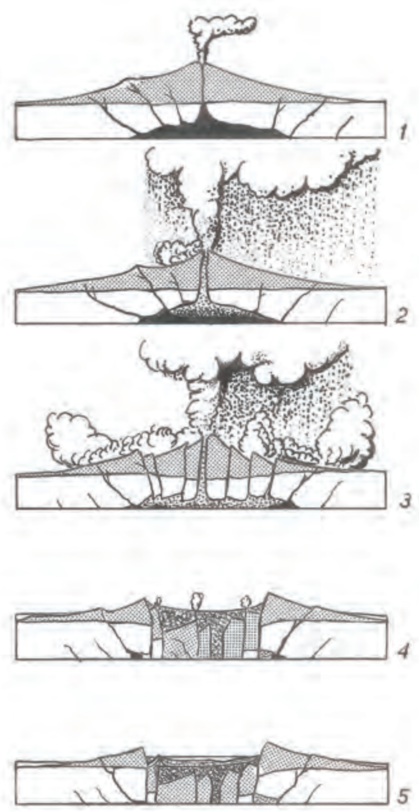


Figure 11.28 Development of a caldera, Crater Lake, Oregon (after H. Williams).

To stand on the edge of a large crater and look into a vent that descends into an apparently bottomless gloom is a memorable experience, but in the usual sense of the word craters are not large – "mere dimples in volcanic summits, or at most somewhat enlarged funnels" says Sir Charles Cotton – but it is easy to find cones whose truncated appearance suggests that the entire top of the mountain has been blown away, leaving a depression many times larger than any vent. These depressions are called calderas (Spanish for kettles. Crater is Latin for a cup, an altogether smaller container). Contrary to appearance, they are not the result of cataclysmic explosion, but of collapse. Monte Somma, the encircling rampart of Vesuvius, and Crater Lake, Oregon are both calderas. To qualify as a caldera a depression must have a diameter of at least a kilometre. Anything smaller is called a collapse pit. Many calderas have a diameter of 10 kilometres or more. They usually mark the sites of great eruptions, and in general the larger the caldera, the larger the eruption. Santorin, north of Crete, Taal and Krakatoa are examples of large calderas that have been invaded by the sea (Figures 11.26 and 11.27).

It is easy to assume that in order to find the material to build a cone or to hurl across the countryside a volcano must excavate a great underground cavern, into which the original mountain eventually collapses

Figure 11.29 Fire-fountaining Pu'Oo, Hawaii.

Figure 11.30 Halemaumau lava pit on Kilauea.

under its own weight, forming a caldera. The trouble with this simple idea is that volcanoes cannot excavate caves. Magma is liquid, and the deeper we descend into the Earth, the more plastic the material becomes. The pressure of the rocks above will ensure that any incipient holes are quickly filled up, and that the cone remains adequately supported – if it is given time. Magma is not only hotter than the surrounding rock, but contains dissolved gases and chemically-active substances that attack the walls and roof of the magma-chamber, detaching and dissolving pieces of the surrounding rock. While the magma continues to support the cone, the layer of rock that separates the two is nevertheless thinned and weakened, and may become unable to support the pressures.

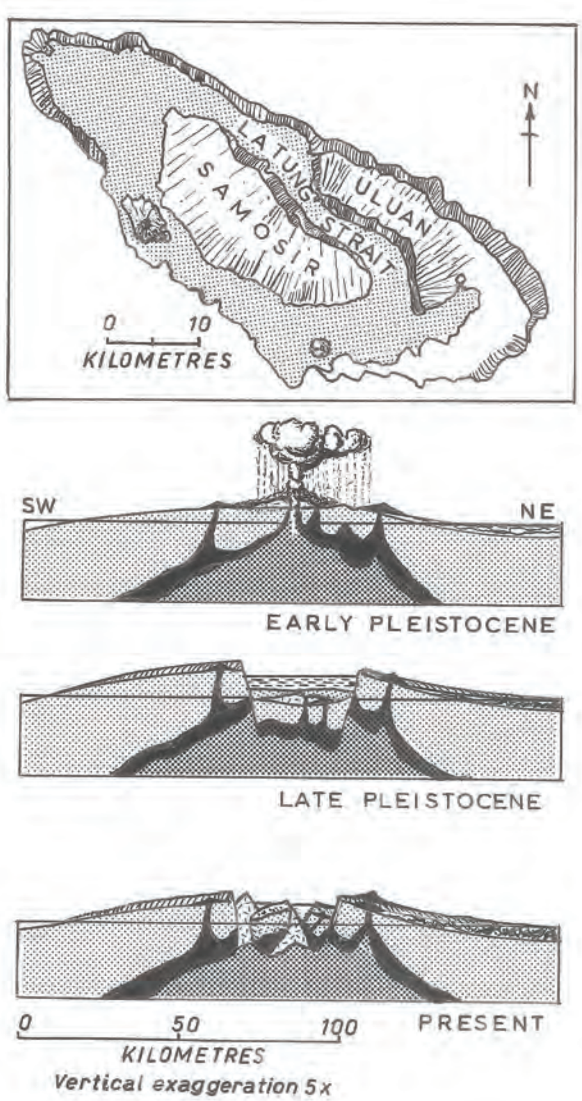


Figure 11.31 Lake Toba, Sumatra. Successive stages of a volcano-tectonic depression.

In the course of an eruption, lava-filled craters are often seen to empty suddenly, the lava quickly vanishing down the vent without warning. There is probably no single reason why this happens, but if the magma suddenly finds its way into an underground crack, or finds an easy path along a plane of weakness between strata, the level has to fall correspondingly, and can do so rapidly enough to leave the cone unsupported, and initiate collapse. Also, the loss of gas and steam when magma reaches the surface is accompanied by a large reduction in the volume of what remains.

In 1941 Howel Williams published a study of Crater Lake, Oregon, which provides a further argument for calderas being the result of collapse (Figure 11.28). The lake fills a depression about 9 kilometres across with 600-metre high walls that are believed to be all that remains of a cone that once rose 3,600 metres. If that is so, some 60 or 70 cubic kilometres of material are now missing. Williams carried out a search of the surrounding countryside to see how much of it he could find. He finished up more than 20 cubic kilometres short. The only reasonable explanation was that it had fallen back into the caldera, either by direct collapse, or to a minor extent by airfall.

Measurements of this kind are not easy to make, and his figures have been questioned, but it is hard to hide 20 cubic kilometres of anything, and it is now generally accepted that subsidence and not explosion is responsible for calderas. The name explosion pit survives for application to a few small features like maars.

Summit calderas are usually the result of a Plinian eruption, but depressions on the top of lava shields, like Mokuaweoweo on the summit of Mauna Loa in Hawaii, are formed rather differently. It is about 3 km long, 6 km wide, and some 200 metres deep. Such depressions are bounded by faults that mark the outer limit of a collapse following the eruption of large amounts of lava from a fissure at a lower level on the flanks of the volcano (Figure 11.29). The nearby but smaller Halemaumau Pit on Kilauea (Figure 11.30) is usually regarded as the typical example of a caldera of this kind. They are centered over main lava-vents, and the rising and swelling of the lava probably initiates the fissuring that leads to the collapse. Such calderas are known as sinks, and other important examples can be found at Nyamlagira and Nyiragongo in the Democratic Republic of the Congo, and Erta Ale in Ethiopia.

Yet another type of caldera is perhaps better described as a subsidence than as a collapse. In these a whole block of material sinks into the magma, but remains intact during the process. Lava is quietly forced up along the fracture that marks the circumference, and becomes a ring dike, like the one surrounding the long extinct caldera at Glencoe, in Scotland, or produces a ring of volcanoes like those at Askja, in Iceland. The plug is not pierced by a central vent, and lava can flow into the depression and conceal it. In calderas of the Kilauean type, the fissures are radial but in the Glencoe type they define the circumference. The outer walls of these calderas are conical rather than cylindrical in form which would be unlikely in all structures formed by collapse. All of these structures are more or less circular but in highly active regions several depressions can join, and faults and other features of tectonic origin take part in determining the shape of a kind of super caldera dignified by the name volcano-tectonic depression. Lake Toba, in northern Sumatra, is an example (Figure 11.31). During the late Pleistocene some 2,000 cubic kilometres of rhyolitic ash was erupted forming a plateau around the lake. Ash and pumice fell as far away as Sri Lanka and India.

The pyroclastic flows that formed the New Zealand ignimbrites left a depression nearly 100 kilometres long and 25 to 30 kilometres wide which contains Lake Taupo and several other dormant volcanoes. Evidence of the more recent ash showers from Lake Taupo can be found in most parts of the North Island. In 1922 there were subsidences along faults to the north-west of the lake, and renewed movements in 1983. They were accompanied by swarms of small earthquakes but the hydrothermal activity of the district was not obviously affected. Although volcano-tectonic depressions may reach tens or even hundreds of kilometres in length, it is not usual to apply the term to rift valleys, like the Red Sea and the East African Rifts. Rift valleys are usually long and narrow and bounded by two major parallel faults between which a block of crust has subsided, and along the course of which major volcanoes are found. We shall return to these in Chapter 37.

It is not surprising to find that depressions like explosion pits, craters and calderas fill with water and become lakes – but that does not end the matter. Renewed eruption beneath a lake may at first produce miniature Surtseyan explosions but, if they continue, the water will all be thrown out or vaporised and play no further part in its course. What happens to the lake between eruptions is more interesting.

If there are still active vents in the crater floor, the temperature is raised and there is a steadily increasing saturation of the water with accumulated gases and soluble material leached from the crater walls. Its actual composition will vary with the state of the volcano's activity. If the lake is small, the solution may become saturated, and evaporation or a small drop in temperature may cause crystals to be deposited. Most volcanic regions can provide examples of blue, green or yellow lakes – some of great beauty, and others reminiscent of the effluent from a chemical works. The lakes in the larger depressions are often kept filled by snow-fed rivers. Except in the immediate neighbourhood of active vents, they seldom have a high content of dissolved salts and may, as in the case of Lake Taupo, be exceptionally pure. On the other hand, a lake in a beautiful setting is apt to attract visitors in such numbers that there is serious pollution of other kinds.

12—Bombs and Boulders, Ashes and Mud

I am ashes, where once I was fire.

LORD BYRON: To the Countess of Blessington

Much of the material erupted from a volcano is fragmented by the violent liberation of gas. These fragments, which can vary in size from fine dust to large rocks, are collectively called pyroclastics (Greek pyr, fire; klastikos, broken). The stiffer the magma, the more likely it is to be explosively shattered, and while pyroclastics can be of any composition, most of them come from acid or intermediate magmas. They are distributed in two different ways; air-fall and flow-deposits.

Material that has fallen through the air is called tephra, a Greek word that should strictly mean ashes but scoria, cinders, pumice, and volcanic dust, sands and gravels all come within the geological classification; a really determined geologist can even make it cover a ten tonne rock. However, there is general agreement to confine the term ash to particles less than four millimetres across and to call anything larger than 32 millimetres a bomb or a block. Stones of intermediate size are called lapilli (Latin, pebbles). A better distinction than these rather arbitrary figures is to keep the term bombs for ballistic missiles hurled like projectiles from a cannon, and to keep the terms ash and lapilli for material dispersed by the wind. In volcanology, words like ash and cinders refer only to physical size and texture; there is no implication that they are the remains of a fire as there is in everyday language.

Volcanoes can produce vast quantities of ash, and can do it very quickly. The Icelandic volcanologist Sigurdhur Thorarinsson estimated that during the first half hour of its 1947 eruption, Hekla was shooting out 100,000 cubic metres per second, and went on at a rate of 30,000 cubic metres per second until 220 million cubic metres had been expelled. This was the equivalent of 80 million cubic metres of solid rock.

How far the particles travel depends upon their size. Large bombs and blocks are not thrown far from the vent but winds can carry dust to great distances and it may remain aloft for years. After the eruption of Krakatoa in 1883, the dust continued to travel round the world for several years, providing spectacular sunsets and incurring the displeasure of astronomers. In New Zealand, deposits of pumice from ancient eruptions cover half the North Island. (Figure 12.1 shows a fairly small eruption from Ngauruhoe). Although fragments of older rock are present in tephra, the greater part of the ash comes directly from the new magma, a point first emphasised in Frank Perret's report on the 1906 eruption of Vesuvius.

Figure 12.1 Ash eruption from Ngauruhoe.

Pyroclastics derived from highly vesicular lava usually take the form of scoria (Greek skor, dung) or pumice, a substance familiar from its common occurrence in bathrooms. There is no clear cut distinction between the two but dark, heavy and angular fragments of basalt or andesite are usually called scoria, while pieces of lighter dacite or rhyolite are called pumice. The walls of the large vesicles in pumice often remain unbroken so that it readily floats and can form huge rafts that drift far from the volcano that produced them before they are dispersed or driven ashore. One such raft travelled 13,000 kilometres at a speed of 27 kilometres per day (eight to ten kilometres per day is a more usual speed, depending upon the size of the

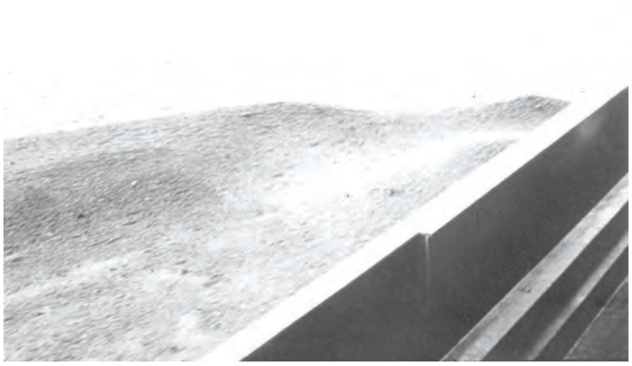


Figure 12.2 Pumice raft from submarine eruption, Curacao Reef, Tonga

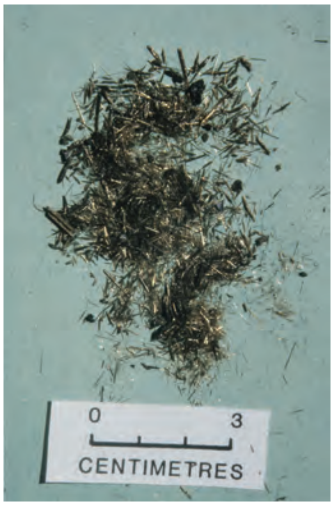


Figure 12.3 Pele's hair.

Figure 12.4 Spindle-shaped bombs about 40 cm length from Mt Usu, Japan.

Figure 12.5 Spindle-shaped lapilli.

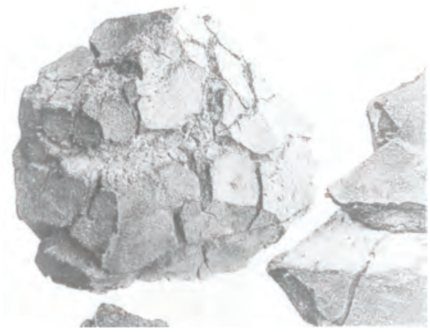


Figure 12.6 Bread-crust bomb about 45 cm diameter from Mont Pelée, about 45cm diameter.

lumps). Pumice was erupted from Rabaul in 1878 that ships took three days to force a way through, and in 1937 the harbour was blocked for several days. The rafts can be thick enough to walk on but the attempt is not recommended as lives have been lost in this way. However, it is safe for some animals which are known to have travelled great distances on pumice rafts, and it is one possible way in which life could become established on remote islands (Figure 12.2).

Here we should introduce Pele, the Hawaiian goddess of fire. Strong winds from the Pacific can carry blobs of liquid basalt from the surface of fountaining lava. As they are carried away, they draw out behind them long flexible threads of a material like fibreglass. It is often a light golden-brown in colour and has become known as Pele's hair (Figure 12.3). The threads usually break from the blobs at their heads. The heads assume a tear drop shape as they fall and are called Pele's tears. Being thicker than the threads, they are black in colour unless viewed against a very strong light. On occasion there have been thick falls of hair in the streets of Hilo, and the birds of Hawaii find it a useful material for nest building.

Volcanic bombs are larger pieces of material that have also been shaped by their passage through the air, tear drops and spindle shapes being common (Figures 12.4 and 12.5).

They are not explosive in the normal sense, their resemblance to a grenade being purely external, but sudden bursting of the cooled outer crust may allow a sufficiently vigorous escape of gas to cause an abrupt change of direction during flight. A certain cynical geologist, faced with the problem of distinguishing bombs from blocks, once proclaimed that a bomb was merely a block with a more attractive figure. Since this usually results from rapid rotation while in flight, this sets an upper limit to the size of bombs – but views of beauty vary. For shaping to take place, the bombs must still be in a plastic condition when erupted.

During the 1954 eruption of Ngauruhoe, the New Zealand volcanologist Jim Healy approached the mountain by air and saw the shaping of bombs taking place:

'…the lava could be seen glowing bright orange even at mid-day… lava was continually spouting for several hundred feet with large blobs rising to 1,000 feet (330 metres). Smaller blobs were hurled to greater heights but all were seen to be glowing bright orange as they went up, and were changing shape as they whirled through the air. Some of the masses I estimated to be 50 feet (15 metres) in diameter.'

The larger masses were clearly blocks (bombs more typically range from the size of a fist to that of a football) but they are well below the upper limit.

In 1930 Stromboli hurled 30 tonne blocks for three kilometres, killing many people. There is a claim that Cotopaxi, in Ecuador, threw a 200 tonne block for fourteen kilometres, certainly there is a block weighing 65 tonnes on the slopes of the volcano. Japanese history recounts that a block measuring 175 by 40 metres flew from Mount Asama in 1783, to become an islet. It seems more than probable that these giants were transported by lahars or some similar means. Blocks 20 metres across can be seen clearly in the photograph of the 1975 eruption of Ngauruhoe (see Figure 7.10).

Among the largest projectiles to be classed as bombs rather than blocks are bread-crust bombs whose glassy crust has been quickly chilled and then fractured by the continuing expansion of gas in the internal bubbles. As a rule, they are roughly spherical, and have fissured either in flight or on landing, particularly when they have fallen into water or landed on snow slopes (Figure 12.6).

Mechanics impose a certain order upon the arrangement of pyroclastics about a vent, i.e. the smallest projectiles are carried to the greatest distance, but since not all eruptions are of equal vigour, the degree of order is somewhat variable. Although the larger rocks are piled near the vent, the interstices fill with fine ash and there is a range of particle size present, a condition described as being poorly sorted. At greater distances not only does the average size become less but there is a smaller range of sizes, and well sorted deposits result. The range of possibilities is quite large, and the strength and direction of the prevailing winds usually decide where the deposits will fall. Often there is a zone in which the material is both well sorted and fairly large because there is insufficient fine material to fill the gaps. Under these conditions ground water can move very readily and any remaining fine material it encounters is washed away, influencing the further course of erosion.

Deposits of bombs, ash and lapilli eventually become compacted and hardened into rock. Percolating fluids aid the process. Because of the differences in the size and chemical composition of the particles involved, petrologists have invented a great many impressive names to describe the results but we shall limit ourselves to distinguishing the broad categories of tuffs, breccias and agglomerates. If its texture is fine, a rock made of cemented pyroclastics is called a tuff (Latin tofus, a porous stone), and if it is coarse, an agglomerate (Latin agglomerare, to wind into a ball). When the constituents also include a quantity of rock from the surrounding country, the term used is breccia, an Italian word originally applied to rubble and broken bits of ruined walls.

Pyroclastic flows have a history rather different from that of ash showers and volcanic bombs. When solid particles are suspended in a gas, the suspension behaves rather like a liquid and large quantities of solid material can be induced to flow down hill at high speed. This 'fluidisation' can be artificially enhanced and used to transport fine powders like flour and cement along pipes. Air or gas is pumped through the powder, not in sufficient quantity to blow it away but just enough to lessen the contact pressure between the particles, thus relieving some of the weight. Once the critical pressure is reached, the powder will flow quite readily. There are several situations in which volcanic particles become naturally 'fluidised'.

The nuées ardentes and ignimbrite flows briefly discussed in our classification of eruptions (Chapter 7) are the most spectacular examples of pyroclastic flows. Alfred Lacroix, who first used the term nuée, made a series of photographs of the nuées that followed the destruction of St. Pierre in 1902 (Figure 12.7). They have recently been assembled in sequence to make an impressive and informative film by Maurice and Katia Krafft. Even more graphic pictures were taken by Frank Perret during the later eruption of Pelée in 1930 and by Tony Taylor in 1951 at Mt Lamington in Papua. The essential part of a nuée is the 'fluidised' cloud of fine incandescent particles that avalanches from the crater, each particle continuing to supply the cushion of gas that gives the avalanche its mobility. The flow also has a denser component whose movement is more constrained by the topography, and which deposits material in valleys and hollows.

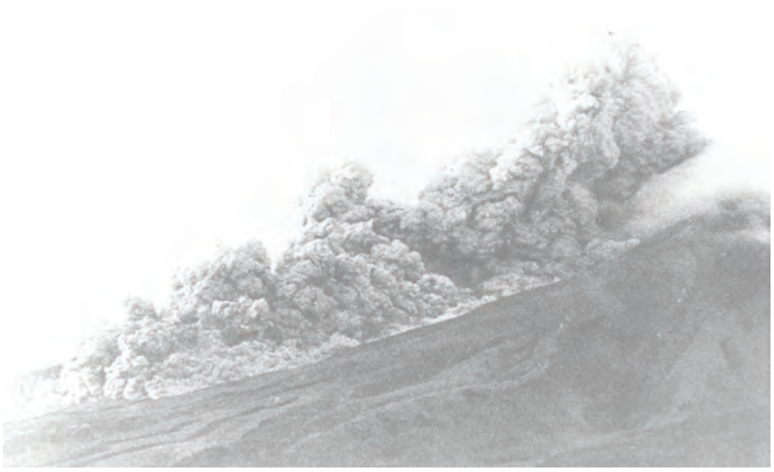


Figure 12.7 Mont Pelée. The nuée ardente of 16 December 1902 heading for the sea.

Observers generally describe initial explosions – either directed upwards from the vent or projected sideways from a plug in the crater which is blasted apart to supply the particles. A brief pause follows – no more than a few seconds – in which the gas reaches the critical pressure needed to sweep the cloud down the mountainside. It can travel five or ten kilometres at a speed of 100 to 200 kilometres per hour or more, devastating everything in its path.

It would be hard to better Perret's description:

'The first thing seen … is a more or less obliquely advancing mass, expanding at a rate so rapid that it should, seemingly, fill the entire heavens in a moment or two; but suddenly the cloud ceases its swift upward expansion, spreading out horizontally, or even downwards on the mountain slope, and at the same time developing upward in cauliflower convolutions of dust and ash. These convolutions grow out of a flowing mass of incandescent material advancing with an indescribably curious rolling and puffing movement which at the immediate front takes the form of forward-springing jets, suggesting charging lions.'

A curious aspect of the advance of a nuée is that it is practically noiseless, not only because the particles are cushioned from one another by gas, but because the peculiar internal turbulence prevents whatever sound waves there may be from spreading outwards. The initial explosions, however, are noisy enough. The purser of a ship in the harbour of St Pierre writes of 'a constant muffled roar' followed by a sound 'like a thousand cannons' when the side of Mont Pelée burst.

The usual temperature of the particles in a nuée seems to be about 600–700°C. This means it is able to soften glass but not melt it, and is certainly lethal to everyone in its path. The nature of the gas has not been placed beyond argument. Some volcanologists report the presence of sulphur dioxide, and others (including Frank Perret, who had a close escape from a nuée) deny it.

The presence of a base surge in an eruption was first recognised by James G. Moore in 1965, at Taal Lake in the Philippines. He describes a series of clouds laden with debris moving radially outwards and carrying blocks, lapilli and ash suspended in water vapour. Every tree within a kilometre was obliterated and objects up to eight kilometres away were sand blasted. Lacroix's photographs of the nuées and descriptions of the damage at St Pierre in 1902 have been considered to show that a base surge was present. Some writers believe them to be related to nuées but the gases involved seem to be at a lower temperature. When water can reach rising magma, the phreatic explosions which result seem particularly likely to generate strong base surges.

The role of nuées ardentes in producing ignimbrite has already been described but geologists are still far from agreed upon the way in which ignimbrites are formed. One reason for this is their very varied character. They grade continuously from a welded glassy material like obsidian through unwelded breccias, to a uniform powdery deposit of pumice. One suggestion is that ignimbrite issues from a vent in the form of a froth, like that from a beer bottle that has been shaken before opening. The rapidity with which the gas escapes has much to do with the character of the final product.

The New Zealand deposits to which the name ignimbrite was first given cover about 25,000 sq. km. There are larger deposits in northern Chile, and those surrounding Lake Toba in northern Sumatra are only slightly less extensive. Ignimbrite eruptions tend to be periodic but the intervals between them are typically about 10,000 years. The volume of material produced in a single eruption is not easy to measure but it is at least an order of magnitude greater than that produced in the largest basalt eruptions (like the one at Laki). It is estimated that Katmai, in Alaska, erupted 28 cubic kilometres in about 60 hours in 1912.

In Nevada there are ignimbrite sheets with volumes of more than 1,000 cubic kilometres but they represent eruptive sequences and not individual eruptions. In New Zealand many separate events were needed to produce the 7,500 cubic kilometres of North Island rhyolite. The deposits vary greatly in thickness, from a few metres up to several hundred metres. Material accumulates in the hollows, leaving a thin veneer on intervening ridges. Drilling has revealed 135 metres of ignimbrite in a single flow, and 500 metres has been reported from the Soviet Union. In Yellowstone National Park the upright remains of forest trees tell a tale of 27 forests buried under successive ignimbrite flows. Intervals of about six hundred thousand years separated the last three eruptions, and another in our own time should not come as a surprise.

Figure 12.8 Secondary lahar after rain, near Mayon, Philippines.

Looked at from a physical point of view, lahars have much in common with nuées ardentes, though they originate in quite different ways. The word is Indonesian and is applied to a type of volcanic mud flow that depends for its mobility and destructiveness on a kind of fluidisation but with water rather than gas reducing the friction between the solid particles.

The necessary ingredients of a lahar are unconsolidated pyroclastics and water, and they are usually started when the water is supplied suddenly from a crater lake. The water may be displaced by an eruption or liberated by the collapse of the crater wall. Volcanic heat may melt a snow field or a glacier. Many lahars are delayed until long after the eruption that supplied the ash. In Indonesia and the Philippines they are typically delayed until the arrival of the wet season when daily thunderstorms trigger a recurring sequence of lahars (Figure 12.8).

Lahars can be hot or cold depending on when their material was erupted. A short distance below the surface of an ash deposit the temperature remains high for a long time. Lahars quickly become solid when they lose their water content, and this happens more rapidly if they are hot or even lukewarm, and limits the distance they can travel. Nevertheless, most of them cover ten kilometres or more, and isolated examples of mud flows travelling for 100 kilometres are known. Mount Egmont in New Zealand is surrounded by a 30-kilometre-wide skirt of lahar debris that stretches to the sea, caused primarily by massive landslides from the cone.

The topography of such lahar deposits is unusual. During the drying out process, thousands of small mounds are formed (Figure 12.9). Each contains a nucleus of large blocks and fragments that prevent the mud from subsiding to the same degree as it does where there are no large fragments.

The speed with which a lahar travels depends upon the steepness of the slope and the viscosity of the mud. About 30 or 40 kilometres per hour is usual, with an upper limit of about 200 kilometres per hour.

Figure 12.9 The hummocky character of the farmland surrounding Mount Egmont reflects its formation by lahars.

The velocities of the lahars on Mount St Helens in 1980 varied greatly and were between five and 140 kilometres per hour.

The lahar that followed the collapse of the wall of Ruapehu's crater lake on Christmas Eve in 1953 stands high on the list of natural disasters in New Zealand. Nearly two million cubic metres of water-charged debris rushed down a convenient channel provided by the headwaters of the Whangaehu River. Twenty-four kilometres from the mountain it swept away the piers of the bridge that carried the main railway line from Wellington to Auckland. Eight minutes later, a holiday express carrying 285 passengers plunged into the gap and 151 of them died in the surging torrent of boulders and mud (Figure 12.10).

Figure 12.10 Bridge and train destroyed by lahar, Tangiwai 24 December 1953.

A young man named Cyril Ellis was first to become aware of the lahar. He found a wall of water surging over the road bridge, parallel to the railway and about 11 metres above the bed of the stream. Seeing the headlight of the approaching train, he attempted to warn the driver by running along the tracks and waving a pocket torch. The driver applied the brakes but it was already too late to stop the engine and six carriages. Ellis returned to the river and is credited with the rescue of 26 survivors. By now, other road travellers had stopped at the river which had become a torrent 300 metres wide. There was a deafening noise and the constant impact of boulders made the earth tremble. Great chunks of glacier ice were carried along with the boulders.

The inquests and enquiries that followed the disaster produced useful information about the character of mud flows. The combination of high density, rapid mobility, and turbulence could quickly produce the force responsible for the destruction of the bridge but the lake could not drain instantaneously, and it is unlikely that the train travellers and their rescuers experienced the worst of it. There were few marks on the bodies recovered, even when their shoes and clothing had been stripped. Chains of rescuers also lost clothing, finding it unwise to venture into water more than about half a metre deep if they were to keep their feet. Those wearing clothing soon carried a heavy weight of silt, mixed with oil from the tender which had been smashed by its fall. Bodies and possessions swept into the willows confirmed the estimates of the depth and extent of the flood. The ash that formed so large a part of the flow was identified as the product of an eruption eight years earlier, in 1945.

Long ago, the Māori people (indigenous people of New Zealand) gave the site a sadly prophetic name – Tangiwai, the waters of mourning, – and the disaster in 1953 was neither the first nor the largest to have come from Ruapehu (Figure 12.11). Within the surrounding Tongariro National Park, there are at least a thousand cubic kilometres of lahar debris, and Sir Charles Cotton has invoked a lahar to explain a 37 tonne block lying 75 kilometres from the mountain. Compared with some examples from other countries, neither the Tangiwai lahar nor the consequent loss of life was unusually great. Kelut, in Indonesia, and Nevado del Ruiz which killed 25,000 people in Colombia in 1985, have both produced mud flows on a much larger scale and we shall return to them in later chapters.

Large scale landslides on the sides of a volcanic cone are only to be expected and may on occasion set off a lahar. Most of them are like normal landslides in other settings but sector collapses are a variant specifically related to volcanoes. Many cones have radial faults or fractures between which large sections of the mountain can subside. Examples are very common and can be found on Egmont, Bezymianny, and Mount St Helens. But not every large valley in the side of a volcano can be attributed to sector collapse and it is seldom long before erosion plays a large part in reshaping them.

Figure 12.11 The Tangiwai railway bridge was rebuilt at a higher level and has survived a number of subsequent lahars, such as the one on 24 April 1975, whose effects are shown here.

13—Volcanoes Under the Sea

Then Surt will fling fire in every direction. Asgard and Midgard and Jotunheim and Niflheim will become furnaces: places of raging flame, swirling smoke, and ashes. The nine worlds will burn, and the gods will die.

Snorri Sturluson: The Prose Edda

Stories of submarine volcanoes are as common as tales of the great sea serpent and usually much better founded. They have been known since antiquity, and the association of fire and water has been widely considered a paradoxical reversal of the natural order of things. The full extent of submarine volcanism has become apparent only within the last few decades. Not only do the oceanic ridges form a virtually continuous volcano (active volcanoes also line the fractures within the oceanic plates) but the ocean floors are liberally dotted with extinct volcanic sea mounts, and pillow lavas erupted under water are probably the most abundant of all volcanic rocks.

Furthermore, there are a number of submarine plateau basalt regions, of enormous size and volume, and comparatively young age (Lower Cretaceous, c.115 million years ago), such as the Ontong Java Plateau north of the Solomon Islands, and the Kerguelen Plateau in the Indian Ocean.

Most of the magmas involved in submarine eruptions are basaltic, and were it not for the presence of the water (Figure 13.1), would produce eruptions of Icelandic or Hawaiian type like those on oceanic islands. The water modifies the eruption in two ways – by its pressure, which of course depends upon the depth, and by its enormous heat capacity combined with ready mobility.

Figure 13.1 Submarine eruption in Solomon Islands 1962.

Figure 13.2 Strombolian fire fountain on Surtsey.

The earliest stage of a submarine eruption in shallow water usually produces little more than a patch of discoloured water which may appear to be boiling, and a quantity of dead fish. This stage is followed by explosions that generate great quantities of steam, blasting jets of ash-laden water to a height of a few hundred metres. These cupressoid explosions (Latin cupressus, a cypress) hurl ash, mud and lava bombs radially outwards in a pattern that some writers have likened to a cypress tree (and others to the tail of a cock). They are quite unlike the turbulent 'cauliflower' clouds of vulcanian eruptions and could perhaps be compared with a heavy shower of rockets.

Meanwhile, a cone is building itself about the vent and if the eruption continues, its top will eventually appear above the surface and form an island. This stage of the eruption is often described as Surtseyan after an Icelandic eruption in 1963 (see Figure 7.18). Once the growing island is able to prevent water from reaching the vent, lava flows may succeed in cementing the island together. Explosions then become confined to the crater, the eruption is no longer submarine, and the actvity usually becomes Strombolian (Figure 13.2).

Surtseyan explosions are violent and produce much more highly fragmented material than basaltic eruptions on land, and scatter it widely. As a result cones produced in shallow water – salt or fresh – have a characteristic profile; broad and low with a large crater, and often perfectly circular and symmetrical. They are known as tuff rings or ash rings.

Unless a submarine volcano succeeds in building an island, its existence, at least before the satellite era, is likely to go unreported. Island building is a struggle with the sea, and history and legend abound with tales of mysteriously appearing and disappearing islands. In more recent times, Bogoslov in the Aleutians and Falcon Island in Tonga are perhaps the best known examples.

Bogoslov, whose Russian name means 'the divine', lies about 60 kilometres north of Umnak, at the Alaskan end of the Aleutian chain. It was first reported in 1768 and given the name Ship Rock. In 1796 it was joined by Castle Rock, a larger island, about three kilometres long and one kilometre wide, lying to the south-east. It rose about 100 metres above the sea, to the accompaniment of explosions that terrified the inhabitants of Unalaska, 80 kilometres away. In 1883 a huge lava dome appeared on the opposite side of Ship Rock amidst a shower of bombs and debris that gradually welded the group into one. Within a few years, it had been breached by the waves to become Old Bogoslov (the former Castle Rock) and New Bogoslov which now dominated the group. In 1906 and 1907 two active cones appeared in the lagoon. They lasted long enough to receive the names Metcalf Cone and McCulloch Peak. Only a fragment of Metcalf was to survive the explosion of McCulloch, which proceeded to blow itself up. At its most developed stage McCulloch had been 150 metres high and looked, according to the Hawaiian volcanologist T.A. Jaggar, like a huge lumpy potato. It climaxed its suicide by covering Unalaska with a layer of ash six millimetres deep. This however, was not the end. There were further eruptions in 1910, 1926 (when another dome appeared) and in 1931. At the last report, the site had become a shallow steaming lagoon, probably marking the position of a single submerged cone rising about 1,800 metres above the sea floor.

Falcon Island, or Fonuafo'ou as it is more correctly called, is to be found in the Ha'apai group, in Tonga, when it is to be found at all. In 1865 HMS Falcon charted a previously unreported shoal in the position of Fonuafo'ou but when HMS Sappho returned to the site in 1877, all she could find was steam. In 1885 it was possible to see a cone 90 metres high but tropical rains and storms removed more than half of it over the next five years. In another five years it was once more the Falcon Shoal, a dangerous reef 30 metres across. It again began to grow and in 1896 stood 30 metres above the waves but by 1900 it had nearly gone again, and in 1913 HMS Cororan could find nothing of it. It went off with a bang in 1927, sending an ash cloud up about a thousand metres. It could be seen 130 kilometres away and continued to erupt until May 1928 when it reached its biggest recorded size. It was then about 3 kilometres long and 100 metres high and still steaming.

Figure 13.3 Home Reef, Tonga. A temporary island due to volcanic activity.

The subjects of Queen Salote, aware that past history showed the need for quick action, planted her flag and claimed the territory of Fonuafo'ou for the Kingdom of Tonga. History was to be repeated. No lavas had appeared during any of the eruptions and the island remained an unconsolidated pile of pyroclastics, unable to resist the onslaughts of the Pacific. By 1950 it was again 15 metres under water but it is unlikely that we have seen the last of it. Other submarine volcanoes in the region have been active recently (Figure 13.3).

The antics of the 'disappearing islands' would probably lose something of their fascination if the off-stage machinery that produces the spectacle were not hidden beneath the waves. If new volcanoes did not from time to time rise from the still submerged segments of the mid-oceanic ridges, it would be surprising indeed.

For a long time the probability that lack of information about the sea floor had unbalanced many of their conclusions had worried geologists and geophysicists, and they warmly greeted the introduction of continuously recording echo depth sounders shortly before World War II. Nevertheless, new data were to pose new problems – but not at once. Few sea captains could see much point in running depth sounders once they were clear of the continental shelves and had several kilometres of water beneath their keels so they turned them off. Knowing this, makers did not provide their instruments with scales designed to indicate great depths.

During World War II Harry Hess, a young oceanographer who was to become professor of geology at Princeton University, served in the U.S. Navy and became commander of a troop transport that moved about the islands of the Pacific. Realising that he had a splendid chance to continue his oceanographic work, he saw to it that his ship had a suitable echo sounder and kept it turned on. By the time the war ended, his records showed that the ocean floor was dotted with an enormous number of small conical peaks. They seemed likely to be volcanic and are now called sea mounts. Over a hundred of them seemed to differ from the rest. They were much larger and seemed to have been sliced off at the top. Hess called them guyots in compliment to Arnold Guyot, the Swiss geologist who had been the first holder of the chair at Princeton.

The bases of most guyots are tens of kilometres across. One to the north of Eniwetok, in the Marshall Islands, is 95 kilometres across at the base and 55 kilometres at the top. Shallow guyots exist but the tops of many of them are one or two thousand metres below the surface. Material dredged from the tops consists of smooth, well-rounded pebbles of highly vesicular basalt, together with a small amount of sediment that contains fragments of reef-building corals, and even some fossil land snails. There could be little doubt that the guyots were volcanoes and that their tops had been flattened by erosion; but why should their tops lie at such different levels, even within a group? Changes in sea level could not explain it so they must have subsided.

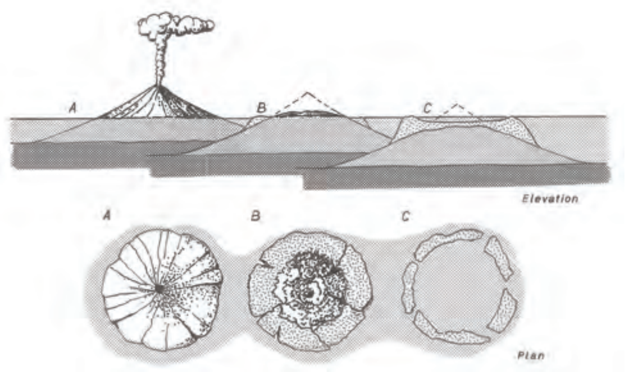


Figure 13.4 Formation of coral atoll from sinking volcano.

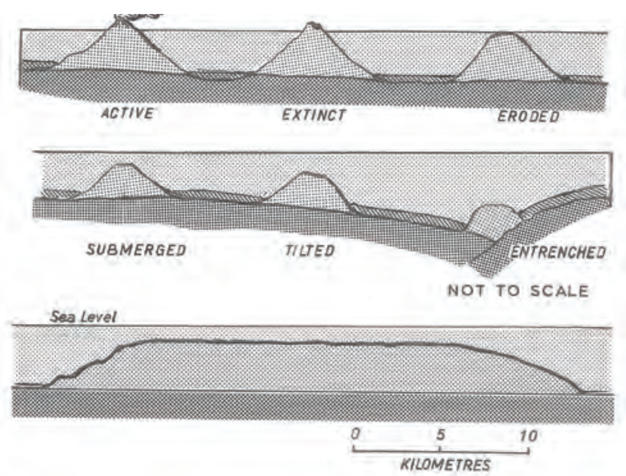


Figure 13.5 Formation of Guyot.

At first, it was suggested that had happened a long time in the past when the Pacific was much shallower, and that rising sea level could account for a significant part of their depth. However, the fossils proved to be Cretaceous and Tertiary so the subsidence must have been quite rapid and recent. The search for an explanation soon suggested analogies between guyots and coral atolls.

Only the larger atolls of the Pacific possess the palm fringed lagoons and human inhabitants. Most are no more than narrow circular reefs of coral, almost awash, and breached by channels that admit the waves of the open ocean. A few of the larger islets accumulate enough soil for a floating coconut to take root but for the most part they are barren and exposed, and avoided by shipping.

Charles Darwin, whose celebrated travels in the Beagle from 1831 to 1836 brought him to the Pacific, noted that corals were rather fussy about where they lived. They expected their water to be clean, warm, well aerated, clear and sunlit. This meant that they could live only in tropical seas and then only at depths less than about 60 metres. How then could one account for coral islands that rose steeply from an ocean floor several kilometres deep? Darwin's explanation was that the coral reefs formed the tops of volcanic islands that had gradually subsided but not so rapidly that the corals were unable to keep their heads above, or just below, the water (Figure 13.4). If they could not keep pace, they would die and the result would be not an atoll but a guyot, its top eroded and flattened during its stay at sea level.

In 1952, drilling at Eniwetok produced convincing proof of Darwin's ideas. Basalt was reached after the drill had passed through no less than 1,500 metres of coral. However, the major problem remained why should volcanoes subside?

During the next decade, ideas of sea floor spreading were revived, magnetic striping was discovered, and the International Geophysical Year initiated a vastly increased and continuing programme of oceanographic exploration, in which Hess played a major part. One result was to provide a plausible life history of a guyot.

It begins as one of the larger volcanic cones that form at a mid-oceanic ridge. As the rising convection current leads to further eruption, adds material to the edges of the plates and forces them apart, the cones are moved outwards and downhill from the shallow waters near the ridge, sinking until they reach the level of the floor of the ocean basin. By then, their summits lie far beneath the surface of the sea (Figure 13.5). During the outward movement several things can happen. The volcano will certainly become extinct when it severs its connections with the magma chambers of the ridge. If the subsiding cone is not large, the hard working corals of the fringing reef may succeed in building it above the level of the peak, and it will become an atoll. If they do not, they will die and the lagoon will fill with the eroded remnants of the volcano. When the top sinks to sea level, wave erosion can plane it flat and further subsidence results in a guyot. All this takes time, perhaps as much as 10 or 20 million years, but it is not the end of the story. The guyot now begins a solemn and relentless progress, riding on the moving sea floor.

At the far side of the plate, it will reach an ocean trench that marks the position of a subduction zone. Down the trench go the guyots and the sea mounts, to be ground up, carried down with the descending plate and reabsorbed into the mantle. Truly a destructive margin! The entire cycle has lasted perhaps 100 or 150 million years.

Recent oceanic surveys have discovered evidence that confirms this final part of the story. On the oceanic sides of trenches there are guyots with tilted tops. One lies just north of New Zealand, near the Kermadec Trench. It is a worthy rival to the peaks of the Himalayas, rising 8,000 metres above its base, and coming within 370 metres of the surface. Less spectacular examples have been found in the Aleutians.

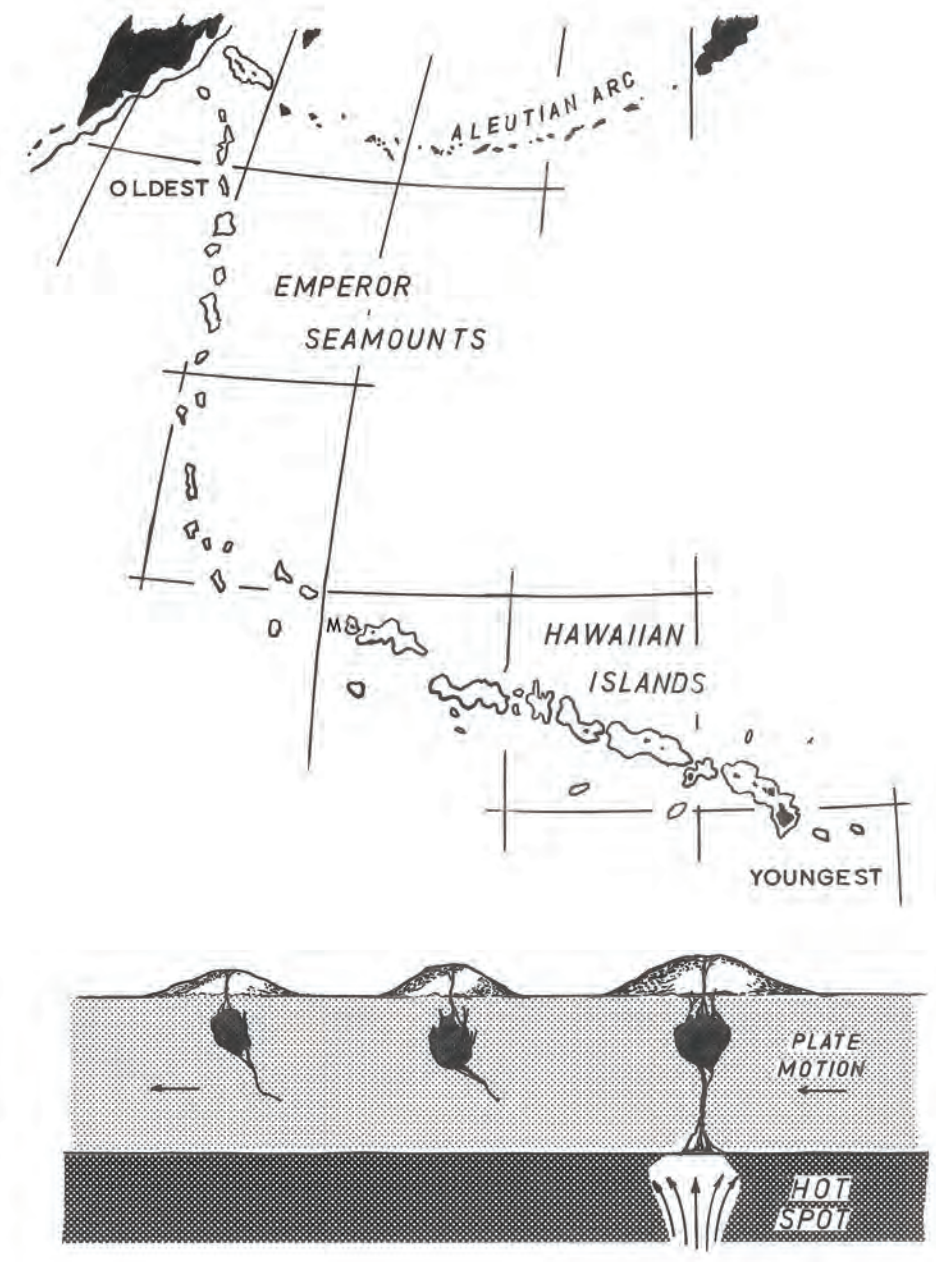


Figure 13.6 Sea floor features of the north Pacific, showing how the movement of a lithospheric plate over a stationary "hot spot" in the mantle develops a chain of volcanic islands. Between the formation of the Emperor Seamounts and the Hawaiian Islands an abrupt change in the direction and speed of the plate motion occurred. This change was somewhat before the formation of Midway Island, marked as M

In New Zealand, at the northern end of the Northland Peninsula, there are several prominent ranges of hills standing up to 600 metres above the surrounding countryside. They are composed of basaltic lava flows. Gravity measurements show that they consist of separate blocks. They are known as the Tangihua volcanics, and are surrounded by marine sediments thought to have been deposited during the Cretaceous, about 70 million years ago. The whole region has since been raised to become dry land and New Zealand geologists think that the volcanic blocks were once guyots and sea mounts. Thanks to a series of tectonic convulsions they have escaped the usual fate of being swept into an ocean trench and destroyed.

A map of the islands and sea mounts of the Pacific will show that the mid-oceanic ridges are not the only linear features that exist. There are long straight chains like the one that extends from Midway Island to Hawaii, or the one starting at Pitcairn Island and continuing for more than 2,000 kilometres through the Tuamotu Group. There is an important difference between these lineations and the mid-oceanic ridges – active volcanoes are found along the full length of a ridge, but in the Pacific chains the volcanoes at one end are active and those at the other end are very extinct. Radiometric dating shows a steady increase in age from Hawaii to Midway.

When discussing the ascent of magma in Chapter 9 we saw that the upper surface of the asthenosphere could develop ‘plumes’ or ‘hotspots’ which in turn fed the magma chambers of the individual volcanoes. It is thought that these ‘hotspots’ remain more or less fixed with respect to the mantle while the lithospheric plate above them continues to move. The volcanoes are in turn carried away from their source of heat and a new one forms, generating the chain of sea mounts and islands. Their ages provide a check on the speed with which the plates are moving, and all the Pacific chains turn out to give rather similar rates of about 11 centimetres per year.

The movement of the Pacific plate seems to have been fairly steady for the past 20 to 40 million years but somewhere in that time there was an important change. The oldest section of each chain is sharply kinked to the north, in response to some major alteration in the direction of the plate movement. Along the Emperor Seamount chain, which continues the Hawaiian chain to the north (Figure 13.6), there are only 13 major volcanoes per thousand kilometres, compared with 18 in the Hawaiian chain. Assuming that the ‘hotspot’ continued supplying heat at much the same rate, there must have been a change in the speed as well as in the direction of the plate motion.

At the present time, the rate of spreading from the East Pacific Rise seems rather small to account for the speed of migration of the volcanism, and it is necessary to assume either that the mantle plume is moving towards the Rise or that the Rise is migrating westwards. The latter is the more popular view but if it is so, opposite trends should be found in island chains to the east which doesn’t seem to be the case. The volcanoes of the Galapagos and Easter Islands have been active for a particularly long time, and it is possible that migration of the Ridge has slowed down the movement of the Cocos and Nasca Plates with respect to the mantle.

14—Springs and Geysers

There could be very curious chapters written on mineral springs… When employed for domestic purposes they choke up, with a strong deposition, the spouts of tea-kettles.

HUGH MILLER: The Old Red Sandstone

Many a prosperous town owes its beginning to the discovery of a natural supply of hot water. The pleasures of prolonged immersion brought Romans to Bath, Vikings to Reykjavik and Māori to Rotorua. It is not particularly surprising that springs in volcanic regions should be hot but it is less obvious why hot springs should occur at places a couple of hundred kilometres from the nearest volcano, like Bath or Spa in Belgium (which has given its name to thermal resorts in general), or at Hanmer and Maruia in the South Island of New Zealand. (Figure 14.1).

Figure 14.1 The Roman Bath that gave the town its name. The Great Bath, reconstructed in the 18th and 19th centuries, is 27 metres long and floored with lead sheets. The spring that feeds it supplies seven million litres of water per day at a temperature of 48ºC.

Figure 14.2 Fumarole on Balbi volcano, Bougainville, PNG.

Very little (if any) water that comes out of the ground originates as magmatic steam. It is meteoric water that has fallen as rain or snow, and subsequently has been heated. There are two ways in which this can happen. Either percolating ground water encounters a body of magma or meets hot rocks that are a cooling remnant of ancient volcanism; or it merely penetrates to a depth at which the normal geothermal gradient has raised the temperature appreciably above that at the surface. How hot it will get varies accordingly. At the lower extreme, a thermometer may be needed to show that the temperature of a spring is a degree or two above that of surrounding surface waters. At the other extreme, the spring can become a jet of superheated steam. Such jets are called fumaroles (old French fumarolle, a smoke hole, the kind you made in your roof when you couldn't run to the cost of a chimney).

Fumaroles are often characteristic of old and dying volcanoes that have given up the habit of full-scale eruption but they are equally likely to be found in the craters of volcanoes that are merely sleeping between out-bursts (Figures 14.2, 14.3 and 14.4). The steam from a fumarole usually contains a great deal more than water vapour. For example, magmatic gases like the various derivatives of sulphur, sulphuretted hydrogen, and carbon dioxide. These readily react with the rocks that surround the vent, and form bright yellow deposits of sulphur that may become thick and extensive enough to be worth mining.

Figure 14.3 White Island alternates between eruptions and fumarolic activity.

At lower temperatures and pressures, fumaroles grade into solfataras, named after a volcano in the Phlegraean Fields near Naples. The last time it produced anything more than gas was in 1198. The solfataras of Tuscany, farther to the north, are said to have inspired Dante's vision of the Inferno.

It can be argued that any kind of emission from a volcano is in some sense an eruption and solfatara fields are generally included in lists of active volcanoes. Oddly enough, the ones that start and stop so that definite dates can be assigned to their eruptions have a better chance of being listed as active than ones that have steadily gone on steaming for centuries. It is changes in a volcano's habits that bring the volcanologists.

Figure 14.4 The incandescent interior of this White Island fumarole, suggests a temperature of about 900°C.

In the three best known regions of extensive hot springs – the North Island of New Zealand, Iceland and Yellowstone National Park – there is believed to be hot rock quite near the surface, and an abundance of faults and fissures that allow cold surface water to reach it and return to the surface after it has become hot (Figure 14.5). Other North Island springs, like those in Northland and the Coromandel Peninsula, lie outside the main region of present volcanic activity but in regions that have been active sufficiently recently for subterranean heat to persist.

The South Island's hot springs are quite different (Figure 14.6). There are no obvious volcanoes, active or extinct, with which they are associated. The springs are aligned along the great Alpine Fault that follows the western side of the Southern Alps and then divides into a number of parallel branches that turn and cross the island at its northern end. Here, the combination of deep fractures, and the upward flexing of the crust (which produced the great mountain range) has both increased the geothermal gradient and provided paths by which ground water can circulate to great depth. Thermal baths have been established at Hanmer

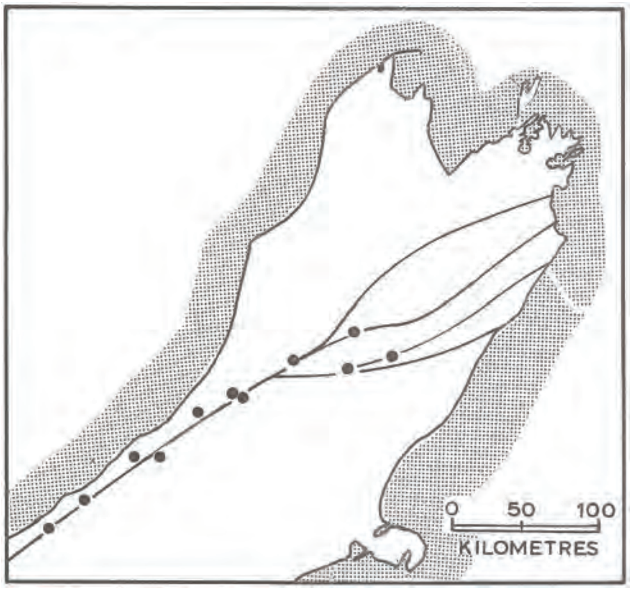


Figure 14.5 (Left) The hot springs of the North Island, New Zealand, are concentrated in the regions of present-day or Recent volcanic activity.

Figure 14.6 (Right) The hot springs of the South Island, New Zealand, align themselves with the Alpine Fault and its branches, and not with active volcanoes.

and Maruia though the temperatures read are only a modest 50-60ºC. It has been suggested that in cases like this, some of the heat involved originates in the friction that attends the intermittently continuing tectonic movements along the fault. Even where there is no additional heat of this kind and no abnormal geothermal gradient, the depth to which water need penetrate to reach the observed temperatures is no more than a couple of kilometres, and fissures are the main requirement for a spa.

Hot springs of tectonic origin are in fact very common, especially along major fault systems like the San Andreas Fault in California, the Anatolian Fault in Turkey, and the Owen Stanley Fault in New Guinea. Recent explorations have revealed what is probably the world's most extensive system of hot springs, extending along some 2,000 kilometres of the Tsangpo Valley, north of the Himalayas, and eastwards into the Hengduan mountains of Yunnan. It seems unlikely that the full extent of the field is yet known.

Few thermal springs are fresh, and the hotter they are, the less likely they are to be so. During prolonged contact with the rocks, the hot water is able to dissolve a range of substances so wide that a chemical analysis begins to look like a table of the elements. Although many rare elements can be found in springs, most waters fall into three groups – those that contain a great deal of calcium carbonate, acid waters rich in sulphates, and alkaline ones containing chlorides. The last two groups differ because of differences in the supply of water, not because of differences in the surrounding rocks. When large quantities can collect, the water tends to take up the highly soluble chlorides, sulphates, carbonates, and bicarbonates of sodium and potassium. When there is less water, acid springs with smaller discharges predominate, and most boiling mud pools tend to be acid. At Wairakei in New Zealand, for example, the valleys contain gushing alkaline springs that deposit sinter, while the springs higher up the slopes are acid.

The temperatures of natural springs are usually well below boiling point, and the violent spitting and puffing by which they attract attention is actually due to gas. Boiling water can be found, particularly where there are nearby fumaroles (Figure 14.7). At the Ketetahi Springs on the slopes of Mount Tongariro, New Zealand, water temperatures range from 74-90ºC. Steam from the main blow hole is at a moderate 120ºC and not greatly superheated.

When the flow and the temperature of a spring are both high, it is likely to contain much dissolved silica, sometimes approaching saturation. When this water lies in shallow surface pools, evaporation and cooling further increase the concentration and the silica is deposited as a surface coating of sinter, or in a series of terraces fringing the pools (Figure 14.8). It is often delicately coloured by iron and other mineral impurities which produce pale pinks and yellows, or by algae whose growth is encouraged by the warmth, and which produce more intense blues and greens (Figure 14.9). Until they were shattered

Figure 14.7 The sprightly leaping of small springs like this one at Reykjanes owes as much to gas content as to high temperature, which is seldom much above boiling point.

by the disastrous eruption of Tarawera in 1886, the Pink and White Terraces of Lake Rotomahana figured in most lists of the world's natural wonders (Figures 14.10 and 14.11). The White Terrace had its origin in a boiling spring that stood against a cliff some 25 metres above the lake. From it, opalescent water overflowed to form a series of semicircular basins that varied in depth from about half to two and a half metres, and descended like a flight of broad marble steps to the lake, becoming colder at each step. The water from the spring was quite saturated with silica, and anything left in the basins became thickly encrusted in a week or two.

The Pink Terrace was similar but the water was transparent and light blue in colour. The basins themselves shaded from white at lake level through an intense rose-pink in the middle part of the flight, to primrose at the edge of the top basin. This was where deposition began but tourists arrived at the bottom by canoe and we follow the order in which they invariably describe it.

The Pink and White Terraces were formed in less than a thousand years. In about AD1000 there was an eruption of nearby Kaharoa that would certainly have destroyed any formation that already existed. This leaves us with the problem of explaining why they have not begun to form once more. Compared with their vanished glories the still impressive terraces of Iceland and Yellowstone are miniatures, as are New Zealand's surviving exhibits at Orakei-Korako, and alongside the geysers of Whakarewarewa. The mounds and terraces of Yellowstone's Mammoth Springs are formed of a somewhat different material called travertine, the water being rich in carbonate derived from the surrounding limestone.

Even when they escape destruction by some nearby convulsion, thermal springs are apt to be short-lived, as they remain sensitive to small changes of water-supply, and clogging of the vent or the access to the source of heat. The Steamboat Springs in Nevada, for example, are reported to be sensitive to "local precipitation, barometric pressure, earth-tides, earthquakes, the discharge from neighbouring wells, and short-term random fluctuations".

For a spectacular and invigorating conclusion to our discussion of springs, we must turn our attention to geysers. Notwithstanding the fame of Iceland's original Geyser, of Yellowstone's Old Faithful, and of Rotorua's Pohutu and Waimangu, even small geysers are not common, and the conditions that produce them are even more easily upset than those responsible for springs.

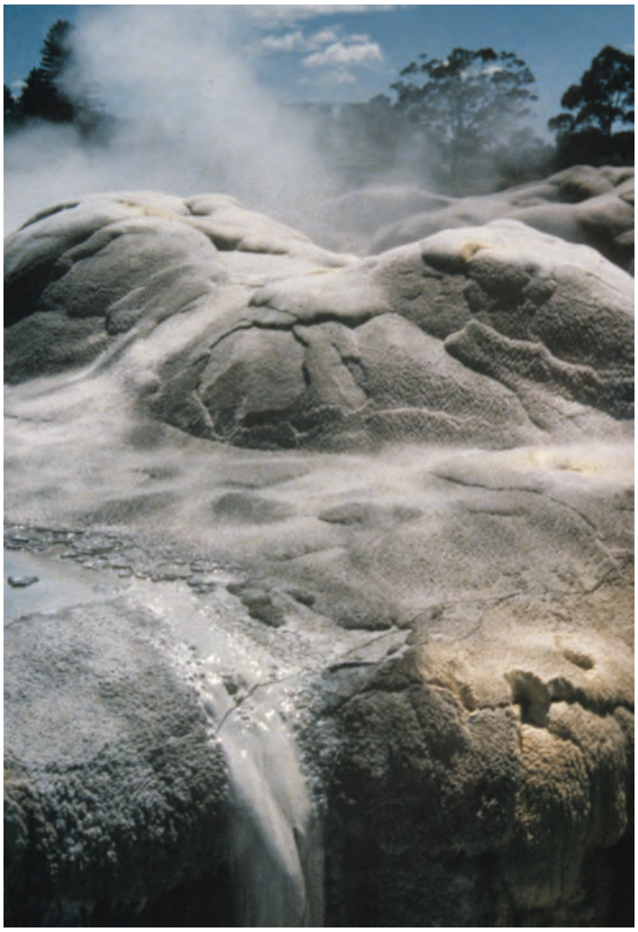


Figure 14.8 Siliceous sinter surrounding Pohutu Geyser, Whakarewarewa, NZ.

More than one volcanologist of repute has written that Iceland, Yellowstone, and Rotorua are the only places they can be found, but that is far from true. They occur in Chile, Japan, and Indonesia, in Kamchatka, the Aleutians, and the Azores – and no doubt in some less-frequented spots as well.

The original Great Geysir was given its name by Bishop Sveinsson in 1647, and derives from geysa, the Icelandic verb "to gush" (Figure 14.12). When in action, it shoots a column of water and steam to an impressive height, but although it is not far from Thingvellir, the famous meeting-place of Iceland's ancient parliaments, there do not seem to be any earlier accounts of it. References to the behaviour of ordinary hot springs go back to 1294, and the reason is probably to be found in Geysir's capricious behaviour. William Morris, who visited it in 1871, reported that Geysir "does not fairly spout out oftener in general than about once in five or six days". Yellowstone's Old Faithful, which can be relied upon to perform every sixty to ninety minutes therefore deserves its reputation.

The shots from a small geyser are much what most people expect. A mild disturbance of the surface may give a few seconds warning, but the eruption itself is like the sudden turning on and off of a tap – surprising and soon over. Larger geysers provide a more varied and long-sustained performance. Let us continue William Morris's account of his dealings with Geysir:

"I had been sleeping rather restlessly, when about 6am I was awoke by the Gusher frowling in a much more obstinate way than we had heard him yet; then the noise seemed to get nearer till it swelled into a great roar in the crater, and we were all out in the open air in a moment, and presently saw the water lifted some six feet above the crater's lip, and then fall heavily, then rise again a good bit higher and again fall, and then at last shoot up as though a spring had been touched into a huge column of water and steam some eighty feet high, as Faulkner and Evans guessed it; it fell and rose again many times, till at last it subsided much as it began with rumblings and thumpings of the earth, the whole effect lasting something less than twenty minutes: afterwards about 9.30am as we were busy washing our clothes in the Blesi-stream there was a lesser eruption: this being over we put on our shoes and went off to the crater and walked over the hot surface of the outer one (Geysir then had "a little crater within the big basin", and indeed it still has) to look at the inner one where the water was sunk a long way down. People thought us lucky to have seen this as Geysir had gushed the morning of Evans' and my arrival, and he doesn't often go off within six days of his last work; nay sometimes people will stay for a fortnight at the Geysirs without seeing it."

Fortunately they are not completely disappointed, for today the nearby Strokkur ("The Churn") obliges at intervals measured in tens of minutes, and can provide a jet reaching 40 or 50 metres on occasion. Not a few must carry away the impression that it was indeed Geysir they saw (Figure 14.13).

It was not until 10 years after Morris saw it that another visitor, Robert Wilhelm von Bunsen (to whom all users of gas-cookers owe a considerable debt) hit upon a plausibly scientific explanation of

Figure 14.9 Warbrick Terrace, Waimangu, showing colours from mineral deposits and algae.

Figure 14.10 Detail of White Terrace by Lake Rotomahana before its destruction in the 1886 Tarawera eruption.

Figure 14.11 Pink Terrace also destroyed in 1886.

what went on in the power-house under a geyser (Figure 14.14). The details of the underground rooms and passage-ways are a matter of conjecture rather than observation, but the smooth central vent that feeds the geyser must lead to an irregular network of pipes and chambers at no great depth. Since the temperature at which water boils depends upon the pressure, the hot surrounding rock and rising magmatic steam can raise the temperature of the water in the underground system well above the boiling-point at the surface. Provided the vent is wide enough, or the surrounding rock permeable enough, to allow a supply of cold ground-water to circulate, a system of convection currents will be set up, and will carry the heat to the surface, and there will be no geyser action. If, on the other hand, the dimensions of the vent or the permeability of the rock restricts the influx of surface-water, the temperature somewhere in the system will rise so far that the pressure can no longer prevent the formation of steam. Once this happens, the expanding steam drives water up the vent, the basin overflows and the pressure is further reduced, generating more steam, and violently expelling water from the vent for as long as the supply lasts. Given the complexities of the underground system and the surges in the basin, the eruption may take the form of a series of thrusts, as in the case of Old Faithful, which pulses eight or ten times a minute; or there may be cycles of eruptions at fairly short intervals followed by periods of quiescence that last many times as long as the series of displays.

Like most simple explanations, this one runs into difficulties when it is examined more closely, and it is doubtful if there is an explanation that would apply in detail to all geysers. It is found, for example, that even just before an eruption the temperature of much of the water-column is in fact below boiling-point, and that things start off with a kind of downward pulse of lowered pressure, so that flashing into steam begins near the top of the column and travels downwards. This happens at the speed of sound in hot water, between one and two kilometres per second, so that things can still happen explosively. The Icelandic volcanologist Th. Thorkelsson stresses the part played by rising magmatic gas, which not only conveys heat, but lowers the effective density of the water-column, and forms bubbles that become nuclei for the formation of steam. The process is like removing the cap from a bottle of soda-water. Since it is much easier to study the eruptive processes of a

Figure 14.12 Basin of Geysir which is now rarely active.

Figure 14.13 Strokkur (The Churn) lies alongside the Basin of Geysir. It erupts every 10 or 15 minutes to a height of about 20 metres.

geyser than to find out what goes on inside the lava-filled pipes of an erupting volcano, they are valued by volcanologists, and studied with close attention.

Almost all records for geysers were once held by Waimangu, in the Rotorua thermal area (Figure 14.15). It is now no more; but from 1899 to 1904 it performed regularly, and achieved a measured shot to 500 metres. It was fed by the outflow from the 17-km-long rift that was formed in the Mount Tarawera eruption of 1886, and lasted until 1917 when an eruption blew geyser and surroundings to bits. It had little claim to beauty – and was dangerous to approach, once killing six tourists. The displays looked more like bomb explosions than fountains, and given the choice one might well prefer the fascinating swirls and eddies of white steam that move eerily across the surface of the chalky-blue lake that has taken its place.

A well-behaved geyser is a lucrative tourist attraction; but they are temperamental creatures, and their proper care and maintenance can be onerous. We don't know who discovered that a geyser can be induced to perform on schedule for an important visitor if it is fed beforehand with bars of soap (or, in these modern days, with washing-powders and detergents), but it became a common practise last century until it was found to upset the geyser's normal behaviour. It is not fully clear how it works, but adding soap alters both the boiling-point and the surface tension, and consequently the size of any bubbles that form.

Alterations to the supply of ground-water are a similar hazard. The number of bores to obtain water for domestic and commercial use in Rotorua is affecting the local geyser field, and giving rise to concern in the tourist industry. Geysir has not had to compete with a growing city, but by 1915 it had become completely inactive, and remained so until 1935 when a notch was cut in the rim of its basin, lowering the water-level by about a metre, and consequently reducing the pressure below. It became active once more, and remained so even when the gap became clogged again; but its habits remain erratic and are anxiously watched by the Icelandic authorities. When one of us was there, they had soaped it that morning in the hope that it would play for a visiting Danish tourist in the afternoon. Nothing happened until after she had gone, but a bus-load of German tourists arrived just in time to see it shoot to a quite impressive 50 metres or so. The summer had been very wet (even by Icelandic standards), and it had not played for several weeks.

Figure 14.15 Waimangu was once reputed to be the world's largest geyser. It lay in a rift opened by the Tarawera eruption of 1886, and blew itself to bits in 1917. Although it was responsible for several fatalities, the people in the picture are running towards it.

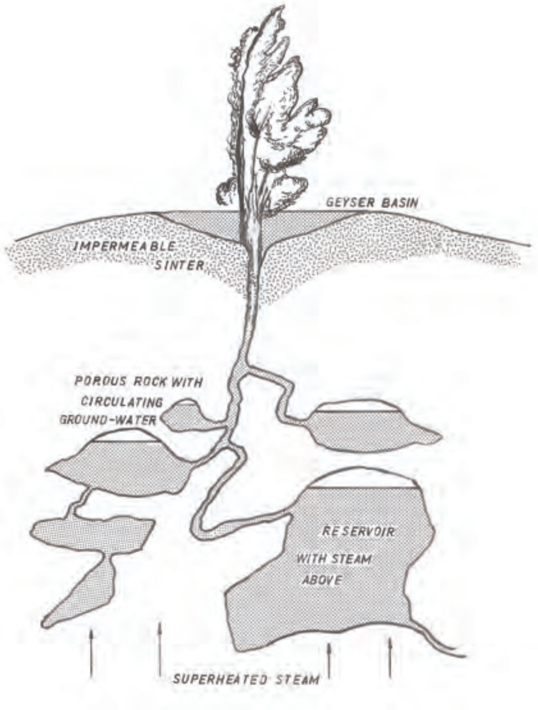


Figure 14.14 Cross-section of a geyser.

15—Taking the Waters

"You disliked the killibeate taste, perhaps?"
"I don't know much about that 'ere," said Sam,
"I thought they'd a wery strong flavour o' warm flat-irons."
That <u>is</u> the killibeate, Mr Weller," observed Mr John Smauker, contemptuously

CHARLES DICKENS: <u>Pickwick Papers</u>

Natural mineral and thermal waters have few if any properties to separate them from infusions that can be concocted in kitchens and laboratories, or from the equally natural waters of lakes, rivers, and seas; but they have long been accorded a superior status by the medical profession, orthodox and unorthodox, and in the minds of both the hypochondriac and the healthy seeking recreation. A recent handbook lists nearly 1,500 spas at which medical facilities are available, in 58 different countries. In 1971, 15 million people found their way to the thermal clinics of Italy, 100 million passed through the hotels near the hot springs of Japan, and in the French department of Puy-de-dôme and the Vichy basin 290 million bottles were filled with mineral water and sold. Such excesses rightly claim attention in a book on volcanic phenomena (Figure 15.1).

It is not surprising that washing the body should have become symbolically linked with spiritual cleansing, and that water should have acquired a religious significance. Already in antiquity naturally-heated or minerally-charged springs had become places of pilgrimage, both in the classical civilisations of the Mediterranean, and in the Orient. Immersion in hot water was soon found to ease rheumatic and injured limbs, washing in the mildly antiseptic solutions helped sores to heal, and drinking mineral-water purged and aided digestion. Buildings grew up to house visitors, to shelter baths, and to provide physical therapy. Sometimes, as on the Greek island of Cos, water was piped to the town from distant springs, and schools of medicine developed under physicians as famed as Hippocrates.

Roman enthusiasm for bathing verged upon excess, and with the fall of the Roman empire the habit of bathing declined, possibly because early Christians favoured cold water and total immersion for baptism. By medieval times washing had again become usual in Europe except among orders of religious ascetics. It lost favour once more when the spread of epidemics was traced to the public baths, which the insanitary practices of the barber-surgeons had made places of healing no longer.

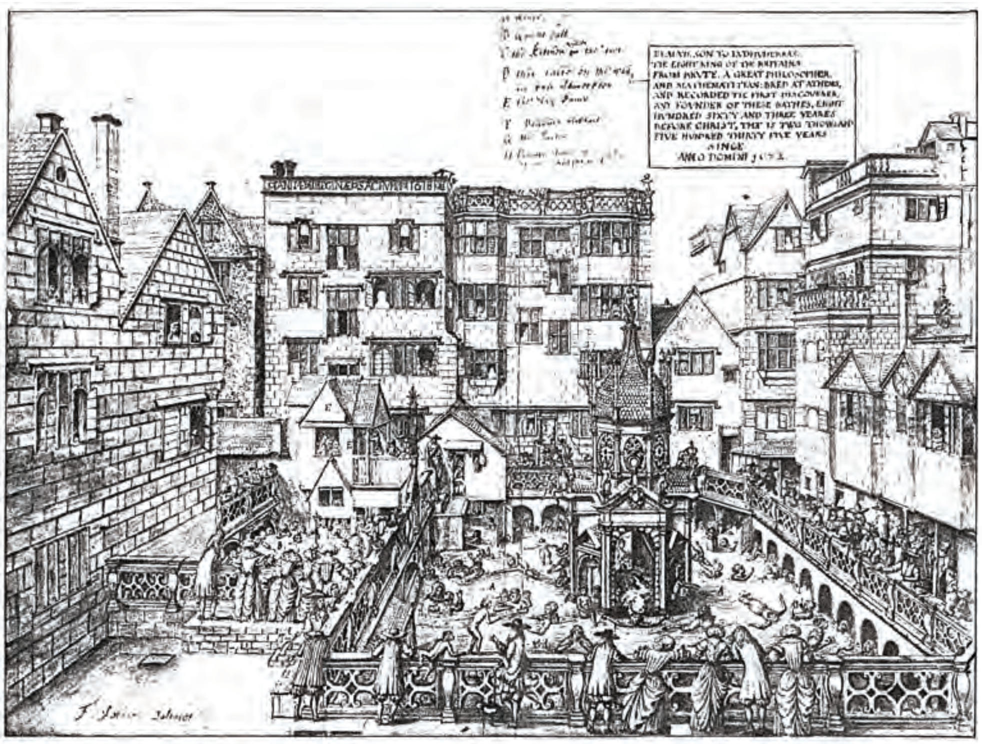


Figure 15.1 In 1675, the waters of the King's Bath attracted both bathers and spectators to Bath.

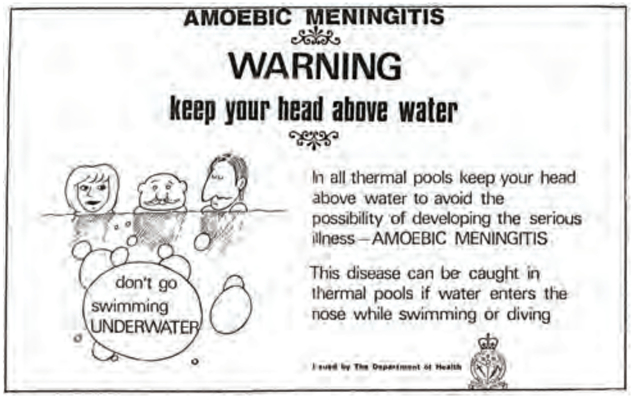


Figure 15.2 Warning of the dangers of amoebic meningitis issued by the New Zealand Department of Health.

In modern times, fatal cases of amoebic meningitis have been traced to warm pools, particularly those in natural surroundings. The amoebas responsible enter the body through the nasal membranes. They live in the soil, and had found their way into the pools after seasonal contamination by flood-waters. Precautions against flooding, removal of diving-boards, and warnings not to immerse the head seem to have solved the problem (Figure 15.2).

During the Baroque period dirt and smells were attacked with powders and scents, and not with water, and even the most magnificent chateau could seldom boast a tub. We cannot confirm the statement that after a few months away from water, skin bacteria reduce odours to a bearable level. When the habit of bathing revived again, Goethe condemned it as a mad enthusiasm for the natural state, but it gained the philosophical blessing of Jean Jacques Rousseau, John Locke, and Henry Thoreau. Mad or not, people soon found that they liked it, and that it did them good, though puritans continued to claim that there was more virtue in cold water than in hot.

Sea-bathing had died out with the Romans, and was not to be taken up again until the English physician Richard Russell popularised the beaches at Brighton and Margate in the middle of the eighteenth century. The French soon took to the water at Dieppe, but the Germans remained content to watch from the shore for another fifty years, and the Italians, doubting the spiritual efficacy of their warmer waters, went in search of ice-water, ice, and snow. Meanwhile, people not given to immoderate enthusiasm or without access to the coast were leading the return to the ancient springs.

With this return came the development of spas, and a multitude of pleasant provincial towns with names ending in -les-bains, -les-thermes, -bad, or –spa sprang up all over Europe. Good hotels, rooms for music and dancing, fashionable churches, and palatial casinos became as essential as the existence of a spring.

Figure 15.3 The Pump Room, centre of "The Comforts of Bath", as recorded by Thomas Rowlandson in 1798.

Gardens and croquet-lawns were laid out, and paths for "therapeutic ambulation" ran beside streams or climbed by easy stages to places with a view. Gentle and civilised enjoyment became a major element of the cure (Figure 15.3).

Given their long history, balneology (Latin balneum, a bath, or a bathing-place) and crenotherapy (Greek krene, a spring) have remained commendably free from quackery – though it cannot be claimed that they have been untouched by changes and fashions in medical practise, or that the pecuniary advantages of humouring the hypochondriac have not been realised.

A great deal of ingenious and expensive plumbing of impressive appearance has been developed to bring the healing waters to the patient. Much of it seems to perform the same functions as a well-directed garden hose. The problem of corrosion, which impaired both function and appearance, has been largely overcome with the introduction of plastics. Curious machinery raises and lowers disabled patients into the water, and x-rays and other electrical contrivances have found their way into the bath-house in spite of the hazards of combining water with high voltages (Figure 15.4).

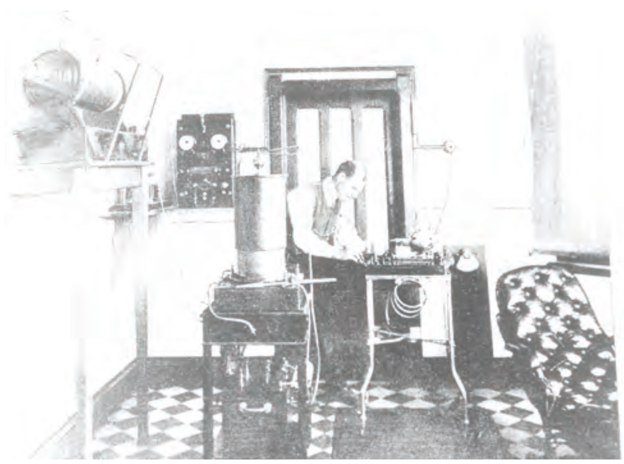


Figure 15.4 Taking the cure in Rotorua, early 20th century. This electrical apparatus would not be allowed today.

The fact that the buildings of the best-known spas of Europe display a certain similarity in architecture that nowadays lends the towns a nostalgic charm is more than a chance result of the style fashionable at the time most of them were built. The handbooks that gave the architects technical details of the plumbing and medical requirements also include designs for the suitable ornamentation of fountains, and advice to see that the counter from which mineral-water was to be served was placed as far as possible from the pump-room door, ensuring that patients took the maximum exercise. It was in order to provide them with shops and kiosks, but inadvisable to give them too ready access to the gastronomic temptations of a café.

Down the ages there has been little change in the range of complaints supposed to benefit from a visit to a spa. Chronic rheumaticky conditions head the list – gout, lumbago, sciatica, arthritis – followed by a whole range of injuries whose rehabilitation calls for heat and physiotherapy. Skin diseases are not far behind, in spite of the chance that more ills will be picked up in communal changing-rooms. In periods when immersion was out of favour, the constipated and the liverish were encouraged to drink the waters. In more recent times, the control of high blood-pressure has been added to the list, and most slimming cures can find a use for thermal waters.

History shows that doctors take time to learn moderation. If a little of something does one good, they tend to assume that more will do better. Medieval patients were encouraged to lie in the water for days, until they collapsed from exhaustion and drowned, a condition raised to medical dignity as <u>suffocates in balneao</u>. After four or five days of prolonged immersion the skin protests, particularly if the water is weakly acid, and the patient suffers weeks of pain and itching before it heals. Both in Europe and Japan this was taken as a sign that the body was ridding itself of infections. Number magic rather than clinical experience usually determined how many hours to bathe or cups of water to drink, and modern spas still tend to offer courses of treatment that last 21 days.

The cosmetic industry has successfully persuaded many ladies that the application of mud to the face improves the skin. Many of the muds in use are volcanic clays, or sediments from thermal springs, but there is commonly an admixture or even a predominance of organic matter like peat. When something more extensive than a facial pack seems called for, most spas are prepared to oblige. Medical opinion seems uncertain whether the benefit (if any) comes from the heat, the mechanical pressure, the physical stimulus of the particles on the skin, or reaction with soluble chemicals. Medicinal use of hot mud is at least as old as Galen. A sixteenth century Czech writer points out that while lying in hot mud-pools is certainly good for

Figure 15.5 Fango or peloid? Whakarewarewa mud pool.

rheumatism, there is a high chance that one's clothes will be stolen. In the present century, spas in Italy and elsewhere were happy to call the material they applied <u>fango</u>, which means mud, but in 1933 an international committee resolved that it should henceforth be called <u>peloid,</u> which comes from the Greek <u>pelos</u> – and also means mud (Figure 15.5).

The cynical may care to reflect on the balneological repercussions of the discovery of radioactivity. It was quickly established that some natural springs were weakly radioactive. Before the first World War, the New Zealand government balneologist was reporting "a growing tendency, which cannot be ignored, to attach a supreme importance to the role of radioactivity in balneology", and goes on to urge respect for the view of Ernest Rutherford that "proof was lacking that the beneficial effect of mineral waters was due to radium" and for his warning that "if radium salts were introduced into the body they could remain permanently in the system and destroy the surrounding tissues". Before long, a Radium Spring had been discovered in the grounds of the Rotorua hospital, and the analysis of every bath in the Government domain contained a measure of its radioactivity. On the whole, mineral springs are little more radioactive than our other everyday surrounds, but until a decade or so ago most bottles of European mineral-water carried an analysis that included an encouraging reference to radioactivity. By 1980 public enthusiasm for radioactivity had waned, and it had vanished from the analyses.

As well as obviously mineralised waters, some volcanic districts also bottle and export water from springs whose principal claim is no more than an exceptional purity, like those at Volvic in the French Massif Central. They have certainly been filtered through great thicknesses of volcanic deposits, but it has to be conceded that the waters of the Auvergne owe the continuance of their legendary excellence as much to the forest cover and the absence of human activity in the catchment basins as to the volcanic character of the region. Purity is not, of course, absolute. Distilled water is not at all pleasant to drink, and the spring water is slightly mineralised with what are claimed to be “essential” trace-elements. It may be noted that connoisseurs prefer waters from a basaltic catchment to the somewhat more acid ones collected from granite – though the Scots insist that water derived from granite is essential to the best whisky.

16—Imposters

The world is full of false forsworne knaves…

ABRAHAM FRAUNCE: Lawiers Logicke

One winter evening in 1908 several people on the verandah of a farmhouse near Gisborne were startled by the appearance of a serpent-like column above the crest of the hill opposite. It writhed for a short time and disappeared below the skyline. The apparition was accompanied by a noise like the snorting of a huge beast, and was heard two kilometres away. On the following morning they found that the valley over the hill had been freshly covered by a layer of mud three or four metres thick, containing pebbles and rocky boulders up to 30 kilograms in weight. It was firm enough to walk on, and covered an area of four hectares. It had apparently been erupted from a vent that was still emitting gas, but there was no evidence of abnormal heat. To have been visible above the hill-top the column of mud must have reached a height of nearly 120 metres.

There have been other similar ejections of mud and gas in this part of New Zealand, and it seems likely that two tsunamis in 1947 were triggered by some such event off the coast. Mud volcanoes can be found in many parts of the world, often close to oil-fields. Many of them are quite small and build regular cones perhaps five metres high, like the ones at Turbaco in Colombia that Humboldt reported early last century (Figure 16.1, also see Figure 16.2). There are bigger ones in Trinidad, where Maruga Bouff is half a kilometre across, on the Arakan coast of Burma, and in the Bibi Eibat oil-field near Baku in Azerbaijan. There the larger examples are hundreds of metres high, and several kilometres across. When Cheyildag erupted in 1970 the outburst of gas caught fire, and was followed by an extrusion of clay that formed a mound 70 metres in diameter.

Figure 16.1 Mud volcanoes at Turbaco, Colombia as recorded by Alexander von Humboldt.

Figure 16.2 Mud volcanoes, Cerro Prieto, Mexico.

Although an erupting mud-volcano can produce hundreds of thousands of tons of material and sends jets of flame to heights of two kilometres, volcanologists are reluctant to accord them full recognition, on the grounds that their behaviour does not involve igneous processes. Most eruptions involve two factors, in widely differing proportions. They are gas pressure, and diapirism (Greek diapeirein, to pierce).

In a sequence of sedimentary strata, the weakest material does not necessarily lie on top. Suppose such a sequence containing a weak layer is folded tightly by regional compression. Each fold will contain a core of weak material that may extend to a depth of several kilometres, and will consequently be under high pressure. Such an arrangement is called a diapiric fold. Over the course of time, the apex of the fold can be progressively thinned by erosion until it can be ruptured by the pressure of the weak material, which is forcibly expelled as a mud volcano. Once a vent has been opened, continuing regional compression can lead to further eruptions.

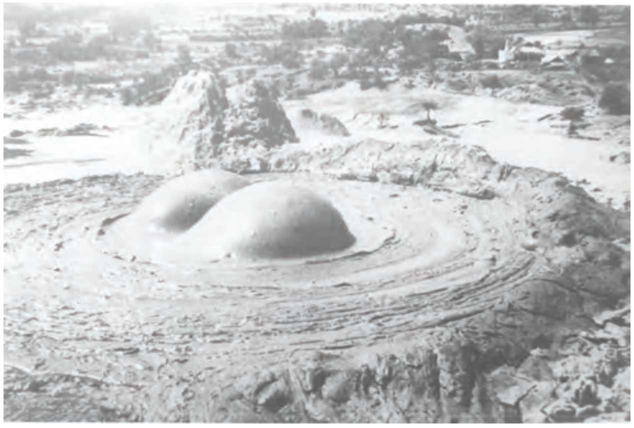


Figure 16.3 Bubbles of natural gas about a metre in diameter form in the crater of a Burmese mud volcano just about to erupt.

The gas present is usually methane, but there can be traces of other hydrocarbons too. At the depths from which it comes it seldom encounters temperatures high enough to ignite it; but when it does, as at Cheyildag, the result can be spectacular. Open vents occasionally produce an emission of gas that carries small stones to the surface, without much mud (Figure 16.3).

The range of naturally and artificially-occurring flames that have been taken for volcanic phenomena is very wide. It includes burning oil-seepages and coal-seams set alight by lightning, burning peat, marsh-gases, and similar gaseous products of vegetable decay escaping through holes in the ground. Spontaneous combustion of sulphide ores has produced reports of active volcanoes in Ireland and in northern Canada.

Lightning strikes can fuse sediments into good imitations of igneous rocks. In Lesotho an extremely small but apparently fresh outbreak of basalt resulted when lightning struck a steel post imbedded in an ancient basalt. Similar melting is thought to account for the appearance of "basalt" near Murchison, in a part of New Zealand well away from any Recent volcanism; but in this case it was probably fire in a coal-seam some 50,000 years ago that provided the heat.

A few years ago the real and the false came together in an Auckland suburb. The local service-station reported unexplained losses of petrol, and it was found that its tanks had been buried in ground that was above normal temperature, leading to excessive evaporation. The possibility that the Auckland Volcanic Field might be reviving received wide publicity, and as a result a nearby resident reported that a bright yellow deposit had formed alongside a rock outcrop in his garden, and was beginning to spread. It looked like sulphur, and chemical analysis confirmed it. There were other reports before it was realised that storm-water was concentrating the sulphur from fertilisers lavishly applied to suburban gardens.

False reports are not uncommon, but it is unwise to ignore them. The causes are many and varied. Booming noises possibly heralding renewed activity of Mount Egmont have been reported on several occasions, and proved to be caused by farmers blasting old tree-stumps. In Hawaii, on the other hand, the glow from fire-fountains has been attributed to farmers burning sugar-cane.

There is nothing like an earthquake for starting false reports. Within the first few decades of European settlement of New Zealand, when the colonists were new to earthquakes, they had been linked to volcanic eruptions in the central North Island (where there were certainly volcanoes, sleeping quietly) and to volcanoes in the Kaikoura Mountains, where there were none. The red flames seen at the time of the 1848 earthquakes in Marlborough were another phenomenon new to them – the <u>Aurora Australis</u>. In Wanganui, which had been sited on swampy ground near the river-mouth, smells accompanying a large earthquake in 1843 were confidently identified as sulphur, like the ones in Gisborne more than a century later, traced to the disturbance of rotting vegetation in a suburban creek.

Large earthquakes often dislodge landslides and send up dust-clouds from the slopes of mountains that can be seen, but not readily reached. This explains why "eruptions" of Umsini, in West Irian, which is not a volcano, are listed in reputable catalogues (Figure 16.4).

A common earthquake phenomenon that does not appear to be widely known is the compaction and settlement of gravel flats. The shaking expels the ground-water, often through crater-like holes, along with sand or mud from between the stones, which can build up into low conical mounts (Figure 16.5). These <u>sand craters</u> are seldom more than a few metres across, but may be very numerous, and water reaching

Figure 16.4 True or False? On the right volcanic steam is rising from the crater of Mount St Helens, but the small "cauliflower" cloud on the left is dust from a landslide in the crater.

Figure 16.5 Crater produced by earthquake, Charleston, South Carolina, 1886.

Figure 16.6 Thiis conical hill beside the Harper River, Canterbury, N.Z., is far from any evidence of volcanism, and has been shaped from sedimentary rock by erosion.

the surface can come from a sufficient depth to be warm. After the Hawke's Bay earthquake in 1931, a farmer tried to clear a blocked well by lowering an iron crowbar on the end of a rope. On recovery it was found to be too hot to hold. Such happenings strengthen popular belief in a close connection between earthquakes and volcanoes.

Reports of submarine volcanoes are notoriously hard to confirm, and some instances seem likely to have been spouting whales. When pumice rafts are reported, they have often travelled far from their source. Algal blooms cause rather similar problems. They stain large areas of sea, and are often mistakenly believed to be the product of eruptions.

The shape of volcanic cones is so characteristic that any conical hill is apt to suggest the idea of a volcano, but erosion can sculpt cones every bit as symmetrical as volcanic ones (Figure 16.6). Some imposters can be picked without examining the rock they are made of, by a curious angle of slope, or an unusual covering of vegetation; but erosion can also shape igneous rocks, like the ignimbrite cones near Lake Rerewhakaaitu, south of Mount Tarawera.

Along with the hills, we must class the holes produced by meteoric impacts, the most famous of which is the Barringer Crater in Arizona (Figure 16.7). Whatever it was that landed in the Siberian headwaters of the Podkammenaya Tunguska in 1908, it left no crater, and volcanism seems to be the only explanation of the flattened forest and the records on distant seismographs that has not been seriously suggested.

Aconcagua, in Argentina, is listed in many references as the world's highest volcano (though some do describe it as extinct). It is not a volcano at all, but a mound of Cretaceous conglomerates and assorted igneous rocks that have been assembled without the least suspicion of help from volcanism. It is 6,960 metres high, and must surely be reckoned the grandest imposter of all.

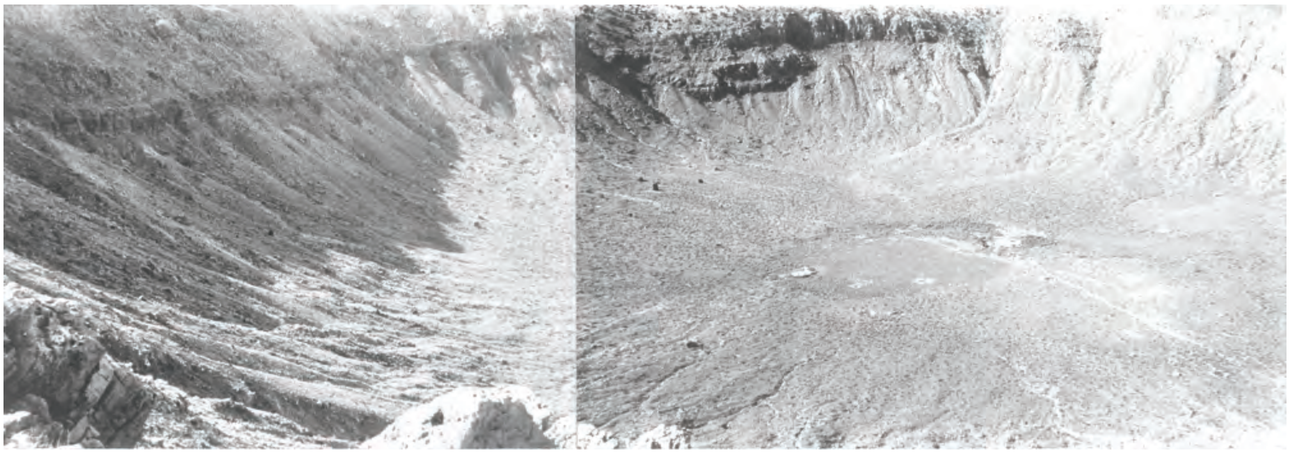


Figure 16.7 Barringer meteor crater, Arizona. It is a kilometre and a half in diameter and 170 metres deep.

17—Devious Means

Go round about, Peer!

HENRIK IBSEN: Peer Gynt

There is no way by which volcanologists can gain direct access to the source of an erupting volcano. By the time erosion has exposed former magma-chambers the surrounding pressures have been released, the material in them has cooled, gases have been lost, and irreversible chemical changes have occurred. Nor have the enormous quantities of material that volcanoes have released from their underground vaults and piled about their vents or strewn over the countryside proved to be the treasure-trove they at first seem to be. Neither the geologist's hammer, not the petrologist's microscope, nor the chemist's test-tube has proved powerful enough to extract from them more than a confused and partial understanding of the processes that bring about an eruption.

Learning how rock becomes magma and trying to predict eruptions and save lives are not separate problems. Both involve the study of changes that precede any outbreak at the surface, and the answers must be sought indirectly, by physical measurements of gravity, of magnetism, and of elastic waves, which convey information about conditions at a distance, in regions likely to remain inaccessible for ever.

Volcanologists use gravity measurements in two ways: either they map the variations in strength around the volcano and try to interpret the pattern in terms of what could lie inside or beneath it; or they make repeated (or continuous) measurements in one place, and watch for changes that could indicate a movement of magma or a deformation of the ground. By repeating mapping after an eruption it is possible to get a good idea of how much material was erupted, and where it came from.

Measurements of gravitational pull can be made very precisely, and the portable gravity-meters (or gravimeters if you prefer) that have been developed to aid the search for oil (Figure 17.1) are of great value to the geophysicist. In theory they are very simple affairs – no more than a weight hanging from a spring and some contrivance for measuring its length. The stronger the pull of gravity, the more the spring stretches. In practice there are all kinds of complications. Springs are affected by changes in temperature, and slowly stretch if you leave them under tension. If the gravity-meter is to be sensitive, the spring must be weak, and the stretch and temperature problems get worse, so that modern meters have become quite elaborate affairs, with the working parts enclosed in a vacuum-flask, and provided with temperature controls. They are sensitive to changes in gravity of one part in 100 million.

Figure 17.1 Making gravity measurements in the field with a Lacoste-Romburg gravimeter.

Geophysicists making a gravity survey take steps to eliminate the drifts of the meter by returning to their starting-point or, if that is impracticable, by "looping" stations in some such order as abcd, bcde, cdef, and so on; but even when allowance has been made for drift and temperature changes a simple map of the corrected readings reveals very little, and the result of the survey is usually presented as an anomaly map. Now, an anomaly is just the difference between what we find, and what we expect to find – and that depends upon how closely we analyse the problem. If we could analyse it correctly and completely we would be left with no anomaly at all.

Suppose that we started with the idea that the Earth was a completely uniform sphere, we would expect to find the same value of gravitational pull at every point on the surface; but because the Earth has a bulge, points at the equator are 21 kilometres further from the centre than points near the poles, and the pull is correspondingly less. If we make the common human assumption that things at home are normal, we finish with a map having negative anomalies at the equator, and positive ones at the poles. If our concerns, as is the case in volcanology, have little to do with the equatorial bulge, it is a simple matter to calculate its effect and subtract it from our anomalies. We can also get rid of the centrifugal force arising from the Earth's rotation, and allow for the fact that few of our observations are made at sea level. This is not quite so straightforward as it seems, for different hills are made of different kinds of rock, and we may need to take samples to the laboratory and measure their density. We must also consider the shape of the surroundings. The corrections to be applied to a reading on a sharp ridge a thousand metres up will not be the same as one in an alpine valley at the same level, but surrounded by mountains that rise to three times the height. They will be different again on a lofty plateau. Consequently, we find maps of a number of differently-named gravity anomalies, depending upon the particular corrections that have been made.

Considering the number of estimated "corrections" that are applied to gravity measurements, the reader may be left wondering that they can tell us anything at all – but we have not reached the end of our troubles. Patterns of gravity anomalies are not like fingerprints, they can be produced in a number of different ways. A thick stratum of dense rock near the surface will exert the same pull as a much thicker one at greater depth, and mathematicians will tell us that there are in fact an infinite number of arrangements that will yield the same gravity pattern. Fortunately most of them are either so improbable that we can forget about them, or so like one other that the differences don't matter.

Because of these problems, gravity measurements are often used back-to-front, to rule out some of the alternative possibilities reached on other grounds. There are many ways of producing a given pattern, but only one pattern for each arrangement of rocks of known density. This is fairly simple to calculate, although it used to be laborious if the arrangement was at all complicated. Now that we all have computers, we can make step-by-step changes to the arrangement, and watch a screen to see the effect upon the pattern.

The magnetism of the lodestone was known to the ancients, and with the coming of the electronic age we have become familiar with more and more powerful magnets made possible by the development of special alloy-steels. It is less generally realised that all substances are magnetic to a greater or less degree, including rocks. The most strongly magnetisable are ores of iron, cobalt, and nickel, which are collectively known as <u>ferromagnetics</u>. The others are classed as <u>paramagnetic</u> or <u>diamagnetic</u>, according to whether a suspended specimen will align itself along or across a strong enough magnetic field. From the volcanological point of view, the most important thing is that ferromagnetism is strongly dependent upon temperature. Changes in the distribution of heat are therefore likely to be accompanied by local changes in the strength and direction of the Earth's magnetic field. These can be followed with portable magnetometers as well as by instruments at fixed observatories, and it is even possible to make measurements from aircraft.

Magnetic changes were noticed several months before an eruption of Mihara, in Japan, and also before eruptions in the Kuriles and Kamchatka. In New Zealand changes in total field-strength occurred a few hours before eruptions of Ruapehu and Ngauruhoe, and on White Island uplift before eruptions seems to be accompanied by a reduction in the strength of the magnetic field.

Although rocks lose their magnetism when their temperature rises above the Curie Point (Chapter 5), a large body of rock cannot change temperature suddenly enough to account for these short intervals. It has been suggested that changes in stress could produce the magnetic changes, but it is more likely that fields generated by natural earth-currents rather than permanently-magnetised rocks dominate the local magnetic field, and that changes in the pattern of these occurred. In all cases where changes have been observed, magma has already reached shallow levels.

Naturally generated electric currents in the ground are related to changes in the Earth's main magnetic field, but they are influenced by many local factors. Back in 1905, J. E. Burbank claimed that currents flow from all sides of a mountain towards the top, but it was soon found that the polarity depended upon soil moisture and soil temperature. It is possible both to record the natural currents, and to feed current into the ground in one place to find out where it goes to by probing in others. How deeply the current penetrates depends upon the spacing of the electrodes, and it is possible to determine the electrical resistance along its path. Since the resistance depends upon temperature the technique has obvious applications to volcanology, but it is not easy to set up the equipment in the field, and its usefulness depends greatly on the characteristics of individual volcanoes.

Changes in the number, strength, and position of the earthquakes near a volcano are an important index of changes underground, and just as the seismic waves from natural earthquakes and artificial explosions have proved powerful tools for probing the Earth's interior and in prospecting, they have found application on a smaller scale in volcanology.

There are two different kinds of earthquake associated with volcanoes. The first is caused in much the same way as the ordinary tectonic earthquakes that also occur in non-volcanic regions. Rocks become strained to the point at which their strength is exceeded, they break, and the stored strain energy is radiated as elastic waves. Large tectonic earthquakes get their energy from the movement of the lithospheric plates, and are concentrated where the strains are greatest, within the subduction zones and along the spreading ridges. The underground movement of magma can also produce strains great enough to fracture rock and generate earthquakes, but the surrounding rocks have usually been weakened by heat or shattered by previous intrusions, so that they can store less strain, and the earthquakes tend to be smaller. They can however be numerous, and often occur in what are described as swarms.

The second kind of earthquake is generated in quite a different way, and a seismograph record of one looks rather different. As magma moves towards the surface, the confining pressure drops, bubbles begin to form, gas is liberated, chemical explosions take place, and elastic waves are generated. The depth at which this can start depends critically upon the balance of several highly variable factors that include not only the composition and physical condition of the magma, but the temperature and pressure. Pressure waves from these explosions can bring surrounding parts of the magma column to the critical condition, and the shocks are often multiple. Because of the weakened condition of the rocks through which the waves travel, their frequencies are usually much lower than those in normal earthquakes.

Although these explosions are never large, there is a great variation in size, and chain reactions are common. A stage can be reached at which a continuous turmoil is produced, soon becoming a vibration with a well-defined period. This is described as volcanic or harmonic tremor (Figure 17.2).The cause of the regularity is disputed. Hawaiian volcanologists have suggested that molten lava rushes past tongues of projecting rock and makes them vibrate like the reeds of a mouth-organ. The Japanese volcanologist Daisuke Shimozuru has found that the deeper the origin, the longer the period of the vibration, and put forward the more likely idea that as the magma releases its gas into underground conduits and cavities the magma in the vent is set into rhythmic oscillation that generates the tremor.

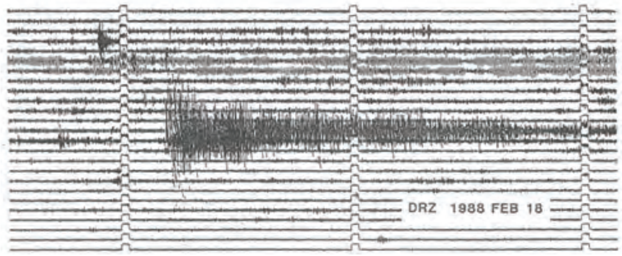


Figure 17.2 Harmonic volcanic tremor in the upper part of the record followed by a magnitude 1.6 earthquake beneath Ruapehu Crater Lake.

Large cavities produce low notes, and small ones produce high ones, as you can check by blowing across the mouths of bottles of different sizes. In 1771 Vesuvius was in eruption and Dr Burney, the historian of music, was in Naples staying with his friend, the pioneer volcanologist Sir William Hamilton, and disapproving of the tone of Italian harpsichords. The worthy doctor noted that the volcano was producing the deepest sounds he had ever heard, and inferred that its throat must therefore be open to a great depth.

At its first onset, tremor often lasts only an hour or two at a time, and has a period of half a second or so. As the activity increases and magma rises in the vent, the amplitude of the tremor increases, it becomes more continuous, and the vibration more rapid, with abrupt changes of amplitude and phase.

Many countries have established networks of seismograph stations for earthquake research, but they are usually too few and too widely spaced to satisfy the volcanologist, and the records cannot always be interpreted soon enough to provide adequate warning of eruptions. To fix the position of an earthquake at least three stations are needed, and a fourth if the depth is to be found as well. At least one instrument must be as close to the epicentre (the spot directly above the origin) as the shock is deep. As most volcanic earthquakes are small and shallow, the instruments must be close to the volcano, and the complexities of its structure usually call for more than the theoretical minimum number.

Few volcanoes can be provided with instrumentation as elaborate as this, but even a single seismograph can give warning that the number of earthquakes is increasing, and give an indication of their distance. In some special cases, when the structure of the volcano is well-known and records of past eruptions have been made, it is even possible to venture some qualitative estimates of changes in the depth of the activity.

It is obviously impracticable to establish manned stations every few kilometres, but in recent years it has become possible to build small instruments that can

Figure 17.3 Aso Volcanological Laboratory in Japan.

Figure 17.4 Temporary seismic station in Cameroon, with buried seismometer and radio link to base station.

be left unattended, and will radio their information to a central station. Finding sites with a direct radio path is not always easy, but networks of this kind are now operating in most countries with established centres of volcanological research (Figures 17.3 and 17.4).

Tradition has it that the ruined Torre del Filosofo on the slopes of Etna was built in 440 B.C. as an observatory for the philosopher Empedocles, who has been hailed as the first volcanologist. There is reason to believe that the tower in fact commemorates the visit of a Roman emperor several centuries later, and all but fragments of the writings of Empedocles are lost. A follower of Pythagoras and Heracleitus, he was certainly deeply interested in fire, and seems to have ended his life by jumping into the crater to prove some point about links between fire and immortality – an experiment that must be considered a failure. It has been claimed that the descriptions of an eruption of Etna in a Latin didactic poem dating from the first century B.C. embody the observations of Empedocles, but the link is tenuous, and he remains a shadowy figure.

The first permanent volcanological observatory with a scientific staff was the Royal Vesuvian Observatory founded in 1847 in what was then the Kingdom of the Two Sicilies. It has had some most distinguished directors, and has survived many subsequent political and volcanic upheavals. Considering its success, it is surprising that more than half a century was to pass before there was a second institution. In

Figure 17.5 Observation post near Merapi Volcano, Indonesia, elevated to view volcano above dense jungle.

1912 public subscriptions were raised to enable the Hawaiian Volcano Observatory (which had begun two years earlier as a geophysical field-station of the Massachusetts Institute of Technology) to become a permanent institution, with T.A. Jaggar as its Director. Its finances remained precarious until 1919, when the U.S. government took it over.

In 1921 concern at the renewed activity of Krakatoa led the Dutch authorities to establish permanent observation posts at a number of Indonesian volcanoes. Several of them still survive, and many new ones have been built by the Indonesian government Figure 17.5).

In Japan, a seismometer had been installed in Kagoshima near Sakurajima volcano as early as 1888, but it was quite a few years later that the first volcano observatories at Mt Aso and Mt Asama were established. After the disastrous eruption of Vulcan in 1937, the Australian government set up an observatory at Rabaul, in New Britain. It passed temporarily into Japanese hands during the war, and they continued to staff it even during the heaviest bombing, when the instruments were moved into tunnels in the wall of the caldera.

Geophysics in the Philippines owes much to the pioneering work undertaken by Jesuit fathers, some of whose activities still continue. In 1952 a government Commission began a more intensive programme that included continuous observations at Taal and Hibok-Hibok, and periodical surveillance elsewhere.

It is of course impossible to provide every volcano with an observatory, but even in countries with very limited resources it is usual for someone from the nearest geological survey to inspect the volcanoes from time to time, measuring temperatures of hot springs, crater lakes, and fumaroles, and perhaps collecting gas-samples for analysis. The occurrence of a major eruption will almost certainly attract observers from universities and other institutions, many of which traditionally concern themselves with particular parts of the world. The U.S. Geological Survey watches volcanoes in Central America as well as those on its own west coast and in Alaska, Italians are to be found in Ecuador and Colombia, Russians in Mexico, and the French especially in Central Africa.

The New Zealand Geological Survey has interested itself in volcanoes since it was founded in the middle of last century, and in 1946 it opened a district office in Rotorua which has numbered volcanology among its concerns. Although successive governments have remained deaf to the pleadings of scientists both within the country and from abroad that they should establish an observatory, interest in geothermal power, and concern for the safety of tourists on the ski-fields has greatly increased the volcanological work being done.

In 1952 the Seismological Observatory established a permanent seismograph at the foot of Mount Ruapehu, and in 1956 staff from the Geophysics Division, acting in the national "do it yourself" tradition, built themselves a small house to be used as a geophysical station. It is now the recording centre for four magnetometers and a small network of seismographs deployed about the Tongariro National Park, and usually houses the equipment for other short-term projects.

Monitoring sensitive apparatus and maintaining telephone lines under alpine conditions is not easy. Storms and the volcanic activity it is designed to watch have repeatedly destroyed or damaged the equipment. The number of seismographs in the Central Volcanic Region is steadily growing. One on White Island continuously sends data to the mainland (between damaging explosions). There is now a volcanologist on the staff of the Geophysics Division in Wellington, and two of the seismological technicians devote part of their time to studying records from the region.

Without the station at Ruapehu, it would have been difficult for New Zealand scientists to become familiar with standard volcanological techniques, and to develop ideas of their own. Not everything that has been tried has turned out to be useful. Earth-current measurements have proved disappointing, and reliable tilt-meters are not easy to design and instal. On the other hand, repeated surveys pioneered by P.M. Otway, of a traditional kind using theodolites and geodimeters, although laborious, have provided a detailed picture of the deformations of the summit area of Ruapehu, in spite of occasional destruction of survey-marks by eruptions (Figure 17.6 and 17.7). Temporary increases of 20 to 25 mm in the diameter of the crater lake have been measured before eruptions.

Ngauruhoe is often shrouded in mist, but air-waves from summit explosions can be recorded on a microbarograph. Simultaneous records of an earthquake and an air-wave are an almost certain indication that there has been an eruption. An automatic camera making exposures every half hour (or more often when the mountain is active) provides a useful record of the behaviour of Ngauruhoe, but unfortunately the growth of the mountain village has blocked the Observatory's view of Ruapehu.

Keeping track of changes in the floor of the crater lake at Ruapehu has not proved easy. After the eruption in 1945 the vent lay at the bottom of a pit some 300 metres deep, which later filled with water to become the lake. In 1950 and 1954 canoeists could find no

Figure 17.6 Surveying around Ruapehu Crater Lake.

Figure 17.7 P.M. Otway with theodolite during Ruapehu survey.

Figure 17.8 The Crater Cat, Ruapehu.

depths greater than 70 metres, although the first full survey, carried out in 1965 by Dr R. R. Dibble of Victoria University of Wellington, found a maximum depth of 298 metres.

A search for practical methods of making periodic re-surveys led the Geophysics Division of the D.S.I.R. to build a small twin-hulled boat, radio controlled, and fitted with an echo-sounder. This elegant piece of modern technology, which became known as the Crater Cat, failed to deliver all the answers (Figure 17.8).

The broad beam of the echo-sounder could not detect deep and narrow vents, and suspended sediment and gas-bubbles prevented it from penetrating to depths beyond about 70 metres. Geological Survey officers, who tied together 10-metre lengths of cord in contrasting colours, wound them around short wooden poles, tied weights to the free ends, dropped them from a helicopter, and noted how far they unwound, proved to have found a better method.

Infra-red photographs show hot objects in lighter tones than their surroundings, and the effects of heat on vegetation, the output of fumaroles, steaming ground, and areas of melting snow and ice show clearly on pictures taken from the air (Figure 17.9). It is also possible to use infra-red scanners to produce television images, and in Sweden, Hawaii, Japan, and the U.S.S.R. they have been used successfully in prospecting for geothermal power. These methods remove some of the drudgery involved in making temperature-measurements, and sensors mounted in satellites have not only improved the surveillance of eruptions, but have revealed the presence of a previously unknown, possibly active, volcano in Tibet.

Keeping up with what volcanoes are doing is not easy. In 1922 an international meeting of volcanologists decided to compile a catalogue of active volcanoes. It now runs to 24 volumes, and has still to deal with Iceland and Alaska. In 1960 it was decided that annual lists of new eruptions were needed. The Smithsonian Institution now organises a Scientific Event Alert Network (SEAN) that issues monthly bulletins, and the Japanese publish one annually.

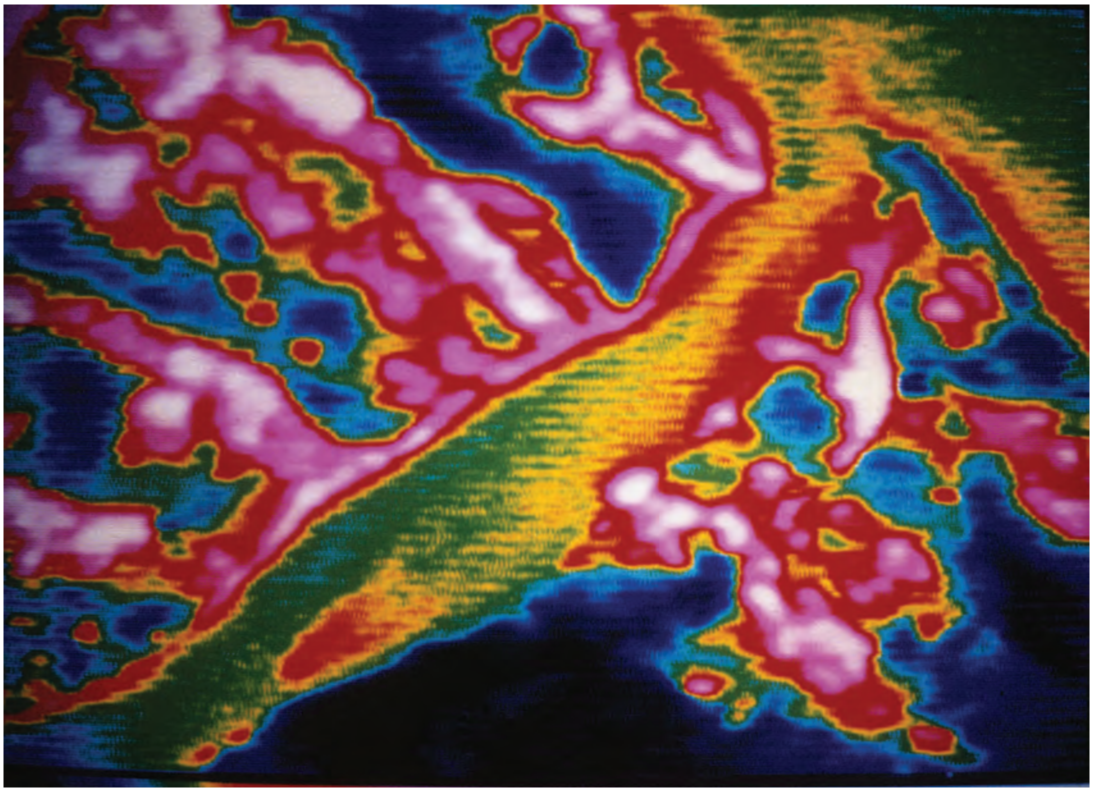


Figure 17.9 Infrared picture of the Ngapuna area near Lake Rotorua. Green diagonal is the Purenga Stream. The colours red, pink and white show increasingly hot ground and hot water.

18—Dating an Eruption

I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.

RUDYARD KIPLING: The Elephant's Child

Deciding how closely a volcano needs watching is easier when you know its past behaviour. Unfortunately history as historians usually understand it seldom offers much help to volcanologists. The great majority of volcanoes lie in places where there are no ancient chronicles, and long written records of the kind that we have for Vesuvius and Etna are rare. Nevertheless, ancient eruptions leave their record in the rocks, and uncertain dates are better than no dates at all; so we find that a great deal of volcanological cunning has been used to extend the written information.

Many primitive peoples have a rich oral tradition, which they take great trouble to preserve, and which usually includes the genealogies of chiefs and rulers. The average length of a reign or a generation provides a rough measure of time, and when a large eruption is recorded in several independent traditions a date can often be ascribed with surprising confidence. This kind of dating can also be complemented by archeological studies, which allow destroyed buildings or buried artefacts to be dated on artistic or stylistic grounds.

An eruption often upsets the rate at which vegetation grows, and leaves a record in the annual growth-rings of trees. Sometimes even the season of the year can be identified. The technique of counting growth-rings is called dendrochronology (Greek dendron, a tree), and is similar in principle to counting varves. Varve is Swedish for a layer, and the layers in question are those arising in lake sediments from regular seasonal changes. When the lake is fed by glacial streams, the changes can be very marked. Narrow bands of coarse material brought down when the ice melts in the spring alternate with fine clay, and a layer of volcanic ash that interrupts the sequence is readily distinguished.

Lichenometry is a rather different kind of botanical technique. Lichens on the surface of new lava-flows grow at a slow and regular rate, and the relative ages of young flows can be estimated fairly well, but conditions seldom remain stable for more than a century or so, and it is harder to establish absolute ages.

The term tephrochronology is applied to a wide variety of traditional geological techniques (including those based on radioactive decay) when collectively brought to bear on the dating of layers of ash. Given this definition, it would be hard to refute the claims of its advocates that it is the most powerful method of dating (Figure 18.1).

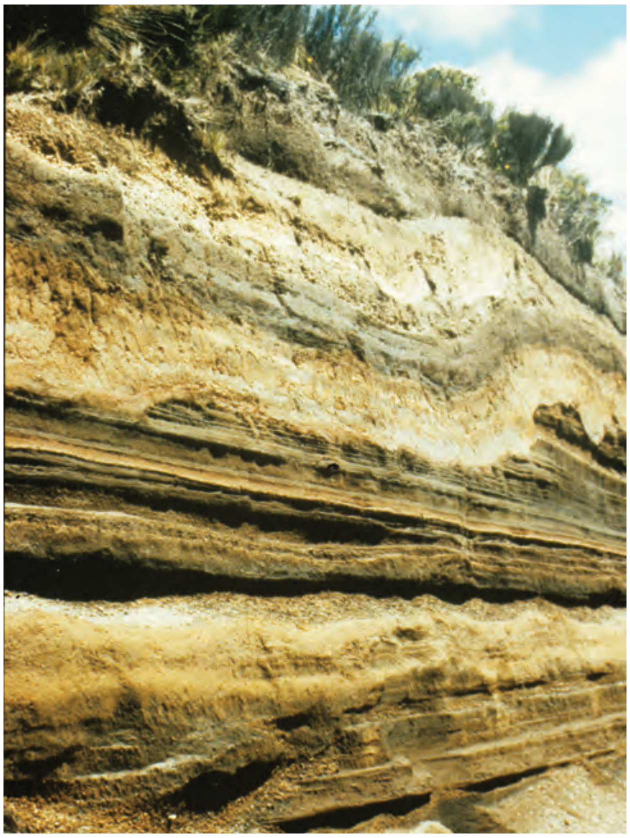


Figure 18.1 Layers of ash from successive eruptions of Lake Taupo and the volcanoes of Tongariro National Park are exposed in road cuttings.

Much geology depends upon the simple idea that a stratum of rock that lies on top of another is likely to be younger, unless it has been intruded. Then it cannot be older than the material it has been intruded into. Tephra from major eruptions can be dispersed over very large distances, forming distinctive deposits that appear in a variety of geological settings. Careful mapping of a volcanic region can establish the relative ages of overlapping ash-layers, and if some of them can be dated by other means, the approximate ages of all of them can be found.

The commonest radioactive method that will give so-called absolute dates is based on the relative amounts of the two carbon isotopes ^{12}C and ^{14}C. The nucleus of an atom contains two sorts of particle: protons, which carry a positive electrical charge, and neutrons, which don't. The number of protons determines what kind of an atom it is, that is to say, how it behaves chemically; but the number of neutrons can vary. Forms of the same element having different numbers of neutrons are called isotopes (Greek isos, equal, topos, a place). Normal atoms also contain negatively charged particles called electrons and unless the atom is electrically charged there are equal numbers of protons and electrons.

Some arrangements of atomic particles are stable, and others are not. An unstable atom will spontaneously eject surplus particles until it reaches a stable state. Unstable atoms are said to be radioactive. The rate at which a radioactive element decays depends upon how much of it there is, so it is usual to compare rates by giving the time it takes for the amount to fall to half the original value. These half-lives vary enormously, from small fractions of a second to thousands of millions of years.

Living wood and other organic material contains a minute proportion of the radioactive isotope of carbon, ^{14}C. This is regularly replenished while it is alive, but when it dies the ^{14}C gradually decays to the stable isotope ^{12}C, and the proportion between the two changes. After 5,568 years there will be just half the original amount of ^{14}C left. External factors like temperature and pressure have no effect upon the half life, and the changing ratio between the amounts of the two isotopes therefore provides a very uniform measure of the time that elapsed since the sample "died".

When using the method to date an eruption, the main precaution needed is to ensure that we have not chosen a sample that was already dead. There are still sources of error – the accuracy with which we know the half-life of ^{14}C which could be out by up to 30 years, and the accuracy with which we can measure the very small quantities of ^{14}C involved. Some early carbon dates could be out by as much as a thousand years, and a few are correct to within twenty. The uncertainty in most cases is a few hundred years.

Sometimes special circumstances allow us to date an eruption by resorting to "tricks" that will only work in a few cases. One of these techniques depends upon the uranium content of some volcanic glasses. The fission products of the uranium leave microscopic tracks in the glass, and the more there are, the older the glass must be. Another method depends upon the direction of rock magnetism, which retains the direction of the Earth's field at the time of cooling. The history of the wandering magnetic poles is now known with sufficient accuracy to make this a useful method. It was first applied to the Icelandic eruptions of about a thousand years ago, and has since been extensively used in Hawaii.

Eruptions have a beginning and an end, but the duration is not easy to define, even when the volcano can be continuously observed. The classical example is Stromboli, which has been showing-off more or less continuously for at least 2,400 years; but there have been major changes in the character of its activity, marked by explosive outbreaks that last for two or three weeks. Another long-lived eruption is that of Yasour in Vanuatu (until recently the New Hebrides). It was in progress when Captain Cook discovered it in 1774, and hasn't stopped yet (Figure 18.2). Small eruptions are necessarily brief eruptions, though the converse is far from true. The shortest major eruption is probably one in Zaire (now the Democratic Republic of the Congo) in 1977, reported by Haroun Tazieff. The "permanent" lava lake in the crater of Nyiragongo emptied in less than an hour, flooding the outer slopes with 20 million cubic metres of fluid lava, moving at an initial speed of 100 km per hour, and killing at least 70 people.

Very large eruptions, like ignimbrite showers, are repeated only at long intervals of tens or even hundreds of thousands of years; but the longer the interval, the larger they tend to be. Short eruptions are over in a few months. The best guide to the likely duration is past history, but it is an unreliable one. Eruptions of Kilauea usually end within a few days, yet one eruption lasted 42 years and another 26. Of the volcanoes in the Smithsonian Institution's catalogue, nine per cent usually erupt for five years or more, but only six per cent of all eruptions last as long as that. In many ways it is harder to predict the end of an eruption than to predict the beginning.

Figure 18.2 Yasour, on the island of Tanna, in Vanuatu, has been in virtually continuous eruption since it was first reported by Captain Cook in 1774.

19—Just for good Measure

With tears and sobs he sorted out
Those of the largest size,
Holding his pocket handkerchief
Before his streaming eyes.

LEWIS CARROLL: The Walrus and the Carpenter

Eruptions are so diverse in nature and varied in their consequences that it is almost impossible to devise satisfactory definitions of size. A physicist studying the thermodynamics of the process will point out, quite irrelevantly, that a social scientist's comparisons of deaths and casualties bear no relationship to the energies involved; yet both kinds of comparison are needed. The only proper response to the question "Which was the biggest?" is the further question "What do you want to know for?" Even when measures have been agreed on and observations made, more than one interpretation of the resulting statistics may be possible. Few of the many standards that have been proposed are free from logical inconsistencies, many misuse the basic concepts of physics, and all are, in the nature of things, difficult to apply. The prospect of approximate answers, however, should be no obstacle to proper definition of the aims.

Dr G.P.L.Walker, lately at the University of Hawaii, has made a valiant attempt to sort out the existing confusions. He distinguished five kinds of "bigness": magnitude, intensity, dispersive power, violence, and destructive potential, and noted that the term "explosive violence" has been applied to each and every one of these, separately, or in loose and variable combination. Only magnitude, intensity, and possibly violence, relate directly to independent physical factors involved in an eruption, and even these are not readily susceptible to measurement.

The use of the terms magnitude and intensity in the closely related science of seismology has become familiar to every newspaper-reader, even if the distinction between them is not always properly understood, and it is unfortunate that the volcanologist has chosen to use the words in very different and less precise ways. Geophysicists instinctively ask for measures of energy, and the scale of earthquake magnitudes devised by Professor C.F. Richter and based on instrumental recordings is closely related to the total energy released. In an earthquake almost all of the energy takes the form of elastic waves, but in a volcanic eruption many forms of energy are involved. Izumi Yokoyama and Peter Hedervari list: the kinetic energy of the ejected material, the potential energy of the rising column of magma, the thermal energy of hot lava and gases, the energy of associated earthquakes, tsunamis, and air-waves, and the energy involved in fracturing or deforming the Earth's crust. Even if it were possible to measure each of these separately, a simple total would not give a true measure, as some of them are successive transformations of the same energy in the course of a continuing eruption.

Whatever its final form, the energy of an eruption starts off as heat, probably the most difficult form to measure. It is therefore usual to select one or more things that can be measured and to consider, in the light of experience, what proportion of the total it is likely to represent. Hedervari's formula involves the volume of the ejecta, their density, their temperature, their specific heat, and the latent heat of the lava. (Specific heat is the quantity of heat needed to raise the temperature of a standard mass of a substance 1^{o}C, and latent heat was explained in Chapter 9). From all of this it is hoped to derive an estimate of the total energy.

Most of us have instinctive ideas of the meaning of basic physical quantities like force, and work, and energy, and power; but it will do no harm to look at them formally, particularly as the scientific world has recently decided to measure them in units whose names are as yet unfamiliar. The definitions of these concepts in most cases go back to Isaac Newton, who laid down three laws of motion that are still the basis of mechanics.

The first of these laws states that things either stay put or go on moving in a straight line unless a force is applied to them. If you apply a force, you will make them change speed or direction. Either kind of change is called an acceleration. Forces are measured by the acceleration they produce in a body of known mass, and the units of force are called newtons. A force of one newton applied to a mass of one kilogram will give it an acceleration of one metre per second per second. (Two "per seconds" are needed. Acceleration is a rate of change of speed.)

When a force moves something it does work, which is measured in joules. (Joule was an English physicist who worked in the middle of last century, and did for heat what Newton did for mechanics.) When a force of one newton moves something a distance of one metre, the work that has been done is one joule. Energy, which is just the ability to do work, is also measured in joules; but no work is done until something moves. The knights of old who unsuccessfully strained and sweated to withdraw the sword Excalibur from the rock did no work at all, but Arthur's almost effortless performance entailed at least a little work. Energy takes various forms – mechanical, thermal, or electrical, for instance – and Joule's best-known work was his measurement of the mechanical equivalent of heat, that is, how much heat was produced by a given amount of mechanical work. Since volcanoes expend their energy in so many different ways, all of this is very relevant to volcanological measurements.

The rate of supplying energy or doing work is called power, and its units are joules per second, also called watts. Watts probably suggest electricity, but can equally be used to measure other kinds of power. Your electric power-board is of course interested in the total amount of energy it supplies you with, and the "unit" charged for on your bill is the kilowatt-hour, a thousand watts supplied for an hour, 3.6 million joules. Obviously joules are on the small size for engineering use, and power-station engineers tend to favour megajoules (millions of joules) or even gigajoules – the first g, by the way, should be pronounced as in giant, not hard as in giggle, which sounds derisory.

The energies of large eruptions range from about 10^{15} to 10^{20} joules. The Laki and Tambora eruptions are considered to fall a little below this upper value, and prehistoric Santorin probably just about reached it. The figure currently assigned to Krakatoa is 10^{18} joules.

One of the most commonly used indexes of "magnitude" is the quantity of material thrown out. Its volume has sometimes been established by careful geological field-work, but is more often estimated from reports of the thickness and extent of an ash-fall, or from descriptions of lava-flows. The amounts can range from the cubic metre of so of lava extruded from a bore-hole at Krafla in 1977 to many thousand cubic kilometres. Proper allowance has to be made for holes and bubbles, and the uncertainty of the results is very large (Figure 19.1).

Professor H. Tsuya has proposed that the results of the calculations for historical eruptions be grouped in logarithmically increasing categories from 0 to IX. He assigned Tambora a IX, Krakatoa an VIII, and the 1950 eruption of Oshima a V. Several writers have described Tsuya's categories as "intensities", and many (including Walker) use the words "volume" and "energy" as if they were interchangeable, with a corresponding confusion of the units they assign to both magnitude and intensity.

There is no volcanological equivalent to the seismologist's "intensity", which categorises the degree of shaking at some specified point; but it seems in accord with normal English usage to apply the word to the rate at which material is discharged during an eruption. It is thus equivalent to power. In large eruptions material has been ejected at rates as high as 10,000 cubic metres per second, but there is no way we can easily relate this to watts, and if we are wise we shall be content to classify eruptions as of low, moderate, or high intensity. Published numbers described as intensities usually prove to refer to something else. If numbers are simple counts of something it should be made clear of what. Other measurements should state what units are being used, or specify the scale on which they are steps.

Dispersive power is not a measure of power, but of the area over which ejecta are strewn, and can provide useful comparisons between eruptions of the same type – but it is little use trying to compare the flow of basalt from an extended fissure with a shower of ash from a narrow vent. For that kind of comparison, measures of energy are essential. In some discussions the height of the erupting column is used to provide information roughly comparable with that given by dispersive power. Attempts to reach a better definition have been based on the area covered by some definite thickness of deposit, but the intensity of the eruption, the degree of fragmentation of the material, and the strength of the prevailing winds all greatly influence the distance to which ejecta will travel.

So far as violence can be defined in physical terms, it is equivalent to the momentum of the ejecta. The momentum of a body is the product of its mass and its velocity, and will clearly be great in a nuée ardente

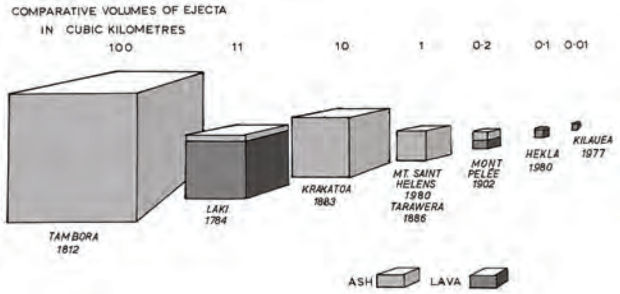


Figure 19.1 Comparison of ejecta in some historical eruptions, based upon data in the Smithsonian catalogue "Volcanoes of the World". The relative proportions of ash and lava are indicated by shading.

or a shower of large lava bombs, and small in the extrusion of viscous lava. What is not clear is how such a quantity could be measured in practice.

A. Rittmann's index of explosiveness (E), which is the ratio of the amount of fragmented material to the total amount erupted, is obviously related to this view of an eruption. Thus, if everything that comes out is ash or pumice, the index is 100, and if it is all lava the index is 0. Rittmann used it to compare whole regions rather than individual volcanoes or eruptions, and found that in island arcs E was usually about 90 to 95, though it rose as high as 99 in parts of Indonesia. High values were also to be found in Central America and the Andes, and may be considered characteristic of subduction zones. For oceanic volcanoes the typical value was about 16, dropping to as low as 3 for a few that produced only quiet effusions of basalt.

Destructive potential, the last of Walker's categories, is intended to quantify the fate of buildings, farmland, and vegetation, and like dispersive power is expressed in terms of the size of the area affected. The values quoted vary from less than a square kilometre to 30,000 sq. km, and include both actual and "potential" devastation. Apart from the dubious propriety of including potential happenings, the concept seems unable to accommodate the varied demands of ash-showers, pyroclastic flows, lahars, tsunamis, and so on.

The Smithsonian Institution's catalogue Volcanoes of the World, faced with the problem of comparing thousands of eruptions, past and present, has chosen to use the Volcanic Explosivity Index (VEI) originally devised by C. Newhall and S. Self. This is based on a kind of integrated appraisal of all the available information. It includes the total volume of ejecta, the height of the eruptive cloud, the duration, qualitative descriptions, and a consideration of the type of eruption. A somewhat questionable correlation with Tsuya's classification forms part of the scheme.

The index does not correlate with either energy or power output, and is likely to be of most use in comparing eruptions of a single volcano. The scale is logarithmic and runs from 0 to 8, but only Tambora has scored as high as 7. As might be expected, small eruptions are more common than big ones. Of the 4,815 examples assigned an index, 3,108 are given a 2. Any attempt to draw statistical conclusions is hampered by the enormous variations in the length of the historical record and the state of geological exploration from country to country. Subjectively assigned weights intended to allow for this are included in the published values. Because of the detailed studies of its ignimbrites, New Zealand accounts for a quarter of the eruptions with an index of 5 or more, of which there are only 53, from 38 different volcanoes. There are 100 volcanoes whose eruptions have reached 4, Iceland's Hekla heading the list with 10 major eruptions.

If this attempt to answer a straightforward enquiry proves bewildering, we are not surprised. The one physical factor involved in every eruption is energy, but there is no way in which the total energy of a particular eruption can be directly measured, and none of the diverse and complicated manifestations accessible to measurement bears any constant relation to it. There are some tables in the Appendix that may at least aid the understanding, but the list of proposed measures and comparisons is by no means exhausted. You shall be spared the explanation of scales based on the duration of darkness at different distances, and on the readings of microbarographs, and from attempts to compare the fury of volcanoes with that of hydrogen bombs. Should you wish to pursue that matter, it might help to know that a megaton bomb releases an energy of 4.2×10^{15} joules.

The simplest attempts to use the lists and catalogues based on these measurements for assessing risks to lives and property reveal that the consequences of an eruption depend overwhelmingly upon accidents of location and of history, and the consequent density of population. There have been very few deaths in Kamchatka and the Kuriles, and leaving aside Alaska, where there have been three, there were none in the continental United States until the eruption of Mount St Helens in 1980. Estimates of the level of activity based on the size of the region and the frequency and duration of its eruptions suggest that the world's most active areas are to be found in Halmahera, the Sicilian arc, and New Zealand, none of which figure in the lists of regions with many casualties.

Differences in the numbers of deaths attributed to the same eruption are often due to different ideas about what should be included in the count. Most lists of volcanic casualties are headed by the 92,000 who died in the 1815 eruption of Tambora, yet 90 per cent of those died from starvation. So did 70 per cent of the 9,350 whose deaths are attributed to the Laki eruption in 1783. Tsunamis accounted for 90 per cent of the deaths from Krakatoa, and 30 per cent of those at Unzen in Japan in 1792. Mont Pelée, where all but a few score of the 29,000 deaths in 1902 were the result of a single nuée ardente, is an unusually uncomplicated situation, though the 1985 eruption of Nevado del Ruiz in which lahars killed over 25,000 people may prove equally straightforward. Since A.D. 1600 about 170 eruptions have caused deaths. In each of the six just discussed the number exceeded 8,000, and these account for over three quarters of the total.

Dr R.J. Blong of Macquarie University, Sydney, who has presented and analysed many statistics of this kind, stresses that the relative importance of the different kinds of volcanic hazard has changed markedly during the present century. Disease and starvation, which account for 40 per cent of the deaths since 1600, now account for only 6 per cent, which may be attributed to better communications and relief measures. The reduction in tsunami deaths from 19 per cent to less than 1 per cent is unlikely to reflect much more than the distance of the most recent large eruptions from the sea. On the other hand, pyroclastic flows and debris avalanches, formerly only 23 per cent of the total, now account for 70 per cent. This change largely reflects the Mont Pelée eruption. Disregarding that event and the effects of starvation and disease, Blong concludes that at the present time pyroclastic flows can be expected to cause 43 per cent of the deaths, lahars 36 per cent, and falling ash and heavier projectiles 17 per cent. Other hazards, which include gases and acid rains, associated earthquakes, and a range of atmospheric effects, contribute only 0.15 per cent to the total. Regional statistics show Indonesia, the Caribbean, and Japan to be the most dangerous places.

Figures like these must be treated with great caution. They depend critically upon a few large eruptions, on their distribution with respect to centres of population, and on whether there were tsunamis and lahars, and so on. Even in places with a long historical record there have been only a few major disasters. In few sciences are “average” or “typical” values likely to prove so dangerously misleading as in volcanology.

20—Divers Dangers

Wherein I spake of most disastrous chances,
Of moving accidents by flood and field,
Of hair-breadth 'scapes i'the imminent deadly breach……..

WILLIAM SHAKESPEAR: Othello

In spite of the problems in obtaining and interpreting the statistics, most authorities agree that in the last five hundred years between 200 and 250 thousand people have died because of some five hundred erupting volcanoes. The variety of ways in which they can kill or injure humans and animals, and damage or destroy vegetation, crops, and buildings is astonishing. Only five eruptions account for three quarters of the deaths, and in each case the primary cause was different. Pyroclastic flows, lahars, and falls of ash and bombs dominate the figures, but tsunamis, which the statisticians have chosen to regard as a secondary cause, account for similar numbers, and although there are no historical instances of people being engulfed in an eruption of ignimbrite, it is potentially the greatest of volcanic hazards.

Tsunamis are the destructive sea-waves popularly called "tidal waves", a name that oceanographers reject on the reasonable grounds that they have nothing to do with tides. Seismologists have had little success in popularising the term seismic sea-wave, and the Japanese word tsunami is now current in English. We have adopted "tsunamis" as the plural, but in Japanese "tsunami" is both singular and plural. It means something like "harbour wave", but its exact origin is lost in the past. Tsunamis started by volcanic events are less well known than the more frequent ones that follow large submarine earthquakes, but they are no less damaging, and the behaviour of the wave is identical in both cases (Figure 20.1).

Figure 20.1 Part of Shimabara town in front of the remains of the Mayuyama Dome of Mt Unzen. During a 1792 eruption from Fugen-dake (the peak in the left distance), either volcanic deformation or earthquakes resulted in a partial collapse of the Mayuyama Dome, causing a tsumani which produced widespread damage. The total death toll from the landslide and tsunami was over 10,000.

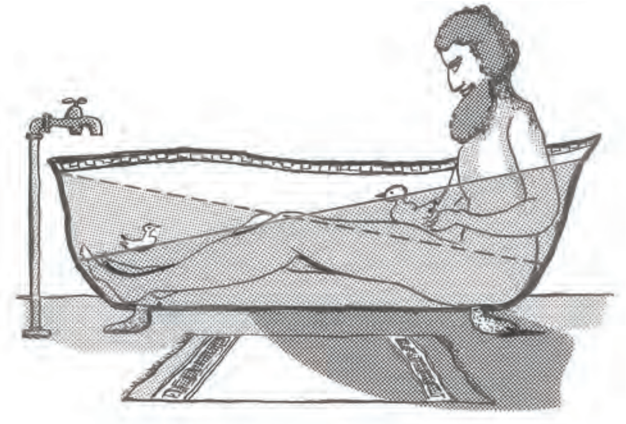


Figure 20.2 Seiche movement, an experiment in the Archimedian tradition.

Physically, they are gravity-waves, the force that tries to restore the displaced water to its original position being gravity. The speed of a gravity-wave depends upon the square-root of the depth, and tsunamis travel across the deep ocean basins at more than 600 km per hour. Their wave-length is very great, often several hundred kilometres, so that ships in the open ocean are as little aware of them as they are of the tides; but when they approach a coast and the water shallows, the front of the wave is slowed down rapidly. The water behind piles up, and breaks into a turbulent surge that rushes inland. A tsunami confined in a bay or an estuary can attain a height of tens of metres in this way, and it has been suggested that the concentration of damage in such places accounts for the name. Once a tsunami has been started it can travel great distances to places unaware of the disturbance that set it going. Tsunamis from Chilean earthquakes have caused damage in Samoa and Hawaii, and have reached Japan and New Zealand.

If a tsunami passes along a coast that has large harbours or inlets with narrow entrances, it can set the enclosed water into oscillation, and perhaps produce more serious damage to vulnerable towns and port facilities than the tsunami itself would have done. Oscillations of this kind are called seiches, a word from the French-speaking cantons of Switzerland. A little cautious experimentation next bath-night will explain the behaviour of seiches (Figure 20.2). It is easy to persuade the water to pile up at one end of the bath and then at the other, alternately covering and uncovering your toes. The movement takes place at a definite speed that depends upon how big the bath is and how full. More water and bigger baths mean slower speeds, but greater risk of experimental disaster. Once the movement has started, little effort is needed to make it bigger.

The Swiss lakes are usually set in motion by wind, but large distant earthquakes can also start a seiche. Wind-generated seiches are often observed on New Zealand's Lake Wakatipu, and less frequently on Lake Taupo. To someone on the lake-shore the effect is like a tide that rises about half a metre in ten minutes or so, and then ebbs for the next ten. There is no wave travelling along the lake, which has "tides" at both ends, but none in the middle. In general, movement of water in lakes and small expanses of water are more likely to be seiches than tsunamis, if only because a tsunami needs room to organise itself.

Earthquake tsunamis are usually the result of faulting or other sudden displacements of the sea bottom. Volcanic ones have a variety of causes, but the earthquakes that accompany eruptions account for nearly a quarter of them. Nuées ardentes and other pyroclastic flows, and submarine eruptions account for another quarter, but most of these are small. Lahars and massive landslides also cause a significant number, and about ten per cent are due to collapsing calderas.

Once again, a few large events dominate the statistics. The tsunamis that occurred at the climax of the Krakatoa eruption in 1883 (Chapter 39) caused more than 34,000 deaths, while only 2,000 were due to ash-fall. Neumann van Padang has put the total death-roll at Tambora in 1815 at 92,000, but fully ninety per cent of these were later deaths from starvation. Of the 10,000 who died at the time of the eruption, perhaps half were killed by the tsunami. The tsunami at

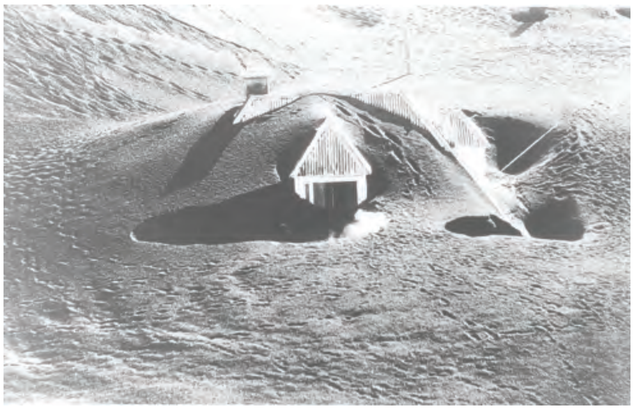


Figure 20.3 House in Heimaey buried by ash, many such houses were afterwards successfully excavated and restored.

Figure 20.4 Buried house, Heimaey.

Unzen in 1792 was generated by a massive landslide from the slopes of the volcano. The best modern estimate suggests that there were 4,300 deaths, but a contemporary record puts the number as low as 707. This probably reflects the chronicler's view of which people were worth counting.

The Krakatoa statistics are less biased, but similar social attitudes are reflected in the fact that more detail was recorded about the 37 Dutchmen who died than about the 35,000 Javanese and Sumatrans and the 726 Chinese who also perished. It has been claimed that the tsunami generated in 1888 by the collapse of the Ritter Island caldera, in the Bismarck Sea west of New Britain, killed more people than any other volcanic tsunami in historic times. The wave reached heights of up to 10 metres, and swept along the New Guinea coast destroying villages and forest, and there was similar damage on many small islands, but the area is not so densely populated as Java. The only believable estimate of fatalities is the one that merely says "many", and it seems likely that Krakatoa holds the melancholy record.

Details of the effects of lahars and pyroclastic flows are given in other chapters, but more must be said about tephra. Most of those killed or injured by falling bombs and other large pyroclastic fragments have been volcanologists or photographers, who should perhaps regard these projectiles as an occupational hazard. Protective clothing is usually worn, and almost any kind of head protection from a pillow to a safety-helmet will keep off the smaller and lighter stones; but not even full armour is proof against large missiles, and injuries have not been confined to the head. Haroun Tazieff, observing an eruption of Nyiragongo, was apparently able to watch the flight of incandescent bombs and to side-step when necessary. The first party to visit Surtsey used the same evasive method, but had to keep it up for three hours before the volcano desisted. For non-professionals the best precaution is to keep well away – though an unfortunate Icelander 15 kilometres from Hekla was killed by a falling "stone".

Ash-falls are more often frightening and inconvenient than fatal. People seem to succeed in finding shelter, and unless poisonous gases are present the ill-effects are usually temporary. Skins become itchy, eyes are irritated, and fine dust works its way to the back of contact lenses, to the discomfort of the eye and the detriment of the lens. Small children and asthma sufferers are often badly affected. After the Mount St Helens eruption in 1980 cases of chronic bronchitis and of silicosis, the classical miner's disease that results from inhaling quartz dust, were reported; but doctors treating the victims considered that some of the bronchitis and asthma symptoms were psychosomatic.

The worst casualties and almost all the deaths from ash occur when roofs can no longer bear the increasing load, and collapse on those sheltering underneath (Figure 20.3). A curious sidelight is the number of elderly people who survive long burial. During the 1906 eruption of Vesuvius an 80 year old man was rescued after five days. Tuhoto, the Māori who had been trapped for three days during the Tarawera eruption in 1886, was reputed to be 104. He was also reputed to be a wizard.

There are many fictional tales of people overwhelmed by lava (Figure 20.4), but although lava is very destructive of property there are few authenticated instances of deaths, even when the advance of the lava has been abnormally swift. The Nyiragongo eruption of 10 January 1977 is an exception (see Section 8). Most victims have been old, or very young, or curious, and have found their retreat cut off. A more serious hazard exists when lava comes into contact with water or ice, and causes dangerous steam explosions and scaldings. It remains true that in all but an insignificant number of cases, people can avoid lava-flows.

Figure 20.5 Volcanologists donning gas masks before taking measurements in White Island crater, New Zealand.

Figure 20.6 Lake Nyos, Cameroon. In 1986 a sudden emission of carbon dioxide gas killed 1700 people, and swept an 25-metre high wave over the promontory on the left.

Given the spectacular displays of lightning in Plinian and Vulcanian eruptions, it is surprising how few deaths have been attributed to lightning strikes, though there are reports of people holding telephones and metal tools receiving electric shocks. It is more likely that deaths of this kind have been attributed to other causes than that there were none. There is a doubtful report of men and beasts on Vesuvius being killed in 1631, and a report of the Philippines Volcanological Commission allots an unstated proportion of the 1,200 deaths during the eruption of Mayon in 1814 to electrical discharges. When lightning struck the First Point lighthouse during the 1883 eruption of Krakatoa, four chained convicts are said to have been burned "underneath their iron rings:".

Figure 20.7 Ground deformation preceding an eruption of Mount Usu destroyed this building at Toya, Hokkaido.

The killing-powers of explosions, showers of bombs and ash, nuées ardentes, lahars, and tsunamis are so immediately obvious that less spectacular hazards like the steady emission of gases from hot springs and solfataras are easily overlooked. Water-vapour is by far the most abundant gas given off by volcanoes, but carbon dioxide, sulphur dioxide and trioxide, carbon monoxide, hydrogen sulphide, and sulphuric, hydrochloric, and hydrofluoric acids are also emitted. In sufficient concentration all of them can kill, and all of them are heavier than air (Figure 20.5).

Any excavation in geothermal ground is a potential source of danger, and natural hollows and depressions can become death-traps. Hot springs encourage the construction of swimming-pools, but if they are to be safe they must be designed so that the water-surface cannot fall below the level of the surround. If it does, the pool becomes a very efficient collector of gas. Few New Zealand houses have cellars, but spaces underneath floors have to be ventilated. Until recently, Rotorua Hospital regularly had to deal with gassings, and several each year proved fatal. Public education and enforced precautions have now greatly reduced the hazard.

Hydrogen sulphide, carbon monoxide, and carbon dioxide are probably the most lethal gases. The two last are colourless and odourless, but the strong smell of "rotten eggs" from hydrogen sulphide is not an effective warning. Small concentrations pervade the thermal areas, and one soon becomes unaware of it. When the temperature of the gas coming from a fumarole is below the boiling-point of water, it is usually rich in carbon dioxide, and fumaroles of this kind are called mofettes (Italian mofeta, a noxious exhalation). Pools of carbon dioxide tend to lie in hollows, and can be very treacherous to small animals. In Iceland, during the 1947 eruption of Hekla, sheep died in hollows through which men had passed in safety. At Eldfell in 1973, the only human death was due to the accumulation of carbon dioxide in a cellar. At Dieng in Java, in 1979, 142 people were killed by a sudden emission of carbon dioxide from a fissure. Ponding seems to have been responsible, but reports of what happened conflict in major respects.

A still more calamitous emission of volcanic gas occurred in West Africa in 1986, killing 1,700 villagers and more than 3,000 cattle. The source of the outbreak was lake Nyos (Figure 20.6), one of a line of about thirty crater-lakes extending north-eastwards from Mount Cameroon. The waters of the lake contain much dissolved carbon dioxide, but neither the origin of the gas nor its sudden release has been adequately explained. The overturning of stratified layers in the 200-metre deep lake and a consequent release of pressure has been attributed either to a phreatic explosion in a feeder-pipe beneath the lake, or to triggering by some external cause such as a landslide or abnormal rainfall. Dead cattle indicate that the lethal cloud was some 50 metres thick, and travelled down a valley for 15 kilometres. After the gas was released the water-level fell by more than a metre. Similar conditions exist in some of the other lakes, and there are traditions of similar events in the past. Two years earlier an outbreak from Lake Monoum, 100 kilometres to the south, killed 37 people, and was apparently acid enough to remove an outer layer of skin.

Prevailing winds can carry gases and fine ash a long way without greatly dispersing them. In Nicaragua, recurrent discharges of steam and gas from Masaya have caused millions of dollars worth of damage to coffee plantations. About 150 sq. km in a strip 8 km wide, down-wind of the volcano are affected. In the 1920s, German engineers attempted to provide it with a chimney, but some of the plantations are at a greater height than the volcano's 700 metres, and the venture proved a costly failure. Subsequent use of bombs and explosives to block the vent has been only a temporary and partial success. Corn and other crops as well as coffee have been affected, and fences, telephone wires, and metal farm equipment have become severely corroded.

Damage of this kind is not always due to direct contact with the gases. Most of them are readily soluble, and if an eruption-cloud passes into a region where rain is about to fall, the drops can become dilute solutions of a range of acids. These acid rains can fall hundreds of kilometres from the volcano, and for weeks after the eruption responsible. Rains after the Katmai eruption in Alaska in 1912 blistered skins in Seward and Cordova, hundreds of kilometres away, and washing hung out to dry in Kodiak was reduced to yellow shreds. Within a month the fumes had travelled 2,400 km to Vancouver, where more washing perished in the acid rain.

Mists and light rains are often more serious than heavy falls, which dilute the acids. Electrical fittings and metals of all kinds become seriously corroded, and zinc is dissolved from galvanised roofs, to pollute and poison water-supplies. Not all acid rains can be blamed on volcanoes. Industrial fumes are an equally serious hazard, and have done great damage to the forests of Germany and other countries in Europe.

Although the earthquakes that accompany volcanic eruptions do not approach the magnitude of the largest tectonic shocks, they can reach damaging intensities close to the volcano, and may be quite numerous. As a result, slight damage can be cumulatively increased to the point of collapse. Many volcanoes are surrounded by old lahar debris and deposits of ash that are poorly consolidated, so that the proportion of structures on bad foundations may be high.

Earthquake damage is more often due to shaking than directly to faulting and other forms of ground deformation, but these are nevertheless important, and more common and extensive in shallow volcanic shocks than in normal tectonic ones. Magmatic intrusions often produce gross earth-deformations, not necessarily accompanied by earthquakes. During the eruptions of Usu in southern Hokkaido in 1944 and to an even greater extent in 1977, substantial ferro-concrete buildings were seriously damaged in this way. They included a hospital, hotels, and apartment blocks. Fortunately the movements are slow, and the occupants were easily evacuated (Figure 20.7).

The files of the Geological Survey office in Rotorua contain a record of the problems of living on top of a hydrothermal field. Geysers have appeared in unlikely and inconvenient places; puddles have come to the boil; holes have appeared in the main streets without warning; and steam has disconcertingly burst from beneath tombstones and deposited sulphur. A respected senior volcanologist whom it would be most improper to doubt tells of the sudden appearance of a geyser in a marquee where a wedding breakfast was being held. It arose from beneath the table, and synchronised its appearance with the moment when the bride cut the cake.

An even more spectacular event is recorded in the New Zealand Geological Society's guidebook. Steam explosions formed two craters in a suburban garden near Rotorua. They decided to mate and become one, and celebrated their union by swallowing an intervening pump. Finding the pump to their taste, they went on to devour a shed with a bicycle and trailer inside before attacking the verandah of the next-door house.

Most disturbances like this are not unprovoked, but begin in abandoned or neglected bores. When the steel casing corrodes and bursts there is a sudden and dangerous uprush of superheated water. Explosions like this have sometimes been the first sign that a house has been built over an old bore, and builders excavating foundations have more than once unwittingly disturbed them.

Among the miscellaneous causes of death in which volcanoes play a part are suicide, murder, and ritual sacrifice. Suicides are most common, though none so spectacular as the 10-km leap from the balcony of a palace in Naples into the crater of an erupting Vesuvius that Daniel Auber expects from the heroine of his opera "Masaniello". In the 1930s the crater of Mihara claimed some 200 victims a year, but the number has since fallen sharply.

Violence resulting in death has occurred not only among fugitives competing for places in boats and transport as at Taal Lake, but in bitter disputes between displaced people, as at Paricutin. Lest it be thought that the idea of propitiating malevolent powers by human sacrifice is confined to remote times and primitive peoples, it should be recorded that in 1980 someone in Cleveland telephoned the sheriff of Cowlitz County with an offer to provide a virgin for sacrifice to Mount St Helens.

21—Warnings and Prognostications

…prophesying with accents terrible
Of dire combustion and confus'd events
New hatch'd to be the woeful time

WILLIAM SHAKESPEAR: Macbeth

At the foot of Mount Tarawera lies a lake that bears its name, and across the lake lies the village of Te Wairoa. In 1886 it had two hotels, an abandoned water-mill, a store, a bakery, a blacksmith, a school, and even a Temperance Hall, a scatter of well-kept European houses and native huts, and a pretty wooden Gothic church with a steep tiled roof and a stained-glass window. Te Wairoa was known to every tourist who visited New Zealand's thermal regions, for it was the starting point for excursions by whaleboat or canoe to the famous Pink and White Terraces described in Chapter 14.

On the morning of May 31 a party of nine visitors, including an Australian doctor and a priest from Auckland, went with a party of rowers, three Māori women, and the well-known Guides Sophia and Kate to the creek where the boats were moored. To their surprise they found it dry, but as they watched the water returned, raising a wave 20 or 30 centimetres high. The rowers became unhappy, but they stood to collect several guineas a head from the tourists, and Sophia insisted that they go on. Together with a second boat, containing Guide Kate and three of the visitors they set off into the clearing mists. Off Kariri Point a third craft appeared. It was a large war-canoe, with a carved prow and tall stern-post, and held a row of standing passengers. The wet paddles gleamed in the veiled light of the rising sun. The tourists were delighted, and Father Kelliher produced a sketch. So did Josiah Martin in the second boat. Then, everyone agreed, the canoe seemed to vanish. The Māoris became alarmed. Were not the heads of the standing warriors bowed, and their hair decked with feathers of the huia and the white heron, emblems of death? The return was made safely, but Tuhoto, a local wizard reputed to be 104 years old, had no doubts about it. It was a waka wairua, a death canoe, and many people would die. Certainly the tribe had no such canoe. Before the week had passed, the story is reported to have reached Dunedin, and just after midnight on June 10, Tarawera erupted. It was the greatest

Figure 21.1 Tarawera Chasm, produced in the eruption of 10 June 1886.

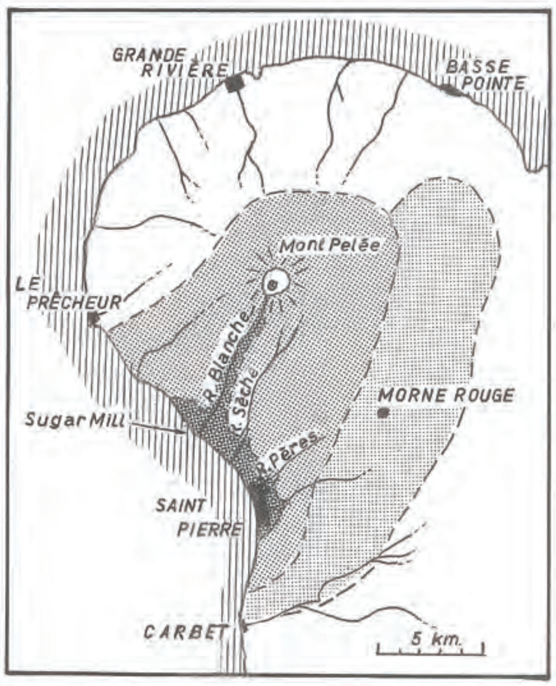


Figure 21.2 Map of Mont Pelée and St Pierre, Martinique.

New Zealand eruption in historic times (Figure 21.1).

After the appearance of the phantom canoe, other tourist parties visited the area, but Guide Sophia, an educated and observant woman, was sure that things were not normal. There was a storm-cloud over Tarawera. The lake-level was up. Formerly temperate pools had become uncomfortably hot, and the geyser Whatapoho ("pain in the stomach") seemed from its groans to be in more agony than usual. Springs and fumaroles that had been quiet for years were again active. She persuaded her tourist charges to forego their usual bathe at the Pink Terraces, and voiced her fears to Joseph McRae, owner of the Rotomahana Hotel. He made his displeasure clear. Māori superstition was unwelcome.

There was no shortage of omens before the eruption. A few hours before it, the Moon passed in front of the planet Mars, and the schoolmaster and a party of surveyors working near Te Wairoa stayed up to watch it. Soon after midnight there were earthquakes – not at first strong enough to waken the sounder sleepers; but the shocks seemed to be getting stronger, and McRae decided to rouse the rest of his guests. From the hotel, Tarawera was hidden by a hill. He climbed the road to the church, and found the mountain in full eruption.

However much of the canoe story is fact and not legend, it is certain that neither phantom canoes nor planetary occultations are common precursors of eruptions, but there are usually signs of some kind. Not every volcanologist would perhaps go so far as the Soviet Professor G.S. Gorshkov in saying that "Nearly every eruption or increase in volcanic activity is preceded by a swarm of earthquakes" and that "One can say quite definitely now that no eruption (no fairly large one, at any rate) should come as a surprise in those volcanic regions where there is constant seismological surveillance". Certainly some phreatic eruptions, like that of Ruapehu in 1975, have had no significant seismic precursors, and it is easy to think of reasons why there should be none.

Saint Pierre, on the island of Martinique, was the largest city in the Lesser Antilles, the island arc that divides the Caribbean from the Atlantic. All the islands of the arc are volcanic, and five of the volcanoes – Mont Pelée and La Soufrière on nearby Saint Vincent, Mont Serra, Soufrière Guadeloupe, and the submarine volcano Kick-'em-Jenny – are clearly active. In 1902 Pelée had two craters, an upper one containing the Étang des Palmistes (the pond with the cabbage trees), a popular picnic-spot, and a lower one whose lake had become the Étang Sec (the dry pond) after an ash eruption in 1851.

In May 1901 a small steam-jet appeared by the lake, smelling of sulphur and killing vegetation; but the first hint of serious eruption did not appear until late in March of the following year, when it was noticed that cracks in the floor of the Étang Sec were emitting vapours. A few days later Professor Landes, a science teacher from the lycée in Saint Pierre, went to investigate. On April 2 he found more new fumaroles at the head of the Rivière Blanche, a seasonal stream that ran down a gully from the upper slopes of Pelée to reach the sea about 2 km north of the town (Figure 21.2).

By the end of the month, there was no doubt that the volcano was erupting. Explosions in the basin of the Étang Sec were sending rocks and clouds of ash into the air, and earthquakes threw things from shelves. Visitors reported that a mount ten metres high had appeared at the edge of the crater, which was no longer dry, but contained a lake 200 metres wide. By April 27 the falls of ash in Saint Pierre had caused businesses to close, and had even blocked roads. Birds and animals had been killed, and an excursion to the mountain planned for May 4 was cancelled. Many people left the city, but others saw it as a refuge, and the population swelled from the normal 26,000 to about 30,000.

Official action seemed necessary, and the Governor made the conventional responses. He and his wife moved to Saint Pierre from Fort de France, 25 km to the south, hoping to prevent alarm; and he appointed a commission.

Torrents of rain had accompanied the showers of ash, and all the streams ran with muddy water, but vast quantities of debris remained in their upper reaches, and on May 5 there was a lahar. Mud and boulders swept down the Rivière Blanche, engulfing a sugar-mill near its mouth, burying forty people, and sending a wave along the coast that overturned a yacht, drowned the crew, and flooded the lower parts of the city. The mud was hot, and it seems likely that an eruption of some kind was involved, but geologists still argue whether the water came from the Étang Sec, or from ground-water along the path of the avalanche.

The disaster brought the city to a standstill, and people began to leave for Fort de France, and to board steamers for Saint Lucia. The Governor feared panic, and established military road-blocks. Reassuring editorials appeared in the newspaper Les Colonies, together with an ambiguous statement prepared by Professor Landes on behalf of the Commission. "The people of Saint Pierre," he said, "had no more to fear from Mont Pelée than the inhabitants of Naples had to fear from Vesuvius." Oddly enough, the peoples' chief fear seems to have been earthquake or tsunami rather than the erupting mountain, perhaps because it had become familiar, and many reacted by seeking higher ground. Les Colonies had other reasons for persuading people to remain in town. They were political. An election was due on May 10. If there was to be an earthquake, said the paper, they would be no better off in Fort de France. The idea that it was dangerous to stay in Saint Pierre was "a foolish error against which the populace should be warned".

On May 7 news arrived from St Vincent that La Soufrière, 150 km to the south, was also in eruption. In Saint Pierre it was considered reassuring. Now that there was a safety-valve, one could sleep soundly.

At ten to eight next morning there were four deafening reports from the crater, and the first of a series of nuées ardentes swept over the town. A hot choking cloud of incandescent ash forced its way between floor-boards and into shuttered rooms, leaving only two survivors and thirty thousand dead. Ships in the roadstead capsized, except for the Roddam, which escaped to St Lucia with 12 dead and 10 severely burned crew-members; and the Roraima which lost its mast, bridge, funnel, and boats. Two of the passengers and 19 of the crew of 47 survived. The rest died of shock and burns.

One lesson of the Saint Pierre disaster is that when a volcano starts erupting, people do not automatically move out of danger, and early measures to avoid panic may stop them from moving until too late. If a volcano has been displaying threatening behaviour on and off for years and lapsing into quiescence again without ill consequences, it is tempting to stay and enjoy the spectacle. Studies of the eruption of Mount St Helens in 1980 show that ordinary citizens have little more appreciation of volcanic risks now than they had in 1902.

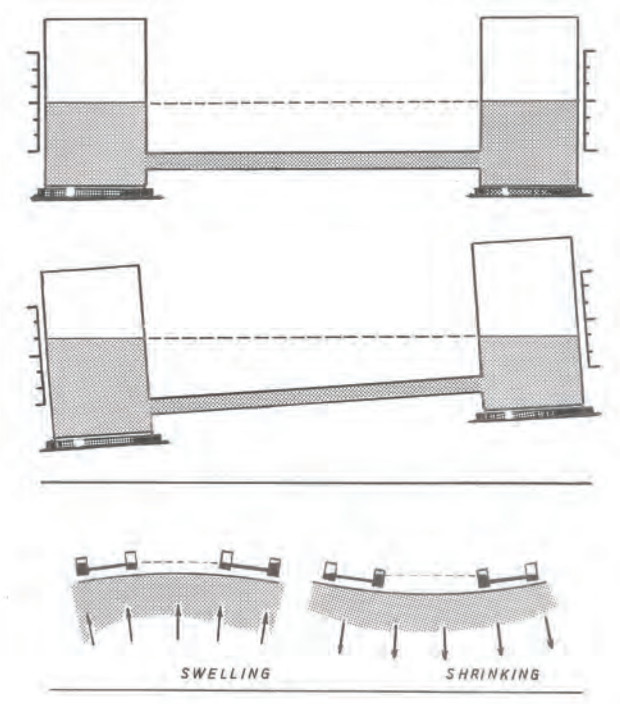


Figure 21.3 Water-tube tiltmeter.

Predictions are easily discredited by false alarms, and it must be clear to the general public whether announcements are preliminary warnings, general alerts, or urgent alarms demanding immediate action. It is better to make predictions in the form of forecasts of activity, and to state, if possible, the degree of probability that they carry. Awareness of cultural differences is essential. One community may greet danger with fatalism and another with panic. A third may react with violence and looting. Because of these differences, generalisations must be questioned, but several researchers have noted that while visitors to a district can easily be persuaded to leave, and often do so of their own accord, long-term residents and owners of property may have to be evacuated forcibly. They have also found that large-scale evacuations can produce more casualties than the dangers they were intended to avert.

An ideal volcanological forecast would specify the time, the place, the type, and the size of the eruption expected, and estimate how long it was likely to last – and it would appear in plenty of time for people to take appropriate counter-measures. Unfortunately eruptions cannot be predicted with the same certainty as solar eclipses. There are too many uncertain factors, and it is not often that the course of an eruption or the moment of climax can be accurately foreseen. Long after conditions have apparently returned to normal such hazards as lahars remain a persistent danger. If there is a catastrophic phase it is usually brief, and can come at any stage of the eruption.

Any one of the many phenomena we have described may provide the first indication that magma is on its way to the surface. It does not then follow that there will be an eruption, or that if there is, that it will issue from the most obvious vent, or follow the pattern of the most recent past eruptions. The activity may stop as unexpectedly as it began, and the volcanologist's preliminary warning be added to his score of failures by those he is working to protect.

Many volcanoes display the preliminary symptoms of activity almost continuously, and warnings of possible eruptions at unspecified future times add little to knowledge, and afford even less guide to action. As magma works its way upwards, however, the indications of its progress become clearer, and forecasts can be successively refined.

Quite a number of volcanoes have the useful habit of swelling perceptibly when magma is being injected from beneath, and deflating once more when the eruption is under way. Kilauea in Hawaii behaves like this, and although the movement is only a metre or so, it begins as long as two years before the eruption, and accelerates as the outburst gets nearer. Etna, Krafla, and several volcanoes in New Guinea perform in similar ways. The movements can be detected and measured by repeated surveys of a conventional kind, aided nowadays by radar distance-measurements, laser beams, and similar fashionable wonders. Much simpler tools will often do the job quite as well, and much more cheaply.

Figure 21.4 Recovering temperature telemetry buoy from Ruapehu Crater Lake.

One of the simplest schemes is to use tilt-meters, which take many ingenious forms, ranging from simple level-bubbles and drill-holes with puddles of mercury at the bottom, to sensitive pendulums with elaborate electronics to record their measurements. The problem with these otherwise elegant devices is that their small size makes it difficult to be sure that they are measuring movements of the mountain, and not just localised effects of soil-creep, temperature change, or the movement of ground-water. For this reason, many volcanologists prefer to use some form of water-tube tilt-meter (Figure 21.3).

In its simplest form it consists only of two vessels connected by a hose and containing water, and some means of reading the water-level at both ends. When it is tilted the water-level rises in one vessel and falls in the other. The further apart they are, the more sensitive is the device. The water-levels can be read periodically by an operator, or arranged to produce a continuous record. In one such instrument the vessel at each end contains a float that hangs from an electrical strain-gauge. The two gauges are connected in a bridge circuit that shows the amount of any differential movement on a chart recorder. When a volcano is swelling, its sides will tilt outwards, away from the crater.

There are even simpler ways of watching for bulges. When the volcano is near the coast, the creep of the tide over rocks and up wharf-piles may change, and differences show up on existing tide-gauges. It is also possible to find increases in the width of cracks on the sides of a swelling mountain. Icelanders drive a length of pipe into the ground on either side of the crack, and measure the changing distances with a ruler. An imminent eruption is usually signalled by a marked and growing increase in rate of growth of the bulge. At Mount St Helens in 1980, simple measurements of the width of cracks proved a highly effective way of following the course of the magma intrusion, and in forecasting subsequent eruptions.

Well-equipped volcano observatories often have a continuously-recording gravimeter to show changes in the Earth's attraction at that particular spot. The most obvious movement on the record is usually the twice daily rise and fall of the earth-tide. Although the solid Earth responds less readily than the oceans to the pulls of the Sun and the Moon, it is elastic enough to rise and fall by as much as 40 cm. Changes of height as large as this are quite easily detected, and so are the much smaller ones that accompany bulges and subsidences, or reflect the withdrawal of steam from a hydrothermal field. Used in conjunction with tilt and survey measurements, gravity readings allow the process of magma intrusion and the accompanying deformations of the ground to be followed in

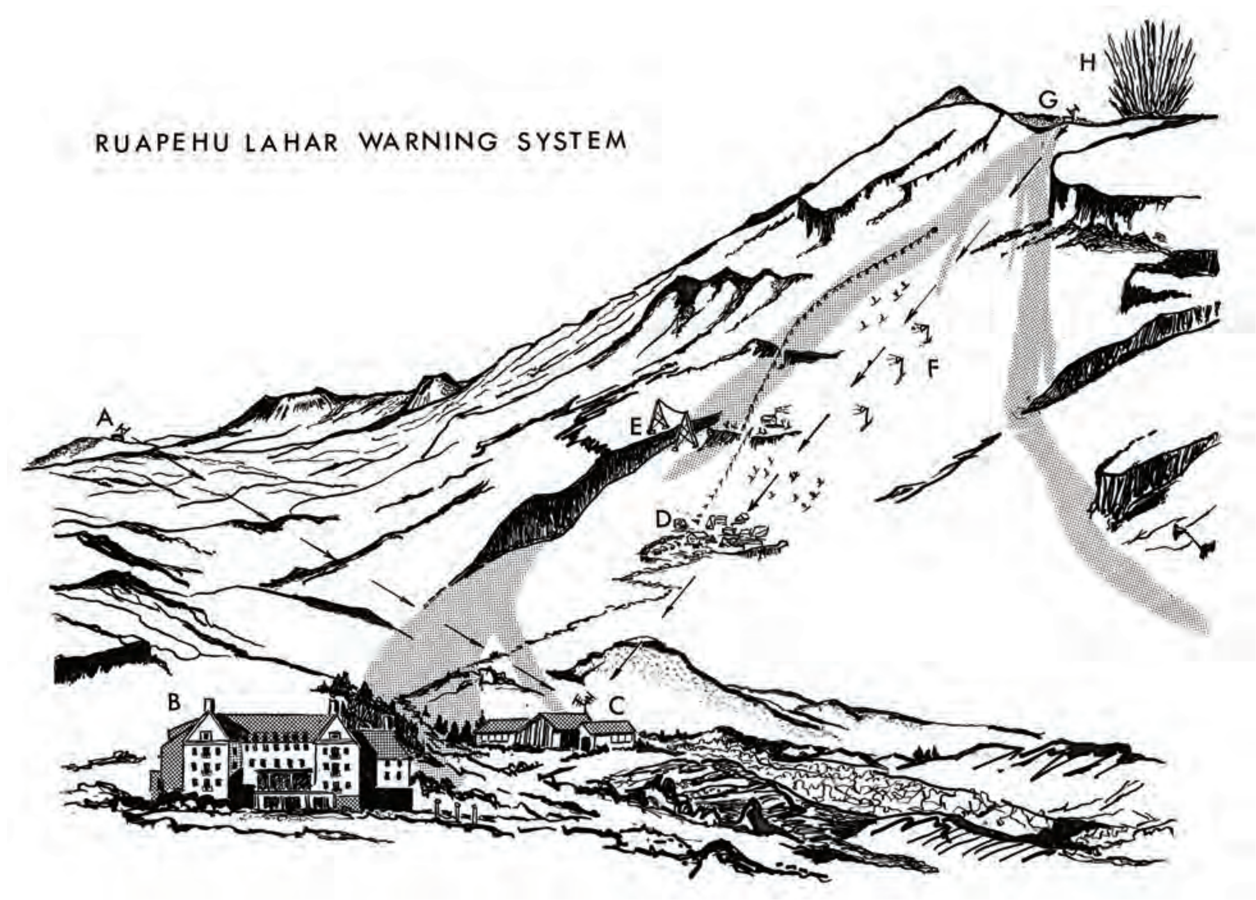


Figure 21.5 The lahar-warning system on Mount Ruapehu. A – Remote seismometer at Maungaku, 30 km from the crater. B – Chateau Tongariro. C – Park Headquarters, where signals from the Dome seismometer at G are automatically compared and evaluated by computer. If danger is indicated, recorded warnings are broadcast to the ski-fields through loud-speakers at F and at the ski-tow junction to the right of the canyon at E. If a cable strung across this canyon is broken, warnings are also sounded at The Chateau, and at Park Headquarters, where there is a village and a motor-camp. D is the main village and car-park. Lahars generated by explosions in the Crater Lake at H have passed through a gap in the crater wall to the left of the Dome, and been guided by the topography along routes indicated by shading.

detail. These combined techniques were used with conspicuous success at Rabaul Observatory when a serious eruption was feared in 1984.

Hopes that temperature measurements will lead to useful predictions have usually been disappointed, even though the temperatures of crater lakes, geysers, and fumaroles have often risen before eruptions. After many years observing Indonesian volcanoes, Neumann van Padang declared that he could find no significant correlations. In the Philippines, however, there have been changes in lake temperature before eruptions of Taal volcano, and in New Zealand sharp rises or falls in the temperature of the Ruapehu crater lake have been regarded as warning signs ever since the present lake was formed in 1946; but there have also been high temperatures without eruptions, and eruptions without high temperatures.

Observations of changes in the temperature and depth of the Ruapehu crater lake no longer call for the major mountaineering expeditions that had to be mounted when the temperature was first measured in 1895, but it has not proved easy to design automatic equipment that will do the job. It is simple enough to measure temperature with thermocouples or thermistors, though corrosion can prove troublesome: but it is less simple to transmit the information into a recording-point. Both telephone lines and radio links have been tried, but cold renders insulation brittle and snaps wires, and ice forms on aerials and interrupts radio transmissions. Good results were obtained by using buoys floating in the lake (Figure 21.4), but excessive lake temperatures and eruptions gave them a maximum life of three months. After losing six buoys (which had to be lowered into the lake from a helicopter) the project had to be abandoned for reasons of cost.

The water of the crater lake has been analysed many times, but regular measurements did not begin until 1966. The chloride content of the steam that rises from fumaroles in the bed of the lake makes it quite strongly acid, but when they become inactive, melting snow gradually dilutes the acid. Before the eruption of 1945, mountaineers were known to swim in it, and indeed the Tourist Department used to distribute posters showing a party of attractive young ladies in swimming suits grouped in the snow on the lake edge. The subsequent rise in temperature and acidity now deters even the foolhardy, and severely limits the life of any equipment used to make measurements in the lake.

Analyses of the changing chemical content of the lake-water and measurements of its acidity have given useful indications of impending eruptions. The mountain behaves in two quite different ways, not unlike humans asleep and awake. The sleeping condition is known as the "closed vent" state. In this condition moderate earthquakes under the lake do not herald an eruption, but in the "open vent" state moderate eruptions can follow quite small earthquakes. When the vents are closed, there is little heat-flow into the lake, but when they are open, it warms up markedly. A combination of high temperature, obvious bubbling of the lake, and the recording of volcanic tremor usually produces a Park Board warning to visitors to keep away from the lake.

The problems in using temperature measurements on their own seem to come from the ease with which weather changes can alter the conditions within a hydrothermal system. These changes are much bigger than any that might be expected to arise from deeper magmatic movements, as it takes much longer for those to be conducted through rock than it does for heat to be re-distributed by convection.

The ski-fields of Mount Ruapehu are the most popular in New Zealand, and attract visitors from all over the world. At times there may be as many as ten thousand people on the mountain. Eruptions are not infrequent, and in 1969 and 1975 lahars damaged buildings and ski-tows. Fortunately they occurred at night, and there were no casualties, but public concern was sufficiently great for the Tongariro National Park Board to ask the Department of Scientific and Industrial Research to design a warning system, which was installed in 1984 (Figure 21.5).

Figure 21.6 During a persistent earthquake swarm that started in 1983 the shore-line of Rabaul harbour rose more than a metre. The swarm continued until mid-1985 without an eruption of any of the surrounding volcanoes.

Most eruptions in the past have been almost immediately preceded by volcanic earthquakes, but even moderately large shocks directly beneath the crater lake do not always presage an eruption, and seismographs on the mountain would also pick up earthquakes in other places. The system finally chosen involves a combination of signs and several observation points.

There are two seismometers, one on the crater rim, and the other at Maungaku, 30 km to the north. Their signals are transmitted by radio to Park Headquarters, where they are compared in a small computer, and conventional visual records are also made. The computer first satisfies itself that the crater seismograph has recorded a shock of at least magnitude 3½, and that the amplitude of the signal at Maungaku does not reach one eightieth of that from the crater. This ensures that even large events more than 3 km away do not initiate a warning.

The second stage follows only if the signal from the crater then fails. Past experience has shown that any eruption large enough to cause a dangerous lahar is certain to damage the Dome Shelter. The transmitter is housed in a steel tank underneath it, but its power-supply is looped through the roof and will be broken. When this happens, sirens on the ski-field are sounded, and loudspeakers tell skiers that they have six or eight minutes to reach the safety of higher ground. Should a lahar reach the ski-field, it will also break a wire strung across the canyon below it and activate further warnings in the Park Headquarters lower down the valley, and in the nearby village and tourist hotel.

As was only to be expected, the mountain has remained quiet since the equipment was installed, but it is unlikely to remain so indefinitely. For over a century, scientists have visited the volcanoes of National Park, but only since World War II have there been resources for anything like a continuous watch. Shortly before the war ended, in 1945, Ruapehu erupted lava and ash, but there were no significant lahars. After the eruption a natural dam of ice and ash was formed, which allowed the lake to rise some six or eight metres above its old level. In 1953 the dam failed, and the disastrous Tangiwai lahar resulted. No eruption was involved.

Ngauruhoe erupted lava in 1945 and 1954, and there have been other significant eruptions since, especially in 1974 and 1975. Tongariro, the third major volcano in the Park, had a major ash eruption in the 1890s, but has been only slightly active in the present century.

Warning systems need not be as elaborate as the New Zealand one to be effective. In Indonesia, watchmen posted around Merapi and Galunggung report lahars by striking gongs, and the alarm is relayed from village to village by the same simple means. In

Japan, there are searchlights trained on the summit of Usu, and alarms are given by the sirens of the local fire-brigade. In the Philippines, lahars from Mayon produce characteristic movements on a local seismograph, and two observers are employed to keep a continuous watch.

Most successful eruption forecasts apply to the future course of eruptions that have already started, rather than to the onset of unheralded ones. Once an eruption is under way, the seat of the disturbance is nearer the surface, but close observation may become more difficult. Successive climaxes of a continuing eruption often show periodicities that enable the time of the next one to be anticipated with some confidence. Prediction remains a chancy business, however, and coincidences are all too readily taken for evidence of real connections. It is not easy to set up formal criteria of success, and few volcanologists present proper statistics with stated limits of confidence. Without them, claims to have identified forerunners remain at best interesting suggestions.

Dr Claude Blot has drawn attention to the existence of sequences of earthquakes that begin with a large deep-focus earthquake that is followed by smaller shocks getting progressively shallower, and nearer to a volcano which finally erupts. By following the progressive movement it is possible to estimate the date and the place of the eruption. These predictions signal the beginning of new outbreaks, and eruptions in Vanuatu, Italy, and New Zealand have been successfully forecast. In some cases, however, all that took place was a marked increase in local seismicity, and in others no significant changes were observed. Apparently some additional criterion must be satisfied before it becomes certain that the end result will be an eruption.

The difficulties that face a volcanologist who believes that a dangerous condition is developing are well illustrated by events in New Guines during the last few years. Scientists elsewhere have praised the success of Rabaul Observatory in charting the growth of a body of magma beneath the flooded caldera that forms the harbour, and following the associated seismic, geodetic, and gravitational changes. While they were happening, matters had not yet become clear, and the guarded statements that professional caution impelled the volcanologists to issue can hardly have endeared them to civil authorities who might at any time have to take draconian measures to ensure the safety of the population.

Improved seismographs had been installed in 1967, and regular monthly counts of shocks beneath the caldera were made, but there were too many for locations to be calculated until computer facilities became available in 1983. In 1971 there had been a change in the activity. Previously monthly counts had fluctuated between 20 and 100, but a pattern of swarms them developed, with several hundred shocks concentrated within a few hours. There were two shocks with magnitudes greater than 5. Between 1980 and 1982 the monthly count several times exceeded a thousand.

There were other signs that activity was increasing. An island close to the crater rim had risen about a metre (Figure 21.6). Gravimeter and tilt-meter readings suggested that the centre of the disturbance was in the harbour south of Tavurvur, an active cone on the crater rim. It was interpreted as a steadily-growing magma body, and because of the limited size of the uplifted area, judged to be no more than a kilometre or two deep. The authorities were advised that an eruption was "possible" but exactly when, it was not possible to say. When? "Before the end of the century"!

In October 1983, the number of shocks rose dramatically to over 5,000, the rate of tilting increased, and cracks appeared in the flanks of the cone. Survey measurements with electronic geodimeters proved confusing and inconclusive, but it was decided that an eruption within a few months was likely. By now accurate locations of the earthquakes from 1977 to 1982 were available. The origins proved to lie within two crescent-shaped areas, believed to represent faults that had opened up in an eruption about 1400 years ago. One extended southwards from Tavurvur, and the other lay eastwards across the harbour near another active cone called Vulcan. The authorities were warned that an eruption within a few months was now likely, and an alert was issued.

Both the rate of tilting and the number of earthquakes went on growing. In January 1984, the monthly count was 8,300, and the possibility that Vulcan, and not Tavurvur, would erupt was being considered. An earthquake of magnitude 4.9 was felt strongly in Rabaul. Movements on the seismographs became so nearly continuous that it was no longer possible to locate the events. The volcanologists told the authorities that the eruption they had previously described as "possible" was now "much more likely".

The pattern of tilts and distortions shown by the survey measurements became more and more complex. In April the monthly earthquake-count was over 13,000. A shock of magnitude 4.8 caused some minor damage. Further uplifts were noted, but the crisis was already past. The climax was reached about April 21, and for the rest of the year, except for minor fluctuations the activity declined. In August 1985 it was pronounced to be "at pre-crisis level". There was no eruption.

22—Eruptions, their Control and Management

"Don't just sit there, do something!"

ANON: Traditional Exhortation

Once a volcano has started hurling things out the top it may already be too late to run, but attempts to mitigate the consequences of eruptions have enjoyed at least a limited success. History shows that the invocation of gods and saints, Christian and pagan, and the exposition of holy relics and sacred objects have an excellent record of effectiveness. Mount Etna, for example, is responsive to the intercessions of Saint Agatha. In A.D. 273, a year after her martyrdom, Catania was threatened by a stream of lava. The inhabitants rushed to her tomb, removed the veil that covered her, and carried it to the edge of the lava. Results were instant and beneficial, and have subsequently (but not invariably) ensued when the veil has been used on other occasions. St Januarius has demonstrated similar control over Vesuvius, and St Raphael over Mayon. If suitably approached, the gods of Japan, Indonesia, Hawaii, New Guinea, and South America also seem prepared to intervene in volcanological matters.

Since a nation's priests are often its chroniclers, there is a much better record of ancient eruptions than we should have had were volcanology considered a purely secular matter – though it is possible that unsuccessful interventions have been discreetly passed over. In 1669, when Etna began erupting lava from several vents including a fissure 20 km long, St Agatha showed a certain tardiness in displaying her usual control. Within a few weeks, the lava had engulfed and destroyed four towns and fourteen villages, with their vineyards and cornfields. Attempts to build protective walls were made, but the lava continued to gain about a kilometre a day, and began to overtop the 20-metre-high wall that surrounded Catania. A brief pause followed, but when signs of renewed movement appeared, Diego de Pappalardo decided to take action. He armed fifty of the townsmen with crowbars and shovels, provided them with wet cowhides to shield them from the heat, led them up towards the source of the lava near Mount Rossi, and directed them to attack the sides of the flow, in the hope of diverting some of it into a secondary channel:

Figure 22.1 House damaged during the eruption of Eldfell in 1973.

"They pierced the solid outer crust of solidified lava, and a rivulet of the molten interior immediately gushed out and flowed in the direction of Paterno; whereupon 500 men of that town, alarmed for its safety, took up arms, and caused Pappalardo and his men to desist."

It is doubtful whether Paterno was in fact endangered, but the result was to have interference with the natural course of Sicilian lava-flows made illegal. As recently as 1971 the law was invoked to prevent an attempted diversion, but in 1983 it was overruled, and carefully placed explosives were used to good effect.

Heimaey is the largest of the islands of the Vestmannaeyjar, and the most important base of the Icelandic fishing industry. In 1973 the township lay between the harbour, protected from the Atlantic swells by a breakwater, and gently sloping fields that extended to the lower slopes of Helgafell, a shapely cone several hundred metres high, judged to have been dormant for the last five thousand years.

On the early morning of January 23 a fissure opened in the fields, only 200 metres from the eastern limits of the town. It grew, and became a 1600-metre-long wall of fire, from the base of which ran a river of lava. Fortunately a storm the previous day had driven most of the fishing fleet into port, and the five thousand inhabitants were quickly evacuated to the mainland, their most immediate concern being sea-sickness on the very rough winter crossing. Two or three hundred remained to attend to essential services.

The fissure soon became a continuous curtain of fire that stretched across the entire two-kilometre width of the island. Lava was pouring out at a rate of 100 cubic metres per second, and flowing down the slope to the sea, where violent explosions were occurring. Before long, the activity became concentrated in the central part of the rift and a spatter-cone began to form, reaching a height of 100 metres within the first few days. It eventually grew more than twice as high and provided Helgafell with a neighbour, later to be called Eldfell (Figure 22.1). For several days the fall of ash was heavy, burying part of the town. It soon lessened, and work in the town and harbour resumed, but the flow of lava continued, and in late March an advancing tongue crushed and burned over two hundred houses, before being halted against the wall of the fish-processing plant. More seriously, it appeared that the encroaching lava might block the entrance to the harbour, though the rate of flow from the fissure was now only a tenth of what it had been at the beginning, and contact with the sea had done something to halt the advance.

Even in the early stages of the eruption efforts were made to control the direction of the flows by building barriers of ash, and by spraying water from fire-hoses on the front to cool and harden the surface. The measures were working, but it was obvious that the resources of the fire-brigade were going to be inadequate, even with the help of the pumps on the harbour dredge. At the end of March the government bought 43 pumps from the U.S.A., capable of lifting 800–1,000 litres per second to a hundred metres. It was found that the best results came from pouring the water some way back from the front of the lava, creating a zone of cool rubble some 50 metres wide, and using bulldozers to erect scoria dykes, against which the cooled material tended to pile up. Over six million tons of sea-water were pumped onto the surface before the eruption ended in June.

Had the operation done no more than ensure that the harbour was kept open, it would have to be considered a success. To the delight of the fishermen it has become better than ever, with a fiord-like entrance that shelters it from all seas. Until the lava encroached it had been rather exposed, with an artificial breakwater that gave only partial protection. The new arrangement is not merely practical, but picturesque, with new arms of the sea gradually becoming sandy coves.

The bulldozers that threw up barriers against the lava continued their work and recovered many buried homes from the ash (see also Figures 20.2 and 20.3); and the town has a new heating-system based on the heat of the new lava. It took the pumps about two weeks to bring the temperature of an area of lava down to 100ºC, and there still seems to be quite enough heat left to last the town for the next 15 or 20 years.

Although helping the outer crust of a lava-flow to cool, or breaking up a crust that has already formed offer methods of steering it, the cost can soon outweigh any possible benefit. However, the power and wide availability of modern earth-moving machinery have greatly increased the chances of effective wall-building. Quite small obstacles, like trees, buildings, and even large boulders can be sufficient to divert the course of a flow; and a temporary halt can start a pattern of surface cooling that becomes cumulative, or a single block can start a pile-up that grows into a major barrier.

During an eruption of Mauna Loa in 1935, Dr Thomas Jaggar of the Hawaiian Volcano Observatory realised the possible value of explosives. The town of Hilo was in danger, and he felt that it was time to see if a flow could be diverted by bombing it. He enlisted the help of the U.S. Air Corps, which used twenty 272 kilogram bombs to attack two targets.

The lava had become ponded above a saddle. If it spilled out to the east, it would reach Hilo; but if it could be persuaded to drain to the west, only waste land would be affected. The first attack was aimed at a wall of rock some distance above the base of the flow. If it could be breached it would turn some of the lava-supply into new channels, and thus allow the old flow to stagnate and cool. There was a possibility that the new flow would merely follow the side of the old one, but at least it would cause a delay, and the bombing could be repeated. The second target was the flow itself. If its surface could be broken, the channel might become clogged with debris, and the greater surface of the stirred-up liquid could help it to cool more rapidly.

The bombs scored direct hits, and broke open the roofed channel of the flow. A new flow began to move through a breach in the levee, and within 24 hours the speed of the main flow dropped from 245 to 13 metres per hour. In 30 hours, it halted altogether. Such a speedy

Figure 22.2 In 1983 a flow of lava on the southern slopes of Etna was successfully diverted from a hotel and an observatory down the road to the left by strategically placed earthworks.

result seemed too good to be true. Whether, as Jaggar believed, breaking the roof of the channel started a solidification that retreated to the source; or whether, as some of his colleagues maintained, the whole thing was a coincidence, similar results followed further bombing in 1942. As Dr Fred Bullard has stressed, such incidents emphasise the very delicate balance of thermal and chemical relations within a lava-flow, and the ease with which it can be upset.

A remarkable intervention was carried out at Etna in 1983 (Figure 22.2). Explosives were used to create a breach, and about 20 per cent of the flow was diverted into a channel previously dug on the western side of it. It flowed into the channel for about three days, and reached a length of about 700 metres. At the same time, there were overflows from the main channel, which were controlled by earthworks. The combined effect was to slow the advance of the most distant front, averting some of the threatened damage to property.

This bald account obscures the problem of planting explosives in the levees bordering the flow. An elaborate system of water-cooling was needed to keep the shot-holes cool until the charges could be implanted at the last possible moment with the help of compressed air. Nor should the heroism of the bulldozer-drivers go unrecorded. They shovelled hot glowing lava away from buildings while protected only by crudely improvised metal shields. So far the operation remains unique; but the techniques will undoubtedly be used again.

In countries that have no organised procedures for dealing with natural emergencies, authorities have shown themselves reluctant to interfere with volcanoes, in case they incur legal responsibility for unforeseen consequences of a well-intentioned act. Not even the knowledge that diverting a lava-flow on to their fields has saved buildings in a town from destruction is likely to deter farmers from demanding compensation. Even if the value of the buildings saved is many times the compensation sought, it is unlikely that owners will hasten to pay for the results of actions they neither ordered nor sanctioned. No doubt ingenious lawyers could frame laws to meet the situation, but it could be hard to find politicians prepared to enact them

Volcanology provides a happy hunting-ground for the litigious. If a geologist publishes a map of hazards showing the probable course of future lava-flows or lahars he will certainly affect property-values. Can the owners seek an injunction against publication or claim damages? And what protection has a geologist acting in good faith if the next eruption proves his predictions wrong? Should a council refuse a permit to a land-owner wishing to build alongside a lava-flow? And if it grants one, should it pay compensation if the building is damaged by a new flow that chooses to run along the flank of the old?

In spite of these legal perils, many countries have taken preventive measures. They range from the tunnels at Kelut in Java (Chapter 39) to the lahar warning system on Mount Ruapehu in New Zealand (Chapter 21). Strategically located breaches in crater walls, dams placed across the heads of gullies, excavations, and other protective earthworks now exist in many places where there is a high likelihood of lahars or nuées ardentes (Figures 22.3 and 22.4).

Figure 22.3 These concrete structures on the slopes of Mount Usu, Hokkaido, Japan are intended to contain or divert lahars.

Figure 22.4 Lahar traps, and gullies through ash faced with stone, Sakurajima, Kyushu, Japan.

23—Volcanoes in Harness

There is no science whose value can be adequately estimated by economists and utilitarians of the lower order

HUGH MILLER : The Old Red Sandstone

Erupting volcanoes afford an impressive spectacle, but it is doubtful whether anybody ever found much use for one. On the other hand, their unashamed exhibitionism proclaims that within the Earth there is a large store of heat, awaiting exploitation by a world clamouring for energy. Attempts to tame some of the gentler sources of geothermal energy are very old, possibly prehistoric. Hot water and steam can be used for bathing and doing the laundry, cooking, or heating buildings, and it is no matter whether the source is natural or artificial. The requirements for such purposes are fairly modest, and there were no large-scale attempts to harness geothermal power until the industrial revolution began to increase the demand for the various minerals to be found concentrated near volcanic vents.

In 1827 Count Francesco Lardarel, a Frenchman in exile at the court of the Grand Duke of Tuscany, realised that natural steam could be used to concentrate the boracic acid already being taken from the pools of condensed steam around the Tuscan vents. It could then be used to convert soda to borax. It was a profitable venture, and the district became known as Lardarello.

The chemical industry soon found a variety of uses for the natural steam, but its high content of corrosive minerals proved a problem, and “clean” steam had to be obtained by using it to heat boilers filled with fresh water. The story of power generation at Lardarello begins in 1897, when a small steam-engine was driven from one of the boilers. Seven years later, when steam from a vent was fed directly to a small piston engine that drove the dynamo that lit the factory, the first geothermal power-station was born.

So far the steam had been collected from natural vents, and the decision to drill bores was a major advance. Superheated steam was obtained, the pressures were higher, and in 1913 a steam turbine was introduced. The electrical output grew to 250 kilowatts. Corrosion was still a problem, and in 1916 when it was decided to instal a major power-station, it once more used indirect heat. The system was rather wasteful, but three units were built, each with an output of 3 megawatts, and they remained in use until 1923. By that time a way had been found to rid the steam of up to 90 per cent of the impurities, and there had been enormous advances in the production of anti-corrosive alloys. In 1944, Lardarello was producing 135 megawatts, but the following year it was wrecked by retreating German armies. It has since been re-built, and the area now supplies Italy with about 365 megawatts.

Unlike many hydrothermal areas, Lardarello produces dry steam, the water-table being about 2 km below the surface. The steam is at a temperature of 245ºC and comes from a reservoir confined beneath an impermeable caprock, through which bores are drilled at intervals of about 200 metres. Today electricity generation has become more important than the original chemical industry, but carbon dioxide, ammonia, ammonium carbonate, sodium perborate, ammonium chloride, and boron carbide are all recovered as by-products. The boracic acid for which the plant was set up in 1812 is no longer economic to produce, and the works were shut down in 1969. Annual production had previously reached 8,000 tons of boracic acid, and 4,500 tons of borax.

An unexpected constituent of Lardarello steam is helium. The gas received its name in 1868, when astronomers watching a solar eclipse in India detected a bright line in the solar spectrum that did not coincide with any of the elements then known on Earth (Greek helios, the sun). In 1895 the chemist Nasini found that it occurred at Lardarello, and about the same time it was found to be present in some uranium ores – but that is another story.

Lardarello remained the only large-scale attempt to use geothermal power for generating electricity until the uses of nuclear fission were discovered during World War II. In early atomic piles “heavy water” was often used as a moderator to slow down the speed of the neutrons. Steam from the hydrothermal field at Wairakei was found to be sufficiently enriched with the heavy isotope of hydrogen for the British and New Zealand governments to embark upon a joint project to produce heavy water and a certain amount of electric power. Before this scheme could be completed the price of heavy water fell sharply, the project became uneconomic, and the British withdrew. Meanwhile, New Zealand's demands for electricity had risen, and her engineers were looking for alternatives to damming the country's rivers. There was plenty of unused water-power in the far south, but most of New Zealand's industry and most of her people were to be found in the north. There were no great coal resources, and the search for oil and natural gas had at that time been unsuccessful. The government Electricity Department, the Department of Scientific and Industrial Research, and the Ministry of Works united to assess the technical difficulties in using the resources of the Central Volcanic Region to produce power. The abandoned heavy water project became the basis of new designs, and in 1958 the world's second geothermal power station, beside the Waikato River at Wairakei, 8 km north of Taupo, began supplying electricity to the North Island grid.

Wairakei was not indeed unknown before the days of the power station. Its tourist hotel, on the main highway, was a popular centre for visitors to the thermal region. Geyser Valley and the Karapiti Blowhole were at its doorstep, and the neighbouring streams and lakes held the world's finest trout. As the explorations proceeded and the scale of the operations became clear, those involved with the tourist business began to voice disquiet about the possible effects of a power station on their thermal wonders. Engineers and scientists were apt to find that their welcome at the hotel lacked warmth.

In 1950 there was little of the concern for the natural environment and conservation of the world's resources that appears today whenever some new use for them is proposed. Even so, it is probable that the general public would have considered power for homes and factories more necessary than the entertainment of tourists. The shortage of power had resulted in inconvenient cuts to city electricity supplies, and they had been greatly resented. It certainly began to look as if the disquiet at Wairakei was justified. Many of the old springs and geysers ceased to perform, and the steam discharge from the Karapiti Blowhole, once billed as "the safety-valve of the North Island"

Figure 23.1 Wairakei bore-field.

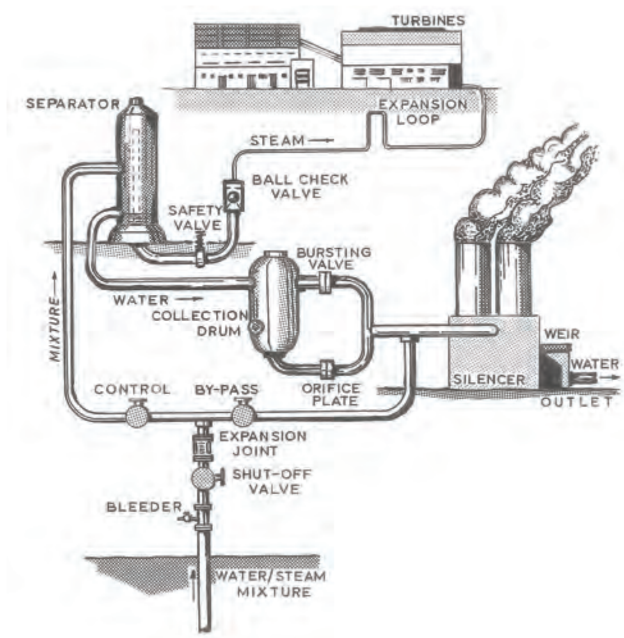


Figure 23.2 Wairakei geothermal power station, showing the layout of the installation, and the path of steam from the bore-field to the power-house.

appeared less impressive than the plumes of steam above the bores in the Wairakei Valley (Figure 23.1). The story ends happily enough. New and greatly increased areas of steaming ground have replaced the old chloride springs of Geyser Valley, and several fumaroles that rival Karapiti have appeared close by. The bore-field and the power station attract tourists, and improvements in roading have increased the flow of visitors. Wairakei has a new and larger hotel, and others have been built not far away. The experience at Wairakei has taught a great deal – not least that things might not turn out so happily next time.

The present arrangement of the Wairakei station is shown in (Figure 23.2). Unlike Lardarello, Wairakei is a "wet" field calling for some additional features. The steam, which comes from depths of 600 to 1200 metres, reaches the surface as a mixture of water and steam that must be separated before it can be fed to the turbines, the hot water being used to generate additional steam at a lower temperature. After discharge from the turbines, the condensate is returned to the Waikato River, which supplies the large amount of cooling water needed. This raises the temperature of the river a degree or two, with some detectable effects upon fish and plant life, to which dissolved mercury and other substances in the discharge also contribute. The station has a capacity of 192 megawatts, about 2.3 per cent of the country's generating power. Since it began working it has used steam from about a cubic kilometre of water. The ground has responded to the withdrawal by subsiding about 3 cm. a year in the centre of the field. A balance now seems to have been reached, with the inflow of ground-water (much of which comes from the river) just about matching the draw-off. Since heat

A B C

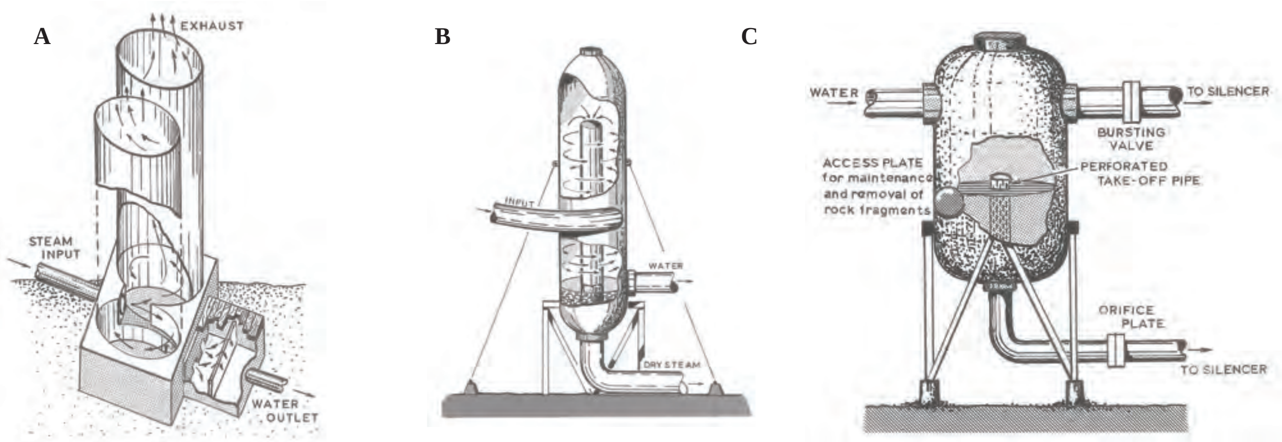


Figure 23.3

A Twin silencer, through which steam is discharged when the bore is under test, or steam is not being passed to the power-house.

B The centrifugal separator removes water, and passes on dry steam.

C Collection drum, for the removal of rock fragments.

must be carried from the depths by a movement of water, a copious supply, and for preference a system of circulation, is needed if a geothermal field is to continue to supply power.

The techniques used to drill for geothermal steam are much the same as those used in drilling for oil – or anything else for that matter – but the steam seldom comes to the surface in anything like the oil-man's gusher. The weight of cold surface-water in the bore is usually sufficient to prevent the deeper water from turning to steam, and it is necessary to start things off by pumping out some of the cold water, the usual method being to displace it with compressed air. Once the pressure has been lowered sufficiently, the superheated water will "flash" into steam and blow the remaining water out the top. After a bore has been "blown" it should continue to deliver high-pressure steam, with a roar that demands silencers as well as separators at the well-head. Figures 23.3A and 23.3B show how they work. Any rock fragments that could damage the installation are removed from the steam before it passes to the silencer (Figure 23.3C). Figure 23.4 shows arrangements at the well-head.

A problem we have still to consider is how to get the output of hot water and steam from a field of from perhaps 10 to 50 separate bores to the places where it will be used. The simple answer is of course "pipes" – but what kind, and how big, and what about losses of heat and pressure? What about the expansion and contraction of a long pipe, operating at high pressure, when it is carrying steam and when the steam is shut off? Fortunately, these are standard engineering problems, but ingenuity is needed to produce economic solutions.

At Wairakei, where the power-house is more than two kilometres from the nearest bores, the total length of the main steam-lines is about twenty kilometres, but the smaller branch pipes from the individual well-heads total very much more. The diameter of the pipes depends upon the pressure – the lower the pressure, the bigger the pipe. The largest one at Wairakei measures a metre across inside, but most of them have only half or three quarters of that diameter. Externally, they are a great deal bigger, for all of them except the waste-pipes and silencers must be lagged. In most steam power-stations the popular material to use is magnesia, though the big pipe at Wairakei is covered with glass wool enclosed in an aluminium sheath. Most of the others are covered with slabs of magnesia, and protected with roofing felt, wire-netting, and a coat of aluminium paint.

In geothermal fields it is sometimes possible to find a nearby deposit of vermiculite, a thermally-altered silicate with excellent insulating properties, and likely

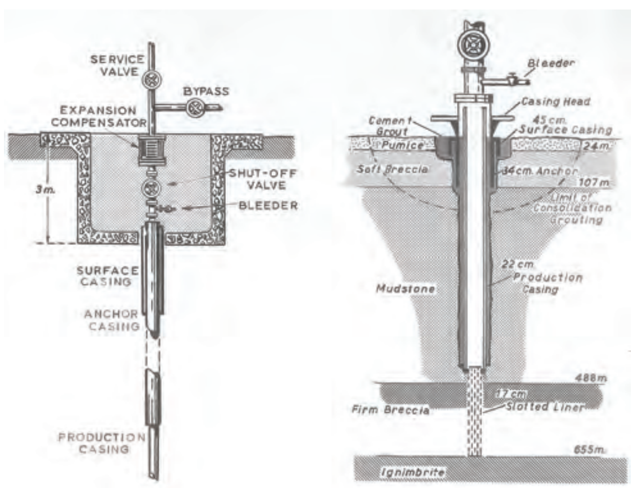


Figure 23.4 Details of a well-head and bore-casing.

to be cheap. Lagging is usually a major expense, and its cost must be balanced against the cost of heat-loss. With hot water, the problem is usually less severe, and the loss can easily be brought down to about 1ºC per kilometre. With dry steam (such as the output from the separators) the temperature must be kept above condensation point to protect the turbines, but a small amount of condensation is actually useful, as the liquid that falls to the bottom of the pipe carries with it most of the remaining soluble chlorides. The combination of these with the hydrogen sulphide that is usually there as well is highly corrosive, and no good at all to turbine-blades. The condensation is brought under control by fitting a small drain to the bottom of the pipe every 150 metres or so. These were originally provided with a spring-loaded valve through which the trapped water would blow off in a puff of steam whenever enough had accumulated. This could be disconcerting to passers-by, and timid souls will be relieved to know that continuously-discharging holes have largely taken their place, the losses of steam being less costly than the valves. This "scrubbing" process of repeated dilution and condensation is extremely efficient. After passing only four traps 99.6 per cent of the solubles have gone, and after ten, only a millionth remains. What reaches the turbines at Wairakei is virtually distilled water, and the steam is much drier than it was on leaving the separator.

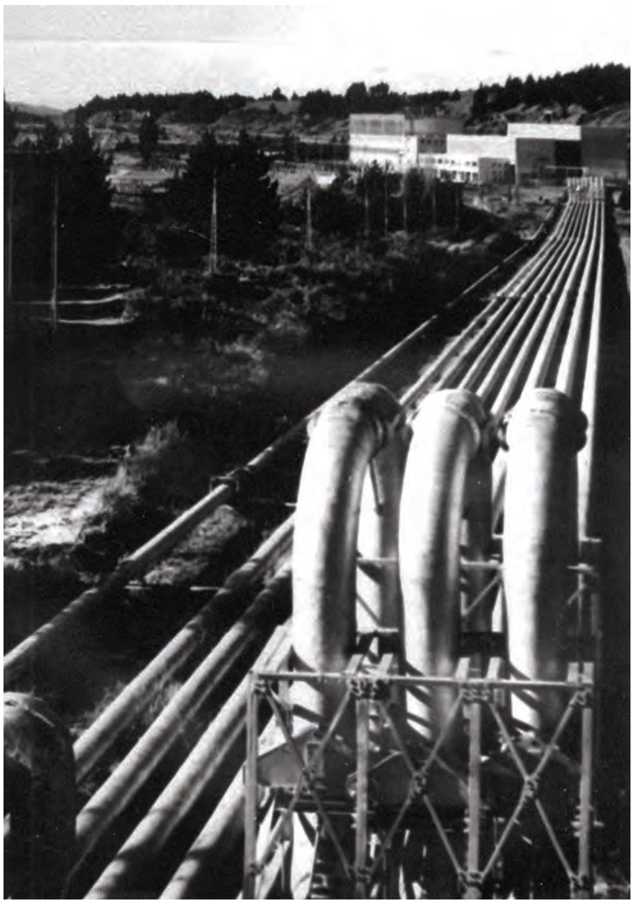


Figure 23.5 Wairakei geothermal power station, with a section of the pipeline carrying steam from the bore-field, including an arched expansion joint.

Expansion is usually taken care of with flexible loops, connected to the main pipeline by short lengths of stainless steel which act as hinges. They are usually placed horizontally, but both at Wairakei and at Krafla they have been found to be a convenient way of getting the pipes across a highway, forming a kind of triumphal arch that impressively proclaims the power of geothermal steam (Figure 23.5). Where the country has many ups and downs more complicated expedients may be needed, such as roller mountings, bellows, and slip-joints, but all of these are costly and unwelcome.

Since the development of Wairakei, geothermal powerstations have been built in other parts of the world, notably at The Geysers in California, which has an estimated output of about 450 megawatts, and at Krafla in Iceland. Other countries with geothermal fields, including Japan and Mexico, are examining the possibility of power generation, and New Zealand geologists and engineers have undertaken exploration and assessment of fields in Chile, Indonesia, and the Philippines. In New Zealand, however, natural gas has been discovered, and although several other geothermal fields have been prospected and test-bores found productive, the immediate future of geothermal power is uncertain. At Broadlands construction of another station has been started, but whether it will proceed is likely to depend on world prices for oil.

Before we pass to other uses of volcanic heat, let us look a little more closely at the geology of Wairakei (Figure 23.6). The information has been pieced together from examination of the cores from the hundred or more production wells that have been drilled, from others drilled for geological exploration, from geophysical investigations, and from classical geology. Near the surface, about 300 metres above sea level, under surficial pumice breccia, there is an impermeable layer of mudstone about 200 metres thick – an old lake deposit that prevents hot water from reaching the surface. Below the mudstone pumice breccia is encountered, which in turn rests upon a thick sequence of ignimbrites, andesites, and rhyolitic lava-flows, extending from a few hundred metres to a thousand metres or more below sea level. It is from this diversified layer that the steam is obtained, usually in the neighbourhood of buried faults, though the existence of some of these "faults" seems to have been inferred from the occurrence of steam. Circular argument is an ever-present danger in exploring the inaccessible. Somewhere below all this it is supposed that the Mesozoic greywackes that are the usual basement rocks in New Zealand are to be found, but this is inference and not observation.

Most of the obvious signs of volcanic activity in New Zealand today lie within a triangle having the Bay of Plenty as its base and its apex at Mount Ruapehu. It

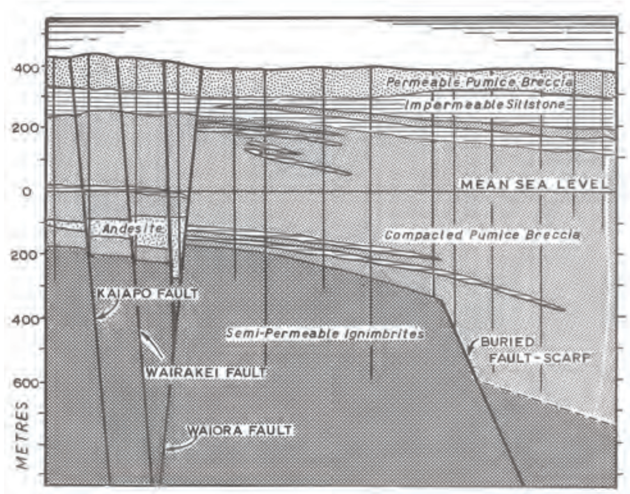


Figure 23.6 Geological cross section of the Wairakei geothermal field.

contains Lake Taupo and a number of smaller lakes, the largest of which is Lake Rotorua. Roto means lake, but we need to distinguish it from the city of 45,000 people at its southern end. City and Lake lie within a caldera formed by an eruption of ignimbrite about 140,000 years ago.

In the fourteenth century Māori villages grew up near the numerous hot springs, and on the shores of the Lakes. The district remained almost undisturbed Māori territory until 1870, when Queen Victoria's second son, the Duke of Edinburgh, became the first of a stream of visitors to the geysers and the silica terraces of Tarawera some 20 km to the south east. The region became known world-wide, but rather surprisingly there was no township until 1882. However, baths were built, and invalids were persuaded of the benefits of "taking the waters". The set-back in 1886 when Tarawera erupted and destroyed the terraces proved temporary, and by the end of 1894 when Rotorua was linked with Auckland by railway its position as both the tourist and commercial centre of the thermal regions was established beyond doubt. Municipal gardens were laid out around a large and impressive bath-house in Tudor style, furnished with quantities of potted palms and an incredible number of marble statues in classical style imported from Italy, all in charge of a Government Balneologist.

Building the city was not without problems. Excavating foundations was apt to tap steam and gas. Cracks in the ground would appear without warning, and extend across roads and gardens, or disappear beneath houses while giving off unpleasant smells. The gases blackened white house-paints, and the vents of septic-tanks were liable to become steam jets. The inhabitants were happy to bathe in natural hot pools, but were understandably reluctant to interfere unnecessarily with geothermal manifestations. It was not until the 1930s that they gained the confidence to make tentative efforts to exploit their underground resources. A few shallow bores were cautiously drilled, in the first instance to replenish supplies of hot water to public bath-houses. These had dwindled as silica deposits encrusted the vents and the development of the town modified the water-table.

Cautious successes led to other suggestions for the use of volcanic heat – in homes, in greenhouses for out-of-season fruits and vegetables, and even for power generation, though the apparently unlimited supplies of water-power and the local expertise in dam-building made the last suggestion seem an eccentricity. Once the public was satisfied that well-drilling would not instantly result in explosions and eruptions, geothermal heating became the fashion, and hotels displayed diagrams showing the workings of their bores and heat-exchangers, the novelty presumably compensating visitors for the fact that the sometimes scalding water was not always hot enough for shaving.

In Rotorua, well-drilling has been very much a matter of private initiative. By 1981 over 800 wells had been drilled, and at least 550 of them were still productive. In addition to domestic uses, geothermal heat came to be used in the manufacture of cane furniture, in laundries, and for distilling water and drying timber at the Forest Research Institute. Rotorua can be hot in summer, and one large hotel found that air-conditioning as well as heating could be thermally powered.

Recently signs appeared that the limit of this extensive exploitation had been reached, and concern was voiced that the geysers and springs in the tourist area at Whakarewarewa seemed to be losing vigour (Figure 23.7). Many domestic installations, particularly the older ones, were ingenious improvisations rather than efficient examples of heat engineering. After failure to get voluntary action, the government decided to enforce the shut-down of all bores within a kilometre and a half of the geyser field, and set a good example by closing the bores at the Forestry Research Institute. The use of approved heat-exchangers in shallow bores is still permitted on payment of a license fee. The result has been a recovery of the height and duration of the geyser displays, and the renewal of activity that had long been dormant.

Iceland, with the strong incentive of a cold climate, undoubtedly leads the way in the extensive and efficient use of hot water, the operations being conceived, in marked contrast to those in New Zealand, as large-scale public enterprises. As long ago as 1830 Reykjavik housewives had been taking their laundry to the hot springs at Throttarlaugar, but as in New Zealand, fully a century passed before

Figure 23.7 The Prince of Wales Feathers Geyser, Whakarewarewa, N.Z. A decline in the vigour of this famous geyser field has been halted by a government decision to close nearby bores.

serious attempts were made to increase the water-supply by drilling. The first bores produced a flow of about 14 litres per second at a temperature of 87ºC, and this was piped about three kilometres to heat seventy houses, two schools, and a hospital, and to fill a covered swimming-pool. The use of geothermal heating was certainly practicable.

In 1939 drilling began at Mosfellveit, 18 km south of the city; two insulated steel pipes were laid, 35 cm. in diameter, and insulated storage-tanks were built. Water at a temperature of 86ºC flowed to the city at a rate of 200 litres per second, and the district heating service Hitaveita Reykjavijur was born (Figure 23.8). Two systems of distribution are used. Water first goes from the storage tanks to booster stations, and then to district pumping-stations. It is taken to the houses either through a single pipe, and flows to the drains; or it is returned through a second pipe to the district stations, mixed with supply-water at a higher temperature, and re-circulated. In either case, the supply reaches houses and buildings at a temperature comfortably below boiling. It is quite suitable for drinking, having only a tiny and harmless trace of dissolved silica, and exactly the amount of fluoride recommended for dental health. The original pipes have been joined by two more, double the diameter, and laid in a concrete conduit. More than 70 bores are now in use, supplying over 2,000 litres per second at temperatures between 83º and 128ºC, from depths up to 3,000 metres. All but one per cent of the buildings in Reykjavik now use the service.

Although more than half the population of Iceland is concentrated in Reykjavik, the rest of the country does not lag behind. Nearly 70 per cent of the houses enjoy geothermal heating, from twenty main district services, supplying a total of 600 megawatts of thermal power. The most unusual scheme is to be found in the Vestermannaeyjar, where the heat is extracted from a still partly-molten lava-flow erupted in 1973, as described in the last chapter. It is expected to supply space-heating for the town of 5,000 people for the next fifteen years – and then? We will see what nature provides.

Smaller heating schemes can be found in many countries, some quite long established. Warm Springs, Idaho, has enjoyed geothermal heat since 1890. Japan has tended to follow the New Zealand pattern of small bores for single homesteads, but there is now a geothermal power-plant at Matsukawa. Public schemes are to be found in Kamchatka, and less expectedly in Hungary and France, which are not obviously volcanic. At Melun, near Paris, bores were sunk for oil exploration, and abandoned. It proved possible to heat water to 60º or 70ºC by circulating it through the old bores, and a modest distribution scheme was begun in the early 1970s. Other suburban heating projects followed, and larger-scale operations are being considered in other parts of France. In Britain, exploratory bores near Southampton and in Yorkshire have yielded water at temperatures from 55º to 75ºC.

There is an almost bewildering variety of small-scale uses for geothermal heat. Many of them can be grouped as “farming”. Crops are dried, seedlings are encouraged, soil is sterilised, pig-feed is cooked,

Figure 23.8 Interior of the municipal pumping-station supplying hot water and heating to the city of Reykjavik.

milk is pasteurised, chicks are incubated, fish are dried, and the temperature of water in fish-hatcheries is boosted. All kinds of tropical plants are grown in cold climates, both in heated glass-houses and in heated soil. Icelanders enjoy tomatoes, bananas, and pineapples, and decorate their homes with cut flowers. They also dry seaweed, produce salt, scour wool, and make confectionery. At Atagawa, it is reported, the Japanese are breeding alligators.

The first large-scale industrial application of geothermal power was in the Tasman Pulp and Paper Mills at Kawerau, in the North Island of New Zealand, where newsprint and a wide range of timber and paper products are produced. This has grown to be the world's largest geothermally-powered industrial plant, drawing its raw material from the pine-trees of the world's largest man-made forest. Among the smaller geothermal enterprises, room must be found to mention the one at Namafjall, near Lake Myvatn in Iceland, which processes diatomaceous earth from the lake bottom. This has a variety of uses as an insulating material, and as a matrix for a wide range of industrial explosives (Figure 23.9).

One of the newest of geothermal power-stations is to be found at Yangbaijing, ninety kilometres north-west of Lhasa. There are two 3,000 kilowatt units, which in 1984 supplied some 38 million kilowatt-hours of electric power to the Tibetan capital. There have been problems with air pollution, and pollution of the Zangbu River, but the effluent is being used to heat green-houses, and for space-heating. Smaller schemes are under construction near other Tibetan centres of population.

Exploiting a volcano has its risks, but the economic benefits are tempting, and it is not unknown for political pressure to outweigh scientific caution. Except in the few instances where the heat is derived from the normal geothermal gradient, the fields being exploited are often not extinct, but dormant. There is always the danger that hydrothermal eruption will bring the operations to a sudden end. At Krafla, for example, eruptions and extraction for power go on side-by-side within one caldera. The consequent excitements have included the sudden intrusion of magma into a bore-hole, and the opening of an impressive rift within tens of metres of the staff quarters (Figure 23.10).

At the Wairakei station, things have been quieter, but not without incident, as the cautionary tale of the "rogue bore" will show. In February 1960, when it was decided to define the limits of the field by drilling an exploratory hole, more than two hundred bores had been successfully drilled already. The site chosen for Bore 204 was about a kilometre and a half to the south-west of the main production field in an area of open farmland where there were no signs of hydrothermal activity, and indeed no signs that there had ever been any. The nearest place where thermometer probes had shown ground temperatures higher than normal was nearly half a kilometre away.

Soon after drilling began, it became obvious that the geology of the site was complicated. It was planned to protect the first 25 metres of the hole with a 40 cm casing. It was pulled out, the hole filled with cement, a new hole drilled down the middle of it, and the whole thing grouted once more.

The next hundred metres were intended to have a 30 cm casing. While this section was being drilled, there were several occasions when the resisting pressure against the circulating pumps suddenly vanished, and quantities of drilling mud began to disappear rapidly into the depths. These porous zones were successfully sealed, and drilling continued, but when the time came to cement the casing in place, six times the estimated quantity of grout proved to be necessary.

Temperatures remained low, and the last bad leak was encountered at a depth of 135 metres. When 300 metres was reached without more trouble, it was decided not to case this section of the bore, and drilling went on uneventfully for another 70 metres. There had been no sign of steam, but then, suddenly,

Figure 23.9 Plant for drying diatomaceous earth, Lake Myvatn, Iceland.

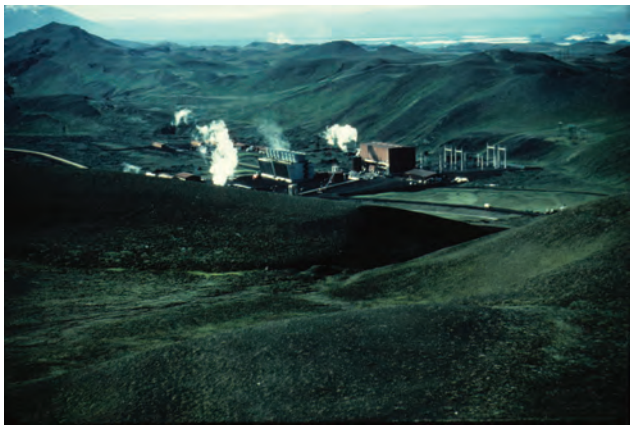


Figure 23.10 Geothermal power station, Krafla, Iceland.

the drill dropped a metre and a half. There was a very bad hole. The drill pipe was raised, the bit taken off, the pipe lowered once more, and sealing mud pumped down. Late on May 3 the pumps failed, and it was decided to withdraw the pipe once more. Just before midnight, when all but the last hundred metres was out, the contents of the bore, instead of being swallowed up, proved to be under pressure. Everything stopped.

More than seven hours went by. At ten to eight, an "eruption" started, with an outburst of steam and muddy water 35 metres to the north of the drill-hole. Cement and water were hurriedly pumped in, in the hope of sealing it off, but instead the explosions became more violent, the pit grew larger, and advanced upon the well-head. First the drill-rig and then the pumps had to be removed; and for the next few days the eruption went its own way. Every few minutes, the main steam-jet would become blocked and then clear itself by hurling mud and rocks as high as 250 metres. This went on until May 8, by which time the pit had become 30 metres deep and reached the top of the 30 cm casing, which was producing a noisy jet of dry steam, carrying fine debris which was gradually building up a crater rim. By mid-July there had been a certain amount of slumping and steam was coming from cracks in the crater floor, but the main discharge came from the bore, and the floor of the crater remained dry. The calculations of Dr C.J. Banwell, from the D.S.I.R.'s Geophysics Division, showed that the equivalent of about 50 megawatts of power was going skywards.

The discharge gradually became wetter. On October 18 it was noticed that the crater floor was flooded, and the water-level was rising very rapidly. Three days later it was within a few metres of the rim, and geysers of dark muddy water began to play from the surface, rising to heights of up to 15 metres. The ground could be felt trembling continuously, and minor "earthquakes" could frequently be felt. At this stage, the public was not encouraged to watch, but the "rogue bore" gradually became something of a show-place for visiting dignitaries.

There were no further attempts to bring the rogue under control until early 1964, when the low parts of the crater wall were built up and quantities of cold water added. For a time the geysers ceased, but over the next five years the muddy eruptions resumed once more, and the tourist industry became aware of its possibilities, and added it to their list of awe-inspiring sights just as the final decline was about to begin. In 1971 the Ministry of Works agreed to help matters by lowering the lake, and it became possible to rely on some kind of eruption every minute or two; but the quiet periods grew longer and longer. By September 1973 a twenty-minute wait was producing only a one-metre eruption, and the vibrations of the ground could only just be felt. By November the temperature of the water (which had been 85ºC two years earlier) was down to 26ºC, and the rogue was finally dead.

Figure 23.11 Another view of Wairakei bore-field.

There was another spectacular blow-out at Wairakei in 1960, when the casing of a bore ruptured at a depth of about 180 metres, allowing steam to travel up a near-by fault zone and to form a miniature volcano at the surface. This led to the collapse of a hill-side, and the creation of a large area of chaotic fissures pouring out high-pressure steam. A new bore was started about 60 metres from the old one, and carefully curved to intersect it at about twice the depth of the rupture. The bores passed within little more than a metre at a depth of 450 metres. Quantities of gravel and cement were injected, the surface activity brought under control, and the old bore sealed up. Later the new bore was cleared of debris, and became a fully productive bore supplying the power-house.

These mishaps, which have parallels in other geothermal fields, justify early reluctance to drill. Meanwhile experience was being gained in the world's oil-fields, and could eventually be brought to bear on the problems.

24—Buildings, Bonanzas, and Brimstone

Geology in a peculiar manner supplies to the intellect an exercise …
of ennobling character. But it also has its cash value.

HUGH MILLER : The Old Red Sandstone

Without doubt the best known product of the underworld is sulphur. No hellish apparition is complete without a smell of brimstone, which is also apt to be reported after earthquakes and landslides. Its presence in volcanic gases, usually as sulphuretted hydrogen or sulphur dioxide, is readily detected by nose and lungs, and volcanoes in their fumarolic stage often deposit large amounts of bright yellow sulphur (Figures 24.1 and 24.2). Because of the readiness with which it combines chemically, eruptions of molten sulphur like those at Shiretoko-iwo-zan in Hokkaido in 1889 and in 1936 are uncommon. On the latter occasion 200 tons were discharged within a few days, but this hardly amounts to a commercial quantity.

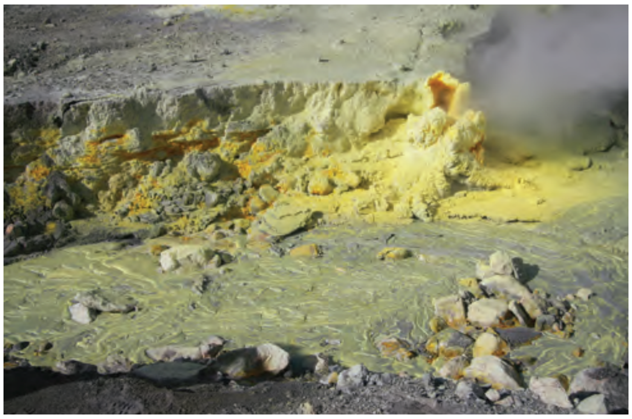


Figure 24.2 Sulphur vent and solidified sulphur stream on White Island, New Zealand.

Sulphur, in the form of sulphuric acid, is more extensively used in commerce than any other chemical. As an element it finds uses in fertilisers and explosives, for bleaching and disinfecting, for vulcanising rubber, and in the paper industry. The deposits of volcanic sulphur in mainland Italy and Sicily have been mined since antiquity. It is therefore a surprise to find that, given the economics of transport and purification, the greater part of the world's sulphur is not of volcanic origin at all, but comes from certain sedimentary deposits in Louisiana and Texas. In Chile, Japan, and Sicily, however, volcanic sulphur retains its local importance. The mine on Cerro Aucanquilcha in Chile, a complex andesitic volcano that still displays weak fumarolic activity, is at a height of 6,000 metres and claims to be the world's highest. A few kilometres away, astride the Bolivian frontier, the deposits of the more active Mount Ollagua are also worked. It is sad to note that the combination of sulphur dust with high altitude brings many of the miners, mainly Indians, to an early death from lung ailments.

Figure 24.1 A flow of sulphur in the crater of Biliran volcano, Philippines.

New Zealand attempts to mine the sulphur deposits of White Island, a lively volcano in the Bay of Plenty, have proved disastrous, both as a commercial venture, and to the twelve employees of the company killed by a collapse of the crater wall and an associated lahar in 1914. Further attempts to exploit the mineral resources of the island in the 1920s and 1930s failed for reasons unrelated to volcanology. The island is now considered unsafe for anything more than brief visits by scientific parties, muttonbirders, and a few fishermen. In the face of periodic attacks by the forces of the volcano, the Department of Scientific and Industrial Research persists with attempts to operate a seismograph linked to the mainland by radio (Figures 24.3).

Borax is another substance that occurs in deposits directly linked to a near-by volcano. It was the original product of the prosperous chemical industry based on the hot springs and fumaroles of Tuscany that Francesco Lardarel founded early in the nineteenth century. It is still mined in Chile, but as with sulphur, more economic sources of borax have now been found.

Fumarolic gases and the waters of hot springs often contain dissolved minerals, leached from the rocks through which they have passed. As they cool, these

Figure 24.3 Remains of sulphur processing factory on White Island after 70 years of attack by corrosive gases.

minerals are precipitated in cracks and fissures, sometimes in the form of large regular crystals. By reason of their beauty or rarity they can be highly prized, even when they derive from minerals as common as quartz, feldspar, and olivine; but in the long run gems like amethyst, moonstone, beryl, and topaz turn out to be less valuable than ores of the common metals.

Many important deposits of gold, tin, lead, and zinc are the result of erosion, transportation, sorting, and concentration by water, and not of direct concern to volcanologists, but mineral veins are always associated with large igneous intrusions, such as granite batholiths. The intrusion of a batholith usually produces tension cracks through which magmatic fluids can percolate to regions of lower temperature, and gradually cool. The constituents with the highest melting-points crystallise first, and the fluids that remain after the rock-forming silicates have been deposited are enriched with metals that did not readily fit the molecular structure of the first substances to solidify. Most of these metals readily combine with sulphur and become members of a family of low-grade but plentiful sulphide ores.

Because of the way in which deposits of ore accumulate, they tend to lie in orderly sequences within a given mineral belt, and wherever one metal is being mined it is very likely that a different kind of mine can be found not far away. It is not easy to generalise about these mineral sequences, as the conditions under which the ores were dissolved and precipitated differ greatly, even within similar tectonic settlings.

Figure 24.4 Mining copper at Cebu, Philippines.

Figure 24.5 Close-up view of Cebu copper deposit.

Metals occurring as "impurities" are often present in large enough amounts to be worked as valuable by-products. Today, the legendary silver-mines of the Andes earn more from their production of tin.

About half of the world's copper comes from a low-grade sulphide ore known as porphyritic copper, which has been deposited in the cracks and fissures found in porphyry, and is probably the most important ore associated with volcanoes (Figures 24.4 and 24.5). The chief copper-belt extends from Alaska to Chile, and coincides with a belt of older intrusive rocks, not with present-day volcanic activity. Porphyritic copper is also mined on the opposite side of the Pacific, in New Guinea, the Philippines, and Japan; and it occurs in Central Africa, Canada, and Australia. The Canadian deposit lies on a peninsula that juts into Lake Superior, and is associated with old basaltic lavas. It was known to the American Indians, and worked by about a hundred companies during last century. Not surprisingly, it is now largely exhausted.

Iron can be concentrated in much the same way, but it is so plentiful a metal that only high-grade ores are worth exploiting, and few volcanic deposits are important. With rarer metals like gold, silver, and uranium the picture is rather different. They are in fact quite widespread in small amounts, but there are few places where there are rich concentrations. Two of them are known to every lover of western films – Cripple Creek in Colorado, and the Comstock Lode in Nevada.

Figure 24.6 The "black" Cathedral of Clermont-Ferrand is an impressive example of the architectural possibilities of the local basalt.

Cripple Creek was once the site of a volcanic cone that stood several hundred metres above the present surface level. Erosion has removed it, and exposed a complex of old feeder-pipes containing basaltic breccia, through which run veins of gold and silver-bearing ore. The capricious occurrence of rich ore and worthless basalt provides an ideal setting for the skulduggery of fictional adventure. Compared with some similar complexes in South Africa the Cripple Creek mines are shallow, even the deepest ones reaching no more than 1,000 metres below ground-level.

Although it had been worked ever since the end of the great Californian gold-rush, the real fame of the Comstock Lode dates from a "bonanza" in 1915, when a new pipe containing particularly rich ore was discovered, and silver worth about 32 million U.S. dollars was eventually extracted.

The Comstock Lode yields silver, with gold as an "impurity", and lies along a mineralised fault-zone. Repeated flooding of the workings by water at temperatures up to 64ºC makes the volcanic origin of the wealth clear; but it has resulted in many casualties, and limited the depth of the mine until costly tunnelling was undertaken to provide drainage and ventilation.

Extreme leaching of lavas eventually produces bauxite, which is predominantly a mixed oxide and hydroxide of aluminium, and is the principal ore of aluminium. Les Baux, near Arles in the south of France, where it was first discovered in 1922, is now a deserted village with a ruined castle once famed for its hospitality to troubadours. The ore was derived

Figure 24.7 The cottages of Rudès in the Auvergne are made of basalt quarried from the Massif Central, and roofed with overlapping *lauzes* of volcanic slate.

from basalt flows erupted in the early Tertiary, about 60 million years ago. Volcanic bauxites can also be found in Jamaica, and in the Australian states of Victoria and Queensland. The richer ores are usually shipped to places like Iceland and southern New Zealand, whither they are lured by cheap electricity for smelting. These countries, rather than the ones where the bauxite is mined, become regarded as sources of aluminium; but then, given a suitable environment and long weathering, almost any rock can end up as bauxite.

Prehistoric peoples in many parts of the world discovered that volcanic glass was useful for making sharp tools. Obsidian became as necessary to ancient cultures as steel is today, and trade-routes have been traced across Europe, Central America, and New Guinea. The report of Hernando Cortez that Aztec priests used obsidian knives to cut the hearts from their living sacrifical victims dramatises the matter, but obsidian also found a multitude of mundane uses, and uses in art.

Many igneous rocks are good building-stones, and some of them can readily be carved into decorative mouldings, statues, or bas-reliefs, or be polished to smooth surfaces with pleasing colours and textures. Many places owe their character to a ready supply of stone. Aberdeen has become known as the "granite city", the decorative properties of porphyry distinguished the architecture of ancient Rome, and a soft and readily-worked pinkish ignimbrite accounts for the ornately carved doorways of Arequipa. Basalt has not enjoyed the same popularity, being harder to work and dark in colour, but it is responsible for the characteristic "black" farmhouse of the Auvergne and the fine cathedral in Clermont-Ferrand (Figures 24.6 and 24.7).

The value of common substances is easy to overlook. They are apparently cheap and plentiful, but are used in large amounts. In both Britain and New Zealand, the largest single use of igneous rocks is for road chippings, and several of the scoria cones in the city of Auckland have been completely quarried away in order to surface its roads. In pre-european times, the Māori had discovered that scoria cones were excellent sites for fortified villages, and some valuable archaeological material was lost before quarrying was stopped. In many countries, scoria is used as a principal ingredient of light-weight building-blocks; and so too is pumice, which is widely used as an abrasive.

A legend current among classical scholars is that the Romans held their buildings together with a cement of superlative quality the secret of which has since been lost. The quality it possessed was in fact the ability to set under water, and the secret was re-discovered by John Smeaton, builder of the Eddystone Lighthouse, in 1755. The so-called hydraulic cement was a mixture of equal parts of earthy limestone and an ignimbritic material called pozzolana, which is to be found at Pozzuoli, near Naples, and also in the Eifel district of Germany (where Smeaton got his), in the Auvergne, and in many other places including New Zealand (Figure 24.8).

Figure 24.8 Small-scale quarrying of pozzolana near Saint Nectaire, Auvergne.

25—Ashes to Ashes, Dust to Dust

“What of vile dust?” the preacher said.
Methought the whole world woke.

G.K. CHESTERTON : The Praise of dust

Volcanic regions are fertile, and history shows that the attractiveness of fertile land is a more potent force than fear of eruptions. The lower slopes of volcanoes are among the most populated places on Earth, and the produce of these lands becomes more and more indispensable as the world’s population grows.

The soil is best understood as the place where the vegetable and mineral kingdoms meet, and agricultural soils contain much organic matter; but the rocks came first. Soils are the product of erosion. Rocks are broken into smaller and smaller fragments that become home first for bacteria and algae, then for mosses and lichens, and later for grasses, shrubs, and eventually trees. The mechanical action of their roots, and the chemical products of their decay aid the transformation to soil, and help to retain water.

Volcanic rocks are as much subject to these processes as any others, but both their physical condition and their composition naturally influence the kind of soil that results. Soil science has become a speciality with a more than usually impenetrable terminology that non-specialists should be spared. Unfortunately we cannot avoid it altogether.

Physically, the extreme kinds of soil are clays, which are impervious to water; and sand, which is excessively porous. Many of the soils most favoured for agriculture are classed as loams, which are a mixture of the two. Differences in climate have a big influence upon the transformation of rock to soil. The famous “black earth” (chernozem) of the Russian steppes may have originated as granite, basalt, or wind-blown loess (Figure 25.1). In temperate climates the granite that became chernozem in Russia may become a grey podzol (Russian pod zoiloi, like ashes) or in the tropics, where weathering can extend to a depth of tens of metres, it can turn to reddish laterite (Latin later, a brick – not because of the colour, but because it is used for brick-making).

Figure 25.1 The loess-covered cone of Fushishan, Shanxi, China.

How quickly a soil can develop depends in a large measure upon silica content, acid rocks taking a very long time to become soil. Lava-flows of any kind take a long time to weather, and so do coarse scoria and pumice deposits through which even heavy tropical rains quickly drain away. In Guatemala and San Salvador there is rhyolitic pumice that has hardly begun to weather after 2,000 years, while basaltic ash from other central American volcanoes has been successfully planted with maize a year after it was erupted. Andesitic and basaltic rocks are inherently more fertile than dacitic and rhyolitic ones. Andesitic ash on the slopes of Soufrière in St Vincent was supporting stable forest within thirty years of the eruption in 1902.

Immediately after an ash-fall there may be problems for existing vegetation and the animals that feed upon it. Not even large trees welcome a “top dressing” more than a metre thick, and very acid deposits or the presence of fluorine can seriously affect the properties of the soil. Fortunately the noxious substances are soluble, and in places where there is adequate rainfall recovery may be a matter of weeks rather than years (Figure 25.2).

The warm temperatures and high rainfalls of the tropics swiftly deplete the soils when forest cover is removed, and unless artificial fertiliser is used their usefulness as farmland may be no more than a few years. A periodic top-dressing of volcanic ash about once a decade can restore lost potassium, phosphorus, and other essential elements, and throughout Indonesia, the Philippines, and Central America the most productive agricultural lands lie downwind of the active volcanoes (Figure 25.3). Not all countries have been so fortunate. In Iceland, much of the limited pasture has been covered by basalt that will not quickly weather, while eruptions year by year continue to claim more land. On the slopes of Etna, where most people are critically dependent on small inherited plots of farmland and vineyard,

Figure 25.2 Re-establishment of vegetation on this year-old ash-deposit on Ō Shima Island, Japan has already started.

the continuing advance of lava-flows is similarly disastrous. In New Zealand quite a different kind of problem appeared.

It did not prove easy to establish pastures on the New Zealand Central Volcanic Plateau, as the soils derived from pumice and ash remained very deficient in humus. The owners of small individual farms could not afford to treat this adequately, and found as well that cattle raised on much of their property failed to thrive, a condition they call "bush sickness". The sickness was eventually found to be a result of a deficiency of the soil in cobalt and other trace-elements, which could be corrected relatively inexpensively by top-dressing with cobalt sulphate, or by providing the animals with salt-licks. Building up humus content was a more costly matter, but state development of large blocks before subdivision has proved to be a solution. High-grade pastures with a large clover content are established, along with carefully planned programmes of fertilisation and stock management. As a result of government intervention the area of pasture land on the plateau was increased by nearly three times between 1950 and 1960, resulting in a 92 per cent rise in the number of cows in milk, and 130 per cent increase in the number of sheep.

In the 1920s, when the suitability of pumice soils for agriculture was still in doubt, it was found that they would grow exotic timber. Depression years followed, labour became freely available, and 172,000 hectares of Radiata Pine were planted. Planting has continued, and more than 4,000,000 hectares of exotic forests now cover the pumice lands. This is probably the world's largest man-made forest, and provides the raw material for two of the country's largest industries, producing pulp, paper, newsprint, paperboard, plywoods, hardboard, and particle boards, as well as sawn timber. The Tasman Pulp and Paper Company's mill at Kawerau has become the world's largest industrial installation based on geothermal power. The New Zealand economy owes much more than tourism to volcanic activity; but the prosperity is vulnerable. Kawerau's forests lie just down-wind of major explosive rhyolitic volcanoes.

Figure 25.3 The richly productive paddy-fields of Java owe their fertility to the volcanic soil.

26—The Sources of Heat

I know not where is that Promethean heat
That can thy light relume …

WILLIAM SHAKESPEAR : Othello

The most important piece of information about the internal heat of the Earth that we can gather from the outside is a measurement of how much heat flows out from the inside. For a good estimate of the total we must measure the heat-flow (or geothermal flux if you prefer to be formal) in a great many different places, as geologically diverse as possible. The heat-flow is the quantity of heat that crosses a given area of surface in a given time. This is the same thing as the product of the geothermal gradient and the conductivity of the rocks, and it is these two quantities that are usually measured. Measuring either presents awkward practical difficulties.

The earliest measurements were made in mines and bore-holes using mercury thermometers, and later, the more convenient electrical-resistance thermometers, or thermistors. Problems appeared at once. The flow of ground-water and the ventilation of mines upset the conditions, and it was even found that in some regions transient surface-effects from the last ice-age still persisted – a good example of how impossible it is to move heat quickly by conduction through rock. Because of this, measurements made at depths less than 200 metres proved to be unreliable.

Drilling holes in rock generates a great deal of heat, and although the circulating drilling-mud carries much of it away, it is still some time before conditions return to normal. Since few deep bore-holes are drilled for geophysical reasons, holes must be borrowed from people who find delays to their operations expensive.

The deepest wells in which temperature measurements have been made reach about 7 km, and temperatures of more than 200ºC have been found in both the U.S.A. and the U.S.S.R. In geothermal fields, of course, higher temperatures than this can be found at quite shallow depth. If the heat-flow is measured at different levels in these deep bores it is found to be more or less the same. This means that in regions where the structure and the conductivities of the rocks are known, temperatures at greater depths can be predicted with some confidence. Calculations of this kind based on data from Iturup, in the Kuril Islands, suggest that at a depth of 50 km beneath the island arc the temperature would reach 700ºC, and in the oceanic region nearby it would be 1,000ºC.

Most geological and geophysical studies that call for data from the whole Earth are seriously biased by the difficulty of making measurements at sea, and obtaining samples from the ocean floor, but measurements of heat-flow are an exception. In 1950 Sir Edward Bullard successfully adapted a device that oceanographers had been using to get samples from the sea floor, so that it could also measure heat-flow (Figures 26.1 and 26.2). Several thermistors are fixed to the side of a hollow tube two or three metres long, heavily weighted at the top end, and provided with a sharp cutting-edge at the bottom. While the device is being lowered the tube is held by a catch that loosely gathers up a length of the supporting cable. The catch is released when a weight that hangs several metres below the tube hits the bottom and allows an actuating cord to become slack. The tube falls freely, and its weight drives it into the bottom sediment. Stabilising fins keep it vertical during its fall. Since the insertion

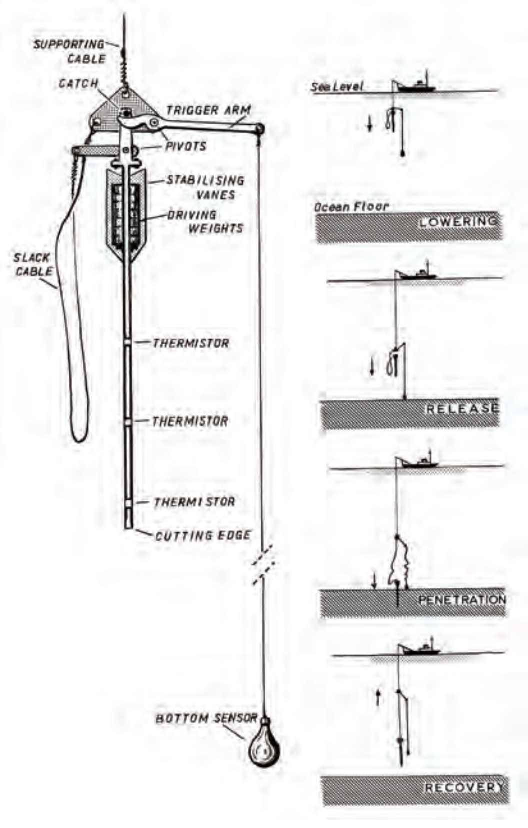


Figure 26.1 Operation of a probe for heat-flows at sea.

of the probe upsets the local temperature conditions, it must not be withdrawn until the thermistors show that they have again become stable. It can then be recovered together with a sample of sediment.

When samples of rock can be obtained, their thermal conductivities can be measured in a laboratory. The usual method is to grind the surface of the sample optically flat, and to sandwich it between copper disks, whose temperatures can be measured by using thermocouples or thermistors. If the upper one is heated by means of an electric coil, and the lower one cooled with a flow of water, the quantity of heat supplied can be found by both an electrical and a direct mthod.

Unconsolidated sediments present more of a problem. In a laboratory a hollow needle-probe containing a heating-coil and a thermistor can be inserted, and the conductivity calculated from the amount of heat supplied and the time it takes for the temperature to rise. A rather similar method, in which a heating-coil is placed in a bore-hole, can be used in the field.

Measurements of heat-flow are usually quoted in microcalories per square centimetre per second, and the average value is about 1.4 or 1.5 of these units. This is convenient when we wish to compare the heat-flow at different points on the Earth's surface, but less so when we are concerned with such matters as the cooling of the whole planet. It is then more convenient to quote the total quantity of heat involved. A calorie is the amount of heat required to raise the temperature of one gram of water by 1ºC and is approximately equal to 4.18 joules (readers on diets should note that their Calorie is a thousand times bigger, and should have a capital letter). Scientists have now agreed to use the joule for measuring all kinds of energy, but old habits persist.

Figure 26.2 Technicians preparing a short probe for measurements of heat-flow in Lake Manapouri, New Zealand.

In the first twenty years after Bullard's equipment came into use, more than 3,000 reliable measurements were made, and there are now many more available for the oceans than for the continents. They fall into two groups – those in normal areas, which range between about one and two units; and those in volcanic regions where values as high as 25 have been found to extend over areas as great as 100 sq. km. On the crests of the mid-Atlantic Ridge and the East Pacific Rise values of about 8 are common, but they quickly fall to normal on either side of the crest. The unexpected discovery was that there was little difference between continental and oceanic values, a topic to which we will return.

How much of this heat comes out of volcanoes? The total output of the Earth is about 10^{21} joules per year. A large eruption produces perhaps 10^{15} to 10^{18} joules, and although the output of a volcano can be spectacular it is localised and short-lived. Eruptions as big as this are to be expected only about once in five years.

If the Earth had been losing heat at the present rate ever since it was formed, it would by now have lost a total of some 2.3×10^{31} joules. This is only about a fifth of the amount needed to raise its original temperature sufficiently to produce a molten core. Clearly there are still large reserves of internal heat. Heat-flow and temperature are far from being the same thing, and it is much harder to explain high temperatures than to explain large quantities of heat.

We have already disposed of Lord Kelvin's simple picture of a cooling Earth; but it has left us with a new set of problems. If he overlooked one important source of heat, could we have overlooked others? The particles that came together to form the primitive Earth must have produced a fairly homogeneous mixture of metallic and silicate material, whose radioactive constituents would at once begin to heat it. Since the outer parts of the planet would be able to cool by outward conduction and radiation from the surface, the first part to melt would probably lie at a depth of about 400 km. The metals are denser than the silicates, but they have a much lower melting-point, and the result would be a shell of liquid containing lighter solid particles. By a process rather like magma intrusion in reverse the heavy metallic liquid would find its way towards the centre, and gravity would finally produce the division of mantle and core.

Opinions about the speed with which this could happen are sharply divided, one view being that is has continued throughout the Earth's history and perhaps still continues; but the more commonly-accepted view is that it was a fairly rapid process. A factor that results in very different time-scales is whether long-lived or short-lived isotopes played the larger part in the initial heating. A third view is that the core was the first to form, and became a nucleus to which the rest of the material accreted. The movement of mass to the centre would transform a large amount of potential energy to heat, mainly through friction and viscous flow, and re-distribution would store some of it as elastic strain.

A source of heat-energy that was much more important in the remote past than it is now is the slowing of the Earth's rotation by tidal friction. The gravitational pulls of the Sun and Moon raise tides in both the oceans and the solid Earth, but the division of energy between the two effects is very uncertain; and so too is the original speed of the Earth's rotation. Supposing the original length of the day to have been about three hours, the slowing by tides in the solid Earth alone would raise its internal temperature by 2,000ºC. If, on the other hand, ninety per cent of it were dissipated in shallow seas, the rise produced would be only 200ºC. The heat being generated at the present rate of slowing must be reckoned as negligible.

During the earliest stages of accretion of a much larger quantity of heat was supplied by the kinetic energy of the accreting particles. Energy released in collisions would have been more than enough to raise the initial temperature to its present value, but nearly all of it would at once have been radiated into space, without having a chance to heat the inside. On the other hand, compression and compaction of the material could raise the temperature at the centre by as much as 900ºC, but would produce no rise at all at the surface.

The radioactive elements that are now making the greatest contribution to the Earth's heat are uranium, thorium, and potassium, which have isotopes whose half-lives range from 700 million to 14,000 million years. These long-lived isotopes are important constituents of both granites and basalts. At an early stage in the formation of the Solar System, short-lived isotopes would also have been present, most importantly an isotope of aluminium with a half-life of 730,000 years. This would remain an effective source of heat for some ten million years. If the Earth came together sufficiently early during the process of formation, these isotopes could have supplied enough heat to cause its initial melting.

It is impossible to over-emphasise the contribution of seismology to our knowledge of the Earth's interior. Seismic waves are not limited to providing estimates of average conditions over long paths, for the combination of results from many earthquakes can produce highly reliable measurements of fundamental properties like density and rigidity right to the centre. One of its earliest achievements was to show that the core was liquid, and later measurements have been unable to vary Gutenberg's value of 2898 km for the depth to the core boundary by more than a kilometre or two.

Since the core is liquid and the mantle solid, we can place limits upon the temperature at the boundary. Seismologists can give us good estimates of the pressure at that depth, so that we can allow for its effect upon the melting-points, but unfortunately the chemists cannot provide equally certain information about the composition of core and mantle. We know that the core must be largely iron, and that allowing for the pressure the melting point at the boundary should be 3,725ºC – but small amounts of impurity could change it quite a lot. Fortunately nickel, which is the element most likely to be present, would not upset it much; but 15 per cent of silicon would lower it by 300ºC, and we have no idea what effect magnesium oxide could have.

Assuming this melting-point to be a lower limit, how much hotter could it be? Since the core is metallic, liquid, and a good conductor of heat there cannot be big temperature differences inside it, and the behaviour of the Earth's magnetic field suggest that movements take place within at a rate that, by the standard of most geophysical processes, is quite high. Increasing pressure increases the melting-point, but the inner core – which is thought to consist of the same material – is solid once more, and we are forced to conclude that there can be no great rise in temperature. The likely temperature at the centre must therefore be close to 4,000ºC.

It is harder to apply melting-point arguments to the mantle, as we are much less sure what it is made of. Seismology tells us that just below the crust its density is about 3.5 Mg/m^3. It increases fairly rapidly for the next 600 km or so, to about 4.25 Mg/m^3, and then more gradually until at the core boundary it reaches 5.5 Mg/m^3. This change in the rate of increase is not marked by a sharp boundary, but the two regions are often distinguished as the Upper and Lower Mantle.

We cannot be certain that any kind of rock found at the surface has come without change from the mantle, but there is not a very wide range of plausible choices if we are to match the density and other physical properties we know. Chemistry and petrology impose further constraints. Popular suggestions are dunite, peridotite, pyroxenite, and eclogite. Laboratory workers have expended much effort in mixing, heating, and squashing these rocks in the hope of reproducing the measured characteristics of the mantle. One of the most popular mixtures is called pyrolite, which is a sort of hypothetical peridotite prepared from a recipe of the Australian geochemist A.E. Ringwood, using three parts of dunite and one of basalt.

During the Earth's early history there has twice been a major sorting-out of constituents in the interior. The first produced the core; and the second, the primitive continental crust. When the core was formed, most of the radioactive elements remained in the mantle, which almost at once separated into upper and lower parts, with a further concentration of radioactivity in the upper one. Formation of the continental crust involved yet another upward movement of long-lived isotopes, depleting the upper mantle beneath the continents, but leaving the oceanic areas unchanged. The result has been to produce roughly equal heat-flows at the surface from rather different temperature distributions inside.

Figure 26.3 brings together the best information we have about melting-points and temperatures at different levels inside the Earth. There is little chance of the entire crust or lower mantle melting, but the temperatures in the upper mantle are quite close to melting-point; and were it not for convection the basalt beneath the sea floor would almost certainly melt. The existence of magma in the upper mantle is therefore not surprising, but it does depend upon lateral variations in the temperature gradient, a possibility we have neglected in considering the broader structure of the Earth, though it is implicit in the ideas of convection and subducted slabs.

It is perhaps justifiable to run the risk of circular argument in the hope of reaching valid conclusions by successive approximation. Composition, melting-points, and inferred temperatures are related, and it is possible to begin from any point we consider soundly based. The melting-point of granitic rocks depends to a great extent upon their water-content, but a reasonable value at the surface is about 700ºC, from which it follows that the continental crust is unlikely to be thicker than 30 or 40 km, a figure that seismologists can confirm.

Seismologists have traditionally referred to the oceanic crust and the lower layer of the continental crust as "basaltic". Along with the description of the upper mantle as "ultra-basic" it is a useful description, but it is instructive to consider its shortcomings. Taking into account observed geothermal gradients

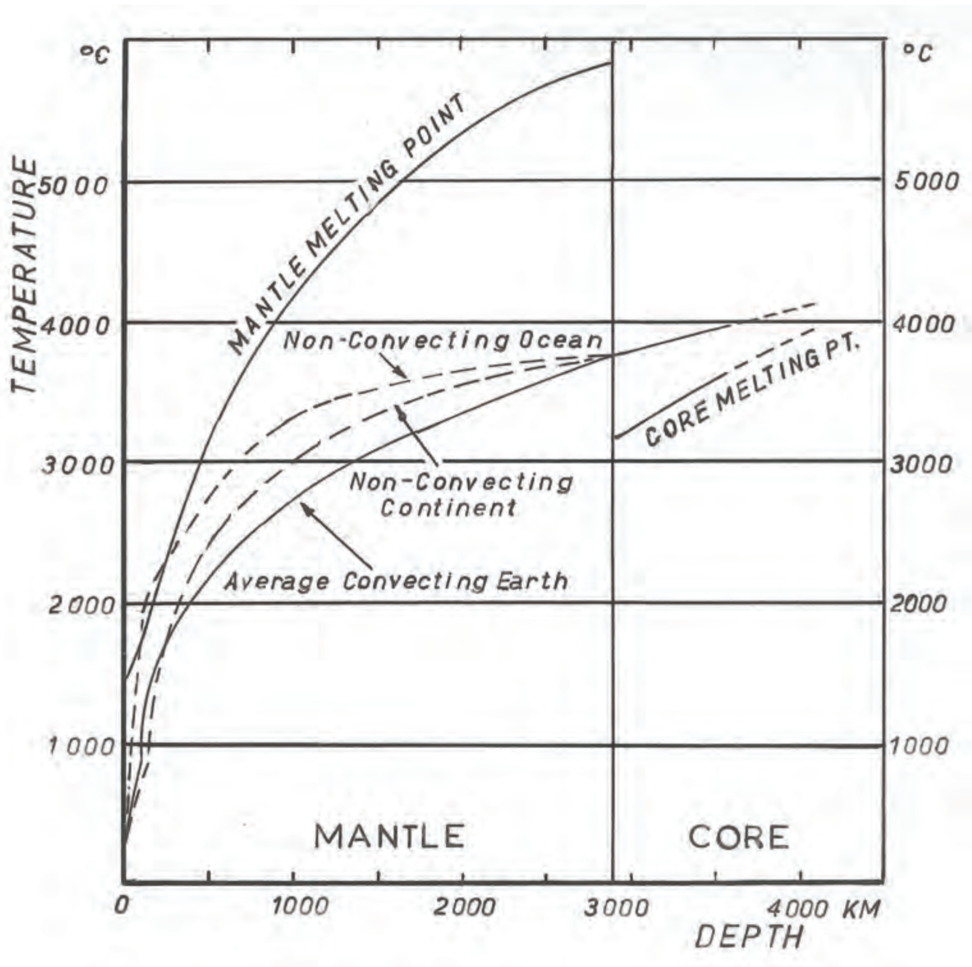


Figure 26.3 Internal temperature of the Earth. This graph shows the limits to the possible values set by different hypotheses about the Earth's internal structure.

and the known effects of pressure, the temperature at the base of a typical continental crust 35 km thick is between 500º and 600ºC. When the heat-flow or the crustal thickness is greater than normal, higher temperatures are to be expected. It is not always possible to detect a sharp transition from a "granitic" to a "basaltic" layer, and it is probable that we should be looking for a different mixture of minerals, and not a change of chemical identity. The traditional argument for a "basaltic" layer – or rather a layer of the coarse-grained gabbro, which matches the velocity of P-waves closely, and was thought more likely to occur at deeper levels – was that it was needed to provide a source for basaltic magmas. The plate-tectonic hypothesis and the upper-mantle structure implicit in it make it more likely that these magmas come from below the crust. Eclogite, a high-pressure modification of gabbro, and a popular candidate for a position in the upper mantle, has far too high a P-velocity to occupy a significant place in the crust. If basic rocks are to be ruled out, what possibilities are left? Much seems to depend upon the amount of water available. If the lower crust is "dry", high-pressure modifications of diorite and granodiorite are capable of producing the right velocities, but if it is "wet", a "basaltic" mix of amphibole, plagioclase, epidote, and garnet becomes more probable.

One indication of temperatures in the upper part of the mantle comes from the study of kimberlites, which occur in geological structures called diatremes (Greek dia, through; trema a hole). These are carrot-shaped holes or pipes passing through solid basement rock and filled with a rather chaotic mixture of angular rock-fragments and nodules, that range from bits of coal to pieces of peridotite and diamonds. Their formation remains somewhat of a mystery, some geologists invoking ever-deepening phreato-magmatic explosions, and others believing in a long-continued and non-violent circulation of fluids that break pieces from the walls and roof. At the surface, they often end in a maar. Were it not for the diamonds it is unlikely that we would know much about them at all, but the great Kimberley mines in South Africa go down almost a thousand metres below the present surface. It is estimated that erosion has already removed another thousand metres of sediment (Figure 26.4).

Kimberlites from the mantle, which include the diamonds, indicate that at a depth of about 100 km temperatures up to 2,000ºC must exist at least briefly. Readers seeking a diatreme may find one beneath a maar, but dry ones in various stages of erosion can be found in Montana, New Mexico, Scotland, Germany, and Australia.

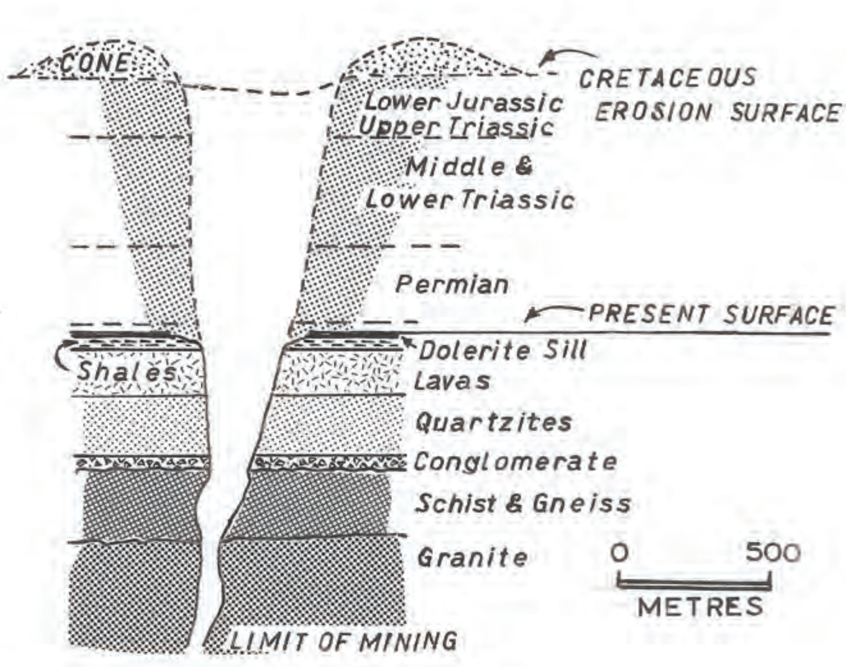


Figure 26.4 Cross-section of the Kimberley diamond mine – a diatreme – illustrating the occurence of Kimberlites.

27—Around the Ring of Fire – I

Circles and right lines close all bodies,
And the mortall right-lined circle, must conclude and shut up all.

SIR THOMAS BROWNE : Hydriotaphia – Urne Buriall

In an early chapter we described the broad geographical pattern of present-day volcanic activity, and the explanation of it that the ideas of sea floor spreading and plate tectonics can offer, and in describing its diverse forms and consequences we considered volcanoes and eruptions in many parts of the world. Many that are worthy of our attention remain to be described. Volcanoes are only part of a broader pattern that is complex and changing, and includes earthquakes, gravity and magnetic anomalies, and topographic relief. In grouping those we have yet to describe we have therefore decided to follow a traveller's route rather than try to fit them to a pattern whose details are still matters of controversy.

Long before the days of plate tectonics, volcanologists felt that there was some special significance in the number of active volcanoes that encircled the Pacific Ocean, and began to write of them as the "Ring of Fire" (Figure 27.1 see next page). Associated with it were earthquakes, and seismologists included the earthquakes, the volcanoes, and associated geological and geophysical features in what they called the "Circum-Pacific Mobile Belt". Later they would describe it as the margin of the Pacific Plate.

As long ago as 1912 the New Zealand geologist Patrick Marshall noticed an important difference between the active volcanoes on the circumference of the Ring, and those of the volcanic islands like Hawaii and Samoa which it enclosed. The volcanoes of the Ring had lavas that were predominantly andesitic, and those of the oceanic ones were basaltic. In the western Pacific he was able to trace an Andesite Line, marking the boundary between the two, but he found it less easy to define along the coasts of South America. Most later writers admit only andesitic volcanoes to membership of the Ring, even when they are geographically very close to the margin.

The Ring is not, of course, a continuous physical feature, but divided into segments that differ widely in character, including both long sections of the active margin of the American continent and island arcs as short as the Bismarck Archipelago or as long as the Aleutians. The breaks in activity and abrupt displacements that mark the divisions coincide with the many transverse fractures that characterise the plate margin. What the segments have in common is that they are zones of subduction.

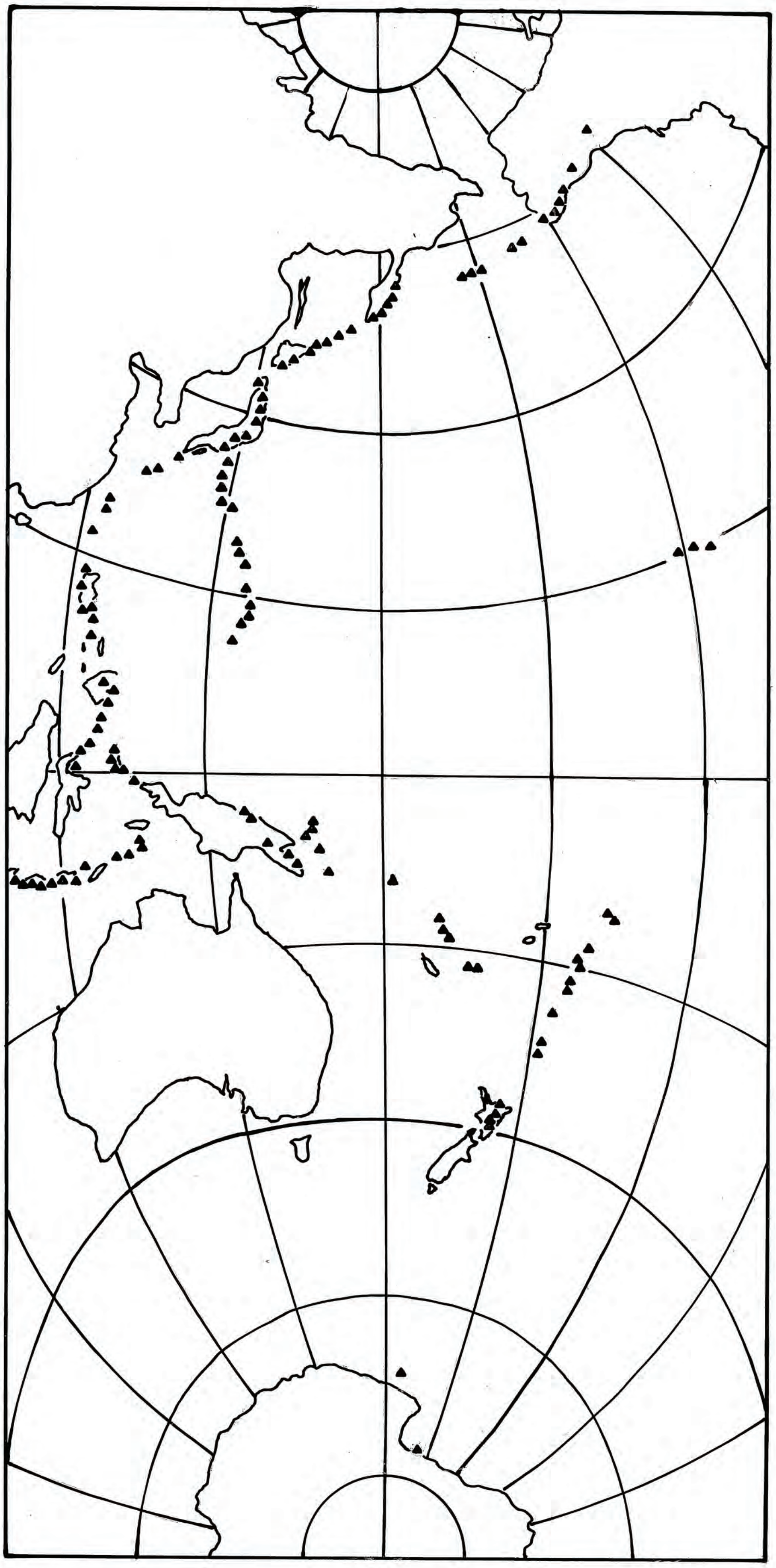
Almost every writer on the world's volcanoes seems impelled to undertake a tour of the Ring. Some go clockwise, and some anti-clockwise, and almost every possible starting-point seems to have been chosen by someone. We shall start at home in New Zealand, and travel clockwise – but not without a preliminary glance over our shoulder.

New Zealand is not one system, but two. In the North Island and northern parts of the South Island, the Pacific Plate is being drawn or thrust beneath the Indian Plate; while in the far south, the Pacific Plate is uppermost, and the Indian Plate is being subducted. The volcanoes of the North Island are active, those in the South Island probably extinct. So most probably are those of the sub-antarctic islands – Auckland, Campbell, and Macquarie – that mark the southward course of the plate margin towards its triple junction with the Antarctic Plate.

The volcanoes of the south may be dead, but there is still vigorous seismicity, and other features of a subduction zone can be traced. Tiny Solander Island – which turns out to be a group of two craggy islets and a few large rocks – guards the western approaches to Foveaux Strait. Unlike the more obvious evidences of older volcanism represented by the basalts of the Otago and Banks Peninsulas, Solander is andesitic. It lies 40 km off the South Island coast and rises abruptly to over 300 metres, but as a representative of recent volcanism seems somewhat inadequate. The same may be said of the "foredeep", for although there is deep water off the Fiordland coast, it is hard to find a proper trench. The deep-focus earthquakes are certainly there, tightly bunched beneath Lakes Te Anau and Manapouri, but their maximum depth is only about 120 km, and the gravity anomalies are not just where they should be to make a tidy pattern.

Those seeking text-book examples will find the North Island altogether more satisfactory. The Hikurangi Trench off the east coast marks the transition from the Indian to the Pacific Plate; a belt of negative gravity anomalies extends from south of Cook Strait to East

Figure 27.1 *The Ring of Fire* – It is impossible to show and identify all the volcanoes that make up the Ring of Fire on two small scale maps; but the maps and names listed on these two facing pages should make it possible to follow the route described in Chapters 27-35, and to identify the structural divisions of the Ring. Names of regions of oceanic volcanism that do not form part of the Ring are enclosed in square brackets.



Kurile-Kamchatka (Ch. 31)
- Bezymianny
- Tobal'chik

Hokkaido (Ch. 31)
- Usu
- Tokachi

Honshu (Ch. 30)
- Fujiyama

Left Branch
- Kyushu (Ch. 31)
  - Aso
  - Unzen
  - Sakurajima
- Ryukyu Is (Ch. 30)
- Taiwan (Ch. 30)
- Philippines (Ch. 30)
  - Taal
  - Mayon
- Sangihe Is (Ch. 30)
- Sulawesi (Ch. 30)

Right Branch
- Kazan-Bonin Is (Ch. 30)
  - Ō-shima
- Mariana Is (Ch. 30)
- Halmahera (Ch. 30)

New Britain-New Guinea (Ch. 29)

Bismarck Sea (Ch. 29)
- Lamington
- Goropu (Ch. 7)

Solomon Is (Ch. 29)

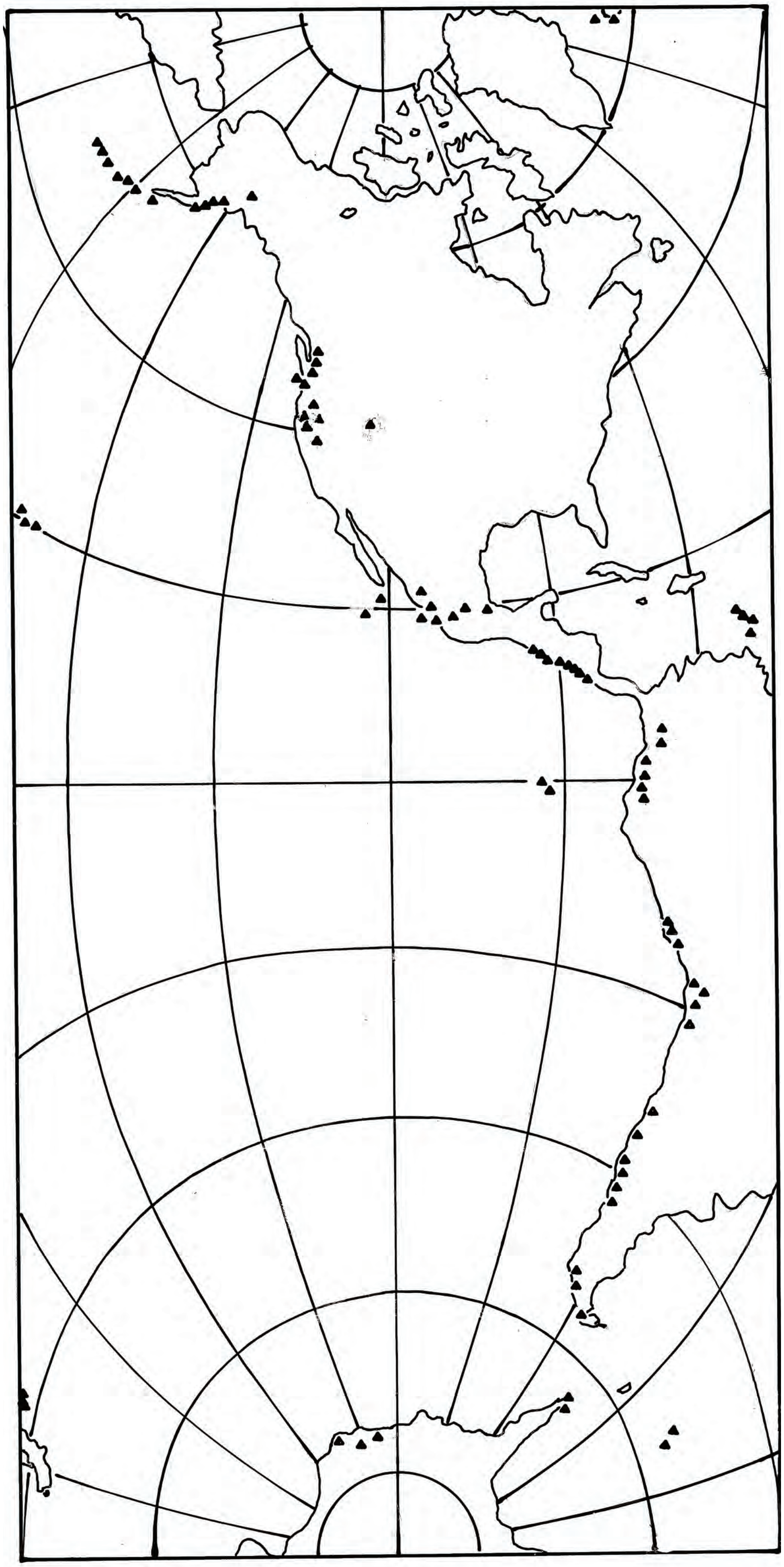
Vanuatu (Ch. 29)
- Ambryn
- Yasour (Ch. 18)

(Samoa) (Ch. 29)

Tonga-Kermadec (Ch. 29)
- Raoul Is.

New Zealand (Ch. 27,28)
- Ruapehu (Ch. 12)
- Egmont (Ch. 12)

Antarctic (Ch. 35)
- Erebus



Aleutian Arc (Ch. 32)
- Bogoslov (Ch. 13)
- Shishaldin

Alaska (Ch. 32)
- Pavlov
- Katmai (Novarupta)

Canada (Ch. 33)
- Edziza

Western USA (Ch. 33)
- Mt Baker
- Mt Rainier
- Mt St Helens
- Lassen Peak

(Hawaii) (Ch. 13)
- Kilauea
- Mauna Loa

(Revillagigedo Is) (Ch. 33)
- Socorro

Caribbean Arc (Ch. 33)
- Mont Pelée
- La Soufrière (St Vincent)
- La Soufrière (Guadeloupe)

Central America (Ch. 33)
- Popocatépetl
- Parícutin
- El Chichón
- Fuego
- Poás
- Arenal

(Galapagos Is) (Ch. 34)
- Fernandina

Columbia-Ecuador-Peru (Ch. 34)
- Nevada del Ruiz
- Galeras
- Reventador
- El Misti
- Ubinas

Bolivia-Chile (Ch. 34)
- Lascar
- Puyehue

Antarctic (Ch. 35)
- Deception Is.

Figure 27.2 White Island in a calm mood.

Cape. Behind it lie the active volcanoes of the Central Volcanic Region, and there are older volcanoes farther to the west. Earthquake activity begins at the Trench. Shallow shocks extend across the island, and deeper activity follows the subducting slab, reaching more than 600 km under north Taranaki.

Whether we choose to dismiss the Ring of Fire as a pleasant but outdated poetic conceit, or still accord it some geophysical significance, most of us will expect to find it marked by signs of present activity, or at least volcanoes that have erupted in the recent past. From this point of view, the beginning (or should it be the southern end?) of the Ring is marked by some small explosion-pits near Ohakune, about 15 km south of Ruapehu, 2,796 metres high, New Zealand's tallest volcano, and already discussed in other contexts.

Forty kilometres to the north in the centre of the island is Lake Taupo – a hole, not a hill. The Lake is a complex of calderas, an inverse volcano that was once the source of prehistoric eruptions of ignimbrite and pumice that have left traces over the whole island. To outward appearances, the other end of New Zealand's chain of active volcanoes is marked by White Island, in the Bay of Plenty, which is lively enough to make those who live near the coast thankful that it lies 50 km off shore (see Figure 27.2). In 1966 Professor Kibblewhite of Auckland University detected persistent underwater noises that came from a group of sea mounts about 190 km to the north-east. They were generally supposed to be active submarine volcanoes, became known as Rumble I, II, III, and IV, and were admitted to the list of New Zealand volcanoes. Recently the identification has been questioned, spoiling a tidy pattern, for a line drawn from Rumble III to Ruapehu passes within 10 km of White Island, Tarawera, and the vents of Ngauruhoe and Tongariro, thus aligning the centres of every eruption during the last century. To the north-west of this volcanic front there is increasingly older volcanism; to the south-east there is none. Mount Egmont, to the west of the front, has not erupted since the eighteenth century, but it is certainly not extinct, and in view of the populated farmland and the towns that surround it, it is probably the most acute of the country's volcanic risks.

28—New Zealand in the Making

… ere Nature's self began to be
'Twas one vast nothing …

ALEXANDER POPE : On Silence

New Zealand volcanism began well before any land that resembles the islands that exist today stood above the Pacific. Volcanic rocks that date from the early Cambrian period, perhaps 550 million years ago, are to be found in north-west Nelson; but it is not until about 240 million years ago, near the end of the Palaeozoic era, that one can find sufficiently numerous and extensive deposits to enable even a tentative map of things as they were to be drawn.

Figures 28.1 to 28.3 are based on maps prepared by Dr G.R. Stevens and Dr R.P. Suggate of the New Zealand Geological Survey. They have been modified in an attempt to show the extent and relative positions of the active volcanoes at each period more clearly by reversing the movements on the great Alpine Fault, along which relative movement of the Indian and Pacific Plates has gradually sheared the country. This is a highly conjectural reconstruction, and Drs Stevens and Suggate are not to be blamed for any shortcomings in it.

Towards the end of the Permian, 240 million years ago, an extensive land-mass, probably continental in structure, lay to the west of the present position of New Zealand. To the south, off its east coast, a field of vigorously-active submarine volcanoes had developed. They produced typically oceanic basalt, but there were a few more-acidic volcanoes on the coast nearby. Later, movement of the Alpine Fault would

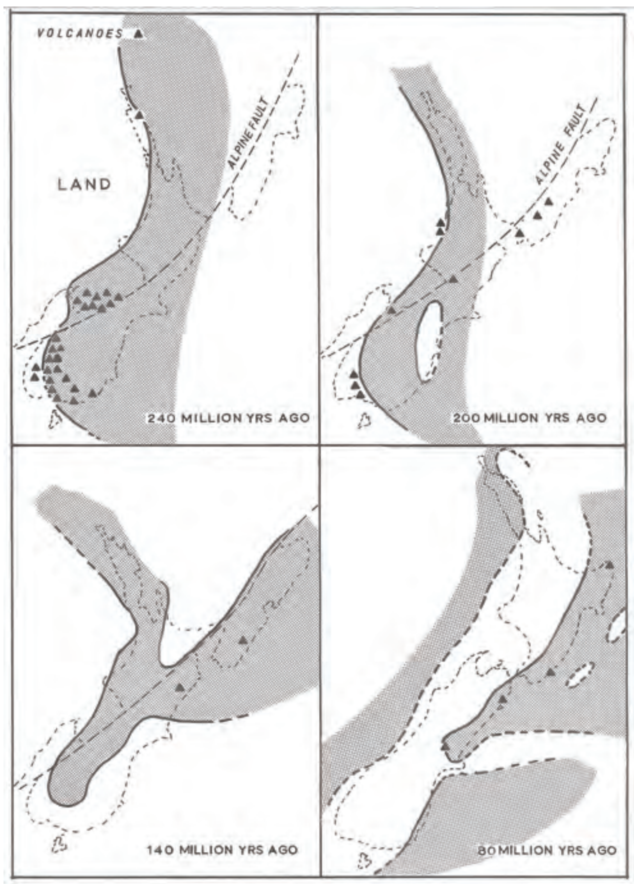


Figure 28.1 New Zealand volcanoes active between 240 and 80 million years ago, based on reconstructions by G. R. Stevens and R. P. Suggate. The broken line shows the former position of the present-day coastline, before displacement by later orogenies and transcurrent movement of the Alpine Fault.

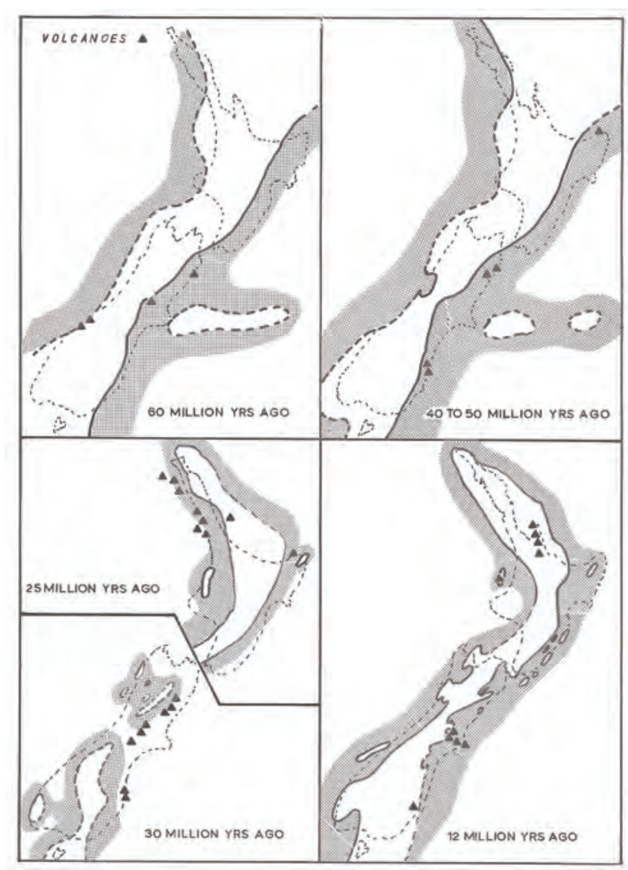


Figure 28.2 New Zealand volcanoes active between 60 and 12 million years ago.

split this field apart – so that its westerly members are now to be found in Nelson, and its easterly ones in Otago. Six hundred kilometres to the north there was a second less extensive and less vigorous centre of Permian volcanism, which produced the layers of rhyolitic lava that separate the limestone beds of Northland.

Over the next 40 million years, during the Triassic period, the rivers of the western continent deposited their sediments in the sea. An island appeared off the coast, and grew southwards to join the land. The tightly-grouped Permian volcanoes died out, and a new line of younger ones appeared along the coast. From the north of the island, a second line ran north-eastwards, perhaps becoming a feature of an island arc, and heralding the future appearance of the Southern Alps and the great Alpine Fault. The dykes and pillow lavas of Island Bay and the Red Rocks, near Wellington, and the igneous rocks of the Wairarapa also belong to the Triassic. By then volcanism had spread more widely, but compared with any other period since the Permian it was a time of comparative quiet.

At the end of the Jurassic, 140 million years ago, dying volcanism persisted beneath a narrow land-locked arm of shallow sea, in what would before long become North Canterbury and Wairarapa. Only an eroded remnant of the old land-mass remained, and the sea covered an enormous deposit of sediment, estimated to have been 27 km thick. Soon it would be folded and raised from the sea-bed in a convulsion known as the Rangitata orogeny. It would last about 50 million years, and when it was over the shaping of the Southern Alps would have begun. At last it is possible to recognise the New Zealand of today, though major changes in the coast-line would continue, some the result of large tectonic movements, and others related to the Ice Ages and changes in sea level.

The first volcanoes that belong to the new pattern appeared during the late Cretaceous, about 80 million years ago, but their positions were not greatly different. They stretched northwards from about Banks Peninsula, in a line parallel to the east coast. They were basaltic, and submarine, for accumulating sediment from the newly uplifted mountains had yet to build the Canterbury Plains and extend the east coast of the North Island seawards. At least another 60 million years would pass before the still-continuing movements that produced the Kaikoura Ranges would begin.

The Cretaceous period was one of particularly intense volcanic activity, and before it was over nearly every part of the country would be affected; but all this did not take place simultaneously, as the successive maps should make clear. In the South Island, the activity

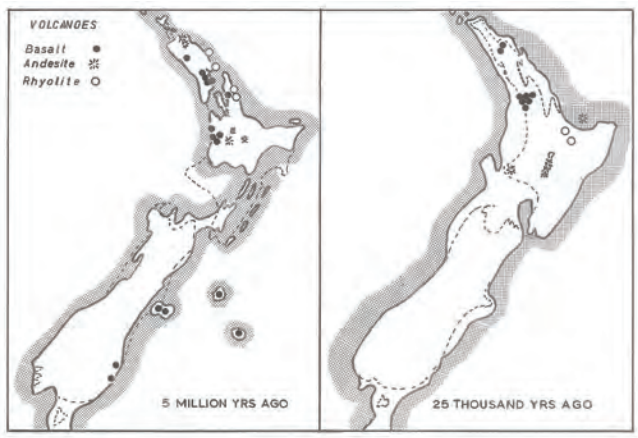


Figure 28.3 Distribution of basaltic, andesitic and rhyolitic volcanoes in New Zealand 5 million and 25,000 years ago.

was intrusive rather than eruptive, but it was very wide-spread, and persisted until well after the end of the Cretaceous, until perhaps 30 million years ago, displaying a last burst of vigour before all activity was abruptly transferred to the far north. This move probably produced the Tangihua volcanics (Chapter 13), but geologists disagree about their age.

Later changes can be more easily followed from the maps. Most of the best-known "extinct" volcanoes of New Zealand, like those of the Coromandel, Banks, and Otago Peninsulas had made their appearance by the end of the Miocene (about 5 million years ago) and were, if not still young, at least in a state of health and vigour, (Figure 28.4).

Though recent studies suggest that the Dunedin volcanoes were not to last much longer. The active areas were moving northwards, and they finally died about a million years ago, leaving the andesitic rocks of Solander Island, and two basalt lava-flows, at Timaru and Geraldine, as final reminders of the

Figure 28.4 The busy port of Lyttelton lies in one of two breached calderas on Banks Peninsula. It is linked with the city of Christchurch by road and rail tunnels through the crater wall. The rail tunnel, pierced between 1861 and 1867 is 2.4 km long, and enabled Julius von Haast to make the earliest important geological cross-section of a volcano.

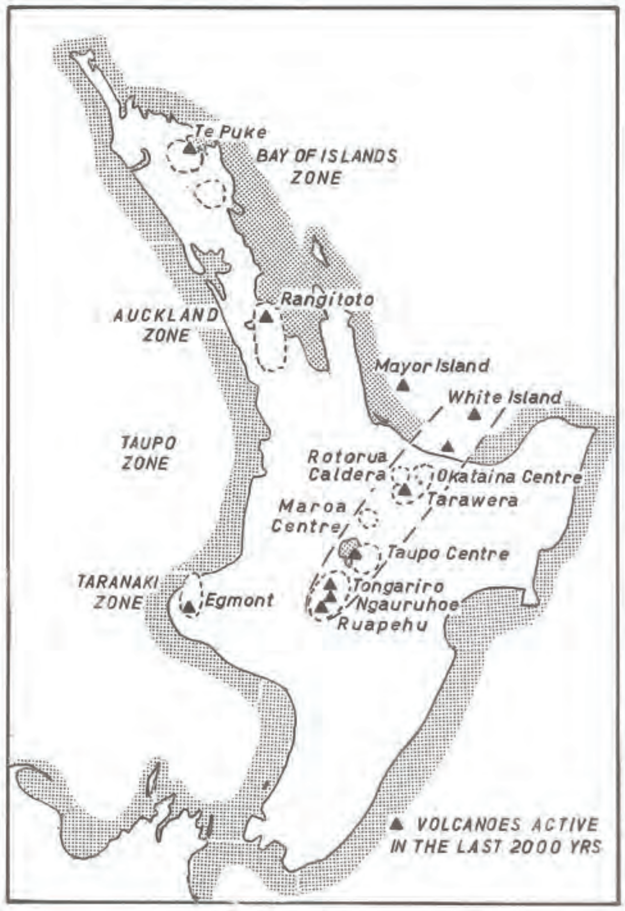


Figure 28.5 Volcanoes of the North Island of New Zealand active during the last 2,000.

volcanic history of the south. The basalts cover about 140 square km, and geologists have not been able to locate their source exactly, but they are found to be magnetised in a direction opposite to the Earth's present magnetic field, making it reasonably certain that they were erupted about a million years ago.

The present-day pattern was then appearing, and was fully established 25,000 years ago, but many prominent features of today's landscape were not built until much later. Figure 28.5 establishes the main centres of activity within the last 2,000 years. Any field that has been active so recently must be considered active still, but these are not the only centres that could wake again. Five volcanoes have erupted within the last century – White Island, Tarawera, Tongariro, Ngauruhoe, and Ruapehu – and two of the submarine Rumbles appear to be active. The dates of the most recent eruptions are summarised in the Appendix.

There is a clear pattern both in the age of the volcanoes and in the predominant composition of the erupted material. The Northland and Auckland zones are characteristically basalt, while andesites are to be found at the ends of the Taupo Zone, with rhyolites in between. Mount Egmont produces very alkaline andesites.

The most obvious signs of activity to be found in the Bay of Islands zone are the hot springs of Ngawha, once among the better-known spas. In recent years its popularity has declined, but investigations suggest that the springs are a potential source of geothermal power. It has been claimed that the last eruptions in the Te Puke field occurred between A.D. 200 and A.D. 700, but an estimate of 15,000 B.C. is probably to be preferred. There are well-preserved scoria cones, and the field as a whole has been active throughout the last two million years. The Whangarei volcanic field, some 90 km to the south, has experienced about 14 eruptions in the last two and a half million years, and although the last of them was about 34,000 years ago, it would be premature to declare it extinct.

Auckland's volcanoes first appeared during the last Ice Age, about 60,000 years ago. There have been eruptions from at least fifty centres within about 20 km of the Central Post Office. They have ranged in character from phreatic explosions that have left circular maars surrounded by gently-sloping tuff rings, to quiet and short-lived effusions of basalt from numerous separate vents (Figure 28.6). A few of these were submarine, and have produced some fine examples of pillow-lavas, but most of them were on land. The character of the overlying rock determined whether there would be an explosion or not, the phreatic eruptions occurring beneath the most recently-deposited sediment or beneath the sea, and the effusive flows in areas of older and more consolidated rock.

Professor E.J. Searle of Auckland University considers the Auckland volcanoes notable both for the concentration of so many individual volcanoes in so small an area, and for the complex structure of the miniature scoria cones (Figure 28.7). Yet what makes the field unique, he writes "is not their size and number, but the fact that a great city has been built around and among them" – but had the volcanoes not

Figure 28.6 Black Reef in Auckland's Waitemata Harbour, exposed only at low tide, is a flow of basalt that once filled the course of a stream valley since removed by erosion. It extends some six kilometres from its source in the crater of Mt Eden.

Figure 28.7 Browns Island or Motukorea in the Auckland Vocanic Field contains a complete scoria cone and several scoria mounds.

shaped the land and formed the city's two harbours, the site might well have lacked the qualities that attracted its first citizens.

There is no very clear time sequence to be found in the grouping of the Auckland volcanoes, but the oldest centres are to be found in Albert Park, Symonds Street, and the Domain, in the heart of the business area. The youngest is the shapely island of Rangitoto (see Figure 3.1). Its last certain eruption was in about A.D. 1100, but all the vegetation is more recent, and this has been read as a sign that there was more activity in the seventeenth century. Although only 5 km across and 260 metres high, it is by far the largest volcano in the field. At the summit there is a crater 60 metres deep and 150 metres across, and there are remnants of older craters on the northern slopes. Distant views suggest that Rangitoto has some kind of summit caldera, but the impression is due to the existence on the southern and eastern sides of a structure that local geologists call a "moat", at a height of about 150 metres. It marks the junction of lava-covered lower slopes with the scoria cone above. A possible explanation is that after a quantity of lava had been expelled from lateral vents, the summit cone subsided into the cavity and left a kind of "wrinkle". In fact, the amount of lava expelled from the Auckland volcanoes is not very great – perhaps 10 cubic km from all 50 vents – but Rangitoto accounts for fully half of it.

Figure 28.8 Mt Egmont viewed from Dawson's Falls.

Figure 28.9 Moturoa, one of the Sugar Loaves, is the remnant of an old andesitic volcano near New Plymouth. During the last 2 million years the centre of activity migrated southwards from here, via Kaitake and Pouakai Range to Mt Egmont.

Mount Egmont, the almost perfect 2548-metre cone dominating the province that bears its original name of Taranaki, last erupted in the first half of the eighteenth century (Figure 28.8). Its isolation is not so complete as the casual viewer might suppose, for the ridge that extends north-westwards towards the city of New Plymouth is the eroded remnant of two older andesitic volcanoes, both of them large. Kaitake is about half a million years old, and Pouakai about half that, compared with Egmont's 50 to 70 thousand years. The Sugar Loaves (Figure 28.9), just south of the city, are the remnant of yet another and still older volcano.

The Central Volcanic Region occupies a great depression averaging some 30 km in width, bounded and cut by faults, and extending for over 250 km from Ohakune, 20 km south of the active Mount Ruapehu, to the Bay of Plenty, White Island, and the submarine Rumbles. Within it can be found not only active volcanoes and a wide range of hot springs, geysers and other hydrothermal manifestations, but ski-fields, forests, lakes, and trout streams, making it not only a major holiday area for New Zealanders, but an attraction to visitors from the most distant parts of the globe.

Volcanic activity has persisted here for perhaps a million years, yet some of the most obvious features of today's landscape have been shaped almost within historic time, being successively modified by outpourings of lava, ignimbrite, and ash, and by great subsidences damming and diverting rivers and streams, and creating basins for new lakes.

Ngauruhoe is the youngest of the three great volcanoes of the central North Island. In about 500 B.C. the foundations of its present symmetrical cone, 2290 metres high, were laid on the ruins of a previous one that was destroyed some 8,000 years earlier. It is really a vent of Tongariro that has outgrown its parent, in all probability only temporarily. The less regular forms of Tongariro (1,986 m.) and the loftier Ruapehu (the highest peak in the North Island, at 2,796 m.) are evidence of a longer and more complicated history in the course of which lava-flows, showers of ash, lahars, phreatic explosions, the opening of new craters, and the appearance and disappearance of summit domes have repeatedly changed their contours. The last significant eruption of Tongariro was in 1896, but both Ngauruhoe and Ruapehu have erupted within the last decade, and are frequently active. Tongariro is certainly only dormant.

Within the Central Volcanic Region are the remnants of six great calderas, Rotorua, Okataina, Kapenga, Mangakino, Maroa, and Taupo. From these centres hundreds of cubic kilometres of rhyolite were erupted, leading to the collapses that formed the calderas. Rhyolites are highly acid rocks, rich in silica and very viscous, and catastrophic explosions occurred, distributing pumice and ash over much of the North Island, and producing the ignimbrites that cover much of the volcanic region (Figure 28.10). The earliest outbreaks in the Central Region were probably at Mangakino over a million years ago, but there were many such episodes, and by about a quarter of a million years ago the activity had become concentrated near Taupo.

The ignimbrites produced in the successive eruptions from the different centres can be distinguished by their chemistry and grain-size, and by the extent to which they have been welded. The gas trapped in the hot rock, at a temperature of 700ºC or more, enables it to flow over low ridges, where it leaves only a thin veneer. In depressions it becomes ponded, and the surface cools and traps the heat in the deeper layers. If the rock is hot enough and the weight of the overlying material sufficiently great, the particles become welded into a hard rock, which tends to develop conspicuous vertical cracks when it eventually cools. This is strikingly apparent in the gorges at some of the dam-sites on the Waikato River (Figure 28.10).

The Mamaku Plateau, an area of about 400 sq. km that lies to the west of Rotorua, consists of welded ignimbrites formed about 140,000 years ago at the climax of the eruptions that produced the Rotorua caldera. These were the last of the welded ignimbrites. The more recent Okataina and Taupo eruptions, although only slightly less gigantic, produced only unwelded material. Okataina has been greatly modified by later events, during which the twin domes of Haroharo and Tarawera rose within the caldera.

The Taupo centre, being covered by water, has been more difficult to study, and is a complex of several calderas rather than a single structure. The western part of the lake more readily suggests its nature, but the most recent eruptions, about 1800 years ago, have been near the Horomatangi Reef, on the eastern side. On this occasion more than 25 cubic km of pumice and unwelded ignimbrite was thrown out. This is more than five times the amount produced in the Mount Saint Helens eruption in 1980. Most of the Taupo eruptions were smaller than this, but not as small as the Tarawera eruption in 1886.

Tarawera is the best-known of a complex of domes within the Okataina caldera. Rhyolite (or more rarely dacite) domes are common within the Central Volcanic Region. They contained little gas and were extruded into existing calderas, thus being spared the violent explosions that had accompanied their formation (Figure 28.11). They include the 757-metre high Ngongotaha, a steep-sided grouping of domes to the west of the Rotorua caldera that grew soon after it was formed; Haroharo to the south, and the larger cluster known as the Maroa volcanic centre, which deflects the Waikato River to the east in a great loop. Tauhara (1,087 m.), just east of the Taupo township, is dacite, as are the two domes on opposite sides of the Rotorua-Taupo highway, just south of its junction with the road to Waikaremoana.

Figure 28.10 The edge of a welded ignimbrite sheet, exposed where the Waikato River cuts through the Mamaku Plateau.

Figure 28.11 Maunganamu, a Recent rhyolite dome near Lake Taupo, Central Volcanic Region, New Zealand.

Although the domes and lava-flows that make up the Tarawera complex are rhyolitic, basaltic scoria was erupted from several of the craters along the 17 km rift that opened in 1886 (Figure 28.12). The last eruption in the north-west part of the Okataina centre, about 4,000 years ago, also produced basalt. At other volcanic vents the appearance of basalt has often been the precursor to a rhyolite eruption, but since a century has now passed without one we can probably rest easy.

Figure 28.12 Waimangu thermal area in foreground, Lake Rotomahana middle and Mt Tarawera background. The 1886 Tarawera eruption produced vents from those in the foreground right up to the rift in Mt Tarawera.

29—Around the Ring of Fire – II

Is the Pacifique sea my home? Or are
The Eastern riches?

JOHN DONNE : Hymne to God my God, In my sicknesse

Between the Rumbles and the Kermadec group there is a gap of 700 km without any obvious signs of volcanism, but within the Kermadecs there are several potentially active volcanoes. Of these only Raoul Island, the largest and most northerly of them, is inhabited, by the staff of a weather-station. It is an andesitic volcano that has erupted more than once in historic times, and in 1964 it became advisable to evacuate it for a time. The southern limit of observed activity is Curtis Island, about 140 km south-west of Raoul, which is in the solfataric stage. Remarkable uplift (7 metres) has taken place in its crater over the 35 year period of 1929 to 1964. It is probable that the very small and isolated Esperance and Havre Rocks, 90 km farther south, are also volcanic; but they are a danger to shipping and generally avoided, and no activity has been reported.

The features of the sea floor between New Zealand and Samoa are unusually long and straight, and the Tonga-Kermadec Trench that marks the western limit of the Pacific Basin is unusually deep and narrow. Neither New Zealand nor Samoa forms part of this system. Samoa lies on the opposite side of the andesite line, and has basaltic shield volcanoes analogous to those of Hawaii, while the linear features of the New Zealand region lie at an angle to the Tonga-Kermadec ones, and are separated from them by a transverse fracture-zone.

Although the Tonga and Kermadec systems are similar in many ways, they are clearly separate, and differ in important details. Between Raoul and Eua, the southernmost of the Tongan volcanoes, there are no island volcanoes for more than 800 km. Midway

Figure 29.1 Mount Garet in eruption on Gaua Island, Vanuatu.

between them the floor of the Trench rises from a depth of about 10,000 metres both to the north and to the south, to little more than 4,000 metres. The submarine volcano, Monowai seamount, is in this area and is frequently active. In another setting, such a depth would be enough to define a fore-deep, but here it merely marks a minor swelling in the Pacific floor, sufficient to define the division between the systems. The division is also marked by a sharp change in the pattern of the earthquake activity. In the Tonga system the active zone becomes twice as wide, there are more

Figure 29.2 The active cone of Bagana, Bougainville, with gas and lava emission. Mt Balbi is in the background.

Figure 29.5 Distant view of Bagana volcano, with rim of Crater B, Mt Balbi in foreground.

Figure 29.3 A lake-filled crater on Mt Balbi, now in a fumarolic stage.

Figure 29.4 View into Crater B, Mt Balbi; probable site of the most recent eruption in 1825.

large deep earthquakes, and the deepest shocks are at about 650 km, rather than at the 570 km typical of the Kermadecs.

Not all the islands of the Tongan group are active volcanoes. The more easterly ones, closest to the Trench, are uplifted coral limestones on ancient volcanic cones, probably five or ten million years old. The active volcanoes to the west form a closely-spaced line parallel to the trench. Submarine eruptions are common, for the volcanoes are young, and have in many cases still to win their battle for permanence against wind and wave. The story of Fonuafo'ou has been told already.

About 200 km south of Samoa, the Trench suddenly makes a right-angled turn to the north-west. It rapidly shallows and merges with the floor of the Pacific near the Wallis Islands. From here a chain of islands follows the margin of the Pacific to the Solomons, but they are not volcanic.

Active volcanoes are once more to be found 2,000 km to the west, in Vanuatu (until recently the New Hebrides). Like the Kermadecs and Tonga, it is a chain of volcanic islands, but it trends north-west and not north-east. The ocean trench lies on the side away from the Pacific, and the zone of deep earthquakes plunges beneath the north Fiji Basin. Here, as in the south of New Zealand, the Pacific Plate rides over the subducting Indian Plate (Figure 29.1).

The Tonga-Kermadec and Vanuatuan systems form a wide V, with its apex in the North Island of New Zealand, tempting structural geologists to suggest links between Vanuatu and the older volcanism of the Northland peninsula; but the southern limit of present activity is reached at two tiny islands about three hundred metres high and not much more than half a kilometre across. Their names are Matthew and Hunter. Matthew Island erupted in 1949 and 1953, and Hunter Island in 1835 and 1895. Political maps assign them to New Caledonia, which lies on the opposite side of the trench. In the name of volcanology and the Ring of Fire, however, we shall claim them for Vanuatu.

Figure 29.6 Rabaul Harbour viewed from the Rabaul Volcano Observatory.

Figure 29.7 Ruins of Higaturu village, destroyed in the 1951 eruption of Mount Lamington.

Figure 29.8 Mt Lamington after the eruption of 1951.

Figure 29.9 Remnant of the spine that formed on the summit of the Mt Lamington dome in 1951. Photographed in September 1962.

Resuming out clockwise circuit we find a number of island chains which, like Vanuatu, front away from the Pacific. The main belt passes through Santa Cruz, the Solomon Islands, Bougainville, and thence to the north-east of New Ireland (Figures 29.2, 29.3, 29.4 and 29.5). A separate arc impinges upon the southern end of New Ireland, and can be traced from western New Britain to several small islands off the northern coast of New Guinea, Bam, Manam, Karkar and Long Islands. All have active volcanoes and have been known for a long time and quite intensively studied, as have the many volcanoes in New Britain. The Admiralty Isles lie between these two arcs, and are remarkable for having erupted rhyolite lava in 1956–57.

The fine harbour of Rabaul (Figure 29.6), the principal township of New Britain, is an impressive caldera around whose rim several active cones rise to over 200 metres. It is a dangerous situation. Not only eruptions from one of the surrounding cones directly affect the area within 10 or 15 km, but the less well-appreciated danger of a major eruption of the whole caldera could devastate an area at least 100 km wide. After a serious eruption in 1937 an observatory was established, and there were recommendations that the town should be moved to a safer site; but in spite of smaller eruptions in 1941 and 1942 the attractions of the site and harbour have proved more powerful than fear of the dangers. The need for continuing vigilance is obvious, and even during the fighting of World War II the Japanese volcanologist Takashi Kizawa did his best to maintain the observations. In 1961 and further in 1967 the equipment at the observatory was modernised, making possible the detailed study of the volcanic crisis in 1983 and 1984 that was described in Chapter 21.

Across the Solomon Sea from New Britain to the south, there is another roughly parallel line of volcanoes in eastern Papua. This continues to the west and includes Mt Victory, Goropu, Mt Lamington, and at least two presently inactive volcanoes similar to Mt Lamington in the New Guinea highlands, Mt Yelia and Doma Peaks. This is an ancient arc, which marks the active margin of the Australian continent, for the waters of the Gulf of Carpentaria and the Arafura Sea cover only a shallow continental shelf. When Mount Lamington erupted in 1951 the area had not been properly mapped. It lies 120 km north-east of Port Moresby, on the other side of the 4,000-metre high Owen Stanley Range.

Somewhere round about 1810 and again in about 1890 (the dates are very uncertain) Mount Victory, 100 km to the east of Lamington, had erupted, and Goropu, south of Victory had made a first appearance as recently as 1943; but there were few indications that Lamington represented a danger. It looked like a group of four craggy peaks, overgrown with dense jungle, and about 1,200 metres high.

Early in January 1951 a few earthquakes were felt, and by January 15 the mountain was visibly active. The tremors increased, and on January 21 the climax followed. Nuées ardentes devastated an area more than 10 km in radius and killed virtually its entire population, estimated to have been at least 3,000 and perhaps as many as 12,000 people. Dr G.A. Taylor, whose courage and dedicated study of the subsequent events earned him a George Cross, has given an account that is a volcanological classic.

The early stages of the eruption may be described as Vulcanian. Clouds of ash rose to 9,000 metres, hot bombs a metre or more in diameter were thrown out, and more ash was carried far to the west and south by prevailing winds. With the main explosion on January 21 the eruption became Peléean, and throughout February the explosions continued to be accompanied by nuées which poured from a breach in the northern side of the crater and rushed down "Avalanche Valley" to the former site of Higaturu village (Figure 29.7). The village and most of the forest cover had already been destroyed, probably by the base-surge that accompanied the main eruption. Taylor reports that in some places the only evidence that forest had ever existed was provided by charred roots carved off level with the surface of the soil.

A few days after the climax, a lava dome began to grow, and when it was shattered by an explosion in March it stood more than 300 metres above the crater floor (Figure 29.8). Meanwhile, in February, a spine had been thrust through a fracture in the top of the dome. It repeatedly crumbled, and explosions blasted material from the dome, to be carried away by the nuées. The debris they left in their path was mainly fine ash and lapilli derived from effervescing dacite, and there were few large blocks. Soon the heavy tropical rains scoured deep gullies in it, producing destructive lahars. Where it lay undisturbed, it was found to be still hot two years later.

In spite of the repeated explosions, the dome continued to grow, and by May it was higher than it had been before its destruction in March. The spine did not reach its greatest height until the following February, when it rose more than 120 metres above the summit of the dome. As the explosions diminished, the dome became a plug in the centre of the crater, and now stands a little higher than the wall, 560 metres above the crater floor (Figure 29.9).

30—Around the Ring of Fire – III

Realms and islands were as plates dropped from his pocket.

WILLIAM SHAKESPEAR: Antony and Cleopatra

The region west of New Guinea is one of extraordinary structural complexity, in which the demands of volcanology, seismology, and gravity often seem to be at odds. Here is the meeting-place of the Eurasian, Indian, and Pacific Plates, and the small Philippines "platelet", which has a miniature "ring of fire" of its own. If we follow the activity on its western side southwards we are led through Mindanao and the Sangihe Islands to northern Sulawesi, and thence around the Banda Sea to the great Indonesian arc; while if we follow the eastern side, we find a gap of at least 1,800 km between the submarine Esmeralda Bank in the south of the Marianas and the line we have been following northwards to New Guinea.

If we turn to the relief and the geological structure for help in bridging the gap between the volcanoes of northern New Guinea and the Marianas we will find that the route lies through Halmahera. Halmahera is a short but well-developed arc fronting towards the west, and separated from the oppositely-curved arc of northern Sulawesi by the narrow Molucca Strait, which constitutes a kind of common fore-deep, and at the same time separates the Ring of Fire from the Alpide Belt. Halmahera's volcanoes are vigorously active, and eruptions have been recorded since the sixteenth century. Some of them, like Gamalama and Makian, have erupted many times, and there have often been casualties.

The southern margin of the Philippines is not marked by a subduction zone, but by a great transcurrent fault. Between Halmahera and Guam there are earthquakes – some of them large, and all shallow until the southern end of the Marianas Trench is reached – but no volcanoes. The Esmeralda Bank, which was reported to have erupted in 1944 and again in 1975, marks the resumption of volcanism, which becomes more vigorous in the central part of the group. Almagan is a prominent cone 750 metres high, but it is less active than the smaller cones of Pagan, several of which have produced ash eruptions or lava-flows within the present century.

Figure 30.1 Mt Fuji today can be compared in shape and surroundings with the drawings in Chapter 11.

Activity continues northward through the Kazan (also known as the Volcano Islands) and the Bonin Islands. Iwo-jima, site of military action during World War II, owes its fame more to that than to volcanic prowess. It is only about 10 km long, and rises to about 170 metres. An "eruption" reported in 1957 seems to have been an explosion of gas that accumulated beneath dirt piled up during the construction of a military aerodrome. The activity is solfataric, but some steam explosions have been reported.

The submarine volcano Myojin, about 420 km south of Tokyo, was the scene of an eruption in 1952, and bears the name of the fishing-boat that first reported it. For a time a small cone protruded above the water, but within a week it had eroded away, and frequent paroxysmal eruptions began. A party of scientists from the Tokyo Fisheries University observed them from a safe distance on September 21, and took photographs. On September 24 a second vessel arrived, carrying seven scientists from the Hydrographic Office. Half an hour after mid-day radio contact with it ceased. The ship had vanished, along with its scientists and a crew of 22. Seismograph and hydrophone records confirm that there was a submarine explosion at about this time, and soon afterwards a small tsunami reached the Japanese coast. It is assumed that the unfortunate ship had moved directly above the vent during a pause in the activity. A little wreckage was eventually found. Embedded in it were pieces of pumice shown by chemical analysis to have come from Myojin.

This is the only recorded tragedy of the kind. After all, there is little chance of a ship being over a small vent in a large ocean unless, like the unfortunate Kaiyo-Maru, it was actually looking for it. Submarine explosions usually form a "bubble-pulse" that raises the water-surface in a dome before it breaks it and allows the products of the explosion to follow. In the case of a volcanic eruption there is a dense turbulent cloud of bombs, ash, and pumice, in which no ship could possibly survive.

Guarding the entrance to Tokyo Bay, just before we reach the shores of Honshu, stands Ō-shima, a Strombolian volcano whose activity has been documented for the last thousand years, and which has been extensively studied by Japanese volcanologists (see Figure 25.2). It is a composite volcano 750 metres high, with a summit caldera 3 or 4 km across, containing a small central cone. This is called Mount Mihara, and the name is often applied to the entire island. There were great eruptions from 1684 to 1691, and again in 1777 and 1778, when lava was discharged from the base of the cone and flowed over the rim of the caldera. This happened again in 1950 and 1951.

Figure 30.2 Mayon volcano, with its symmetric cone. In 1984 the district was menaced by lahars, but 73,000 people were safely evacuated.

Passing Ō-shima on the left and sailing into Sugami Bay we can – if the clouds are kind – obtain the most famous of the thousand and one views of Mount Fuji, surely the most pictured mountain in the world. It is a composite cone 3776 metres high, with a crater 700 metres across and 100 metres deep. The last important eruption was in 1707, when three new craters appeared in the southeast flank at heights between 2,500 and 3,000 metres. The main vent then opened, and hurled bombs, lapilli, and ash over a large area, some reaching Tokyo, 100 km to the north-east (Figure 30.1).

The fame and prominence of Fuji should not lead us to forget that like many composite cones, it has companions, though none match it in height. Fuji is one of a group of eight or nine cones within the Fossa Magna (Latin, the great ditch), a volcanic depression that stretches across central Honshu and marks a major break in the geological structure of Japan. It can be traced not only in the volcanoes and in the topography, but in the pattern of deep and shallow earthquakes, and in the gravity anomalies.

Now that we have gained the mainland of Japan, we must pause and look back at the volcanoes to be found to the west of the Philippine Plate, although they do not strictly form part of the Ring of Fire. The pattern is more complex than that to the east, with short segments that change direction and character, and do not all face the same way. We will look at the Banda Sea region in a later chapter, and begin at Una-Una, an island volcano in the Gulf of Tomini, just south of the Equator in northern Sulawesi. It erupted in a spectacular fashion in 1983, but fortunately the population had been evacuated before nuées ardentes destroyed most of the vegetation. It marks the southern end of an arc that passes through the eastern part of the Minahassa Peninsula, and thence via the Sangihe Islands to southern Mindanao. Its cuvature is opposite to that of the Halmahera arc, and there are deep earthquakes beneath the Celebes Sea to the west. Eruptions are frequent along the whole length of the arc, involving more than a dozen volcanoes.

With the exception of Palawan to the west, nearly all the islands of the Philippines have recently active volcanoes. They include a number of shapely cones, of whose perfection the Filipinos are justifiably proud, though it could be held that their very small craters give them a pin-headed aspect. The crater of Mayon, near Legaspi and by common consent the most perfect, is only 200 metres across, though its cone rises over 2,400 metres (Figure 30.2, see also Figure 11.1).

When Hibok-Hibok, on Camiguin Island off the north coast of Mindanao (there is another Camiguin north of Luzon) erupted in 1951, 500 people were killed by nuées ardentes, but when Mayon erupted in 1984, timely evacuation prevented major tragedy. After a brief Strombolian phase, the eruption became Vulcanian, sending clouds to a height of 15 km, spilling lava from the crater, and rolling incandescent blocks and other pyroclastics down the flanks.

About 16,000 people within 8 km of the crater were safely evacuated, but eight were buried under debris, and one was killed by hot steam. A more intense eruption followed a month later, and on this occasion 73,000 people, including many from the nearby city of Legaspi, were evacuated to some 50 different reception centres without further deaths. During this phase of the eruption, heavy rains generated many lahars (Figure 30.3).

Figure 30.3 Lahar due to rain eroding fresh ash-fall, Mayon. See also Figure 12.8

Figure 30.4 The eroded flanks of Volcano Island., Lake Taal.

Taal is a very different kind of volcano (Figure 30.4). It is a caldera filled with a large lake, and lies only 50 km south of Manila. It is a potential source of ignimbrite, and without doubt the country's most serious volcanic problem. In the centre there is an island four or five kilometres across, which marks the site of many historic eruptions. As long ago as 1572 colonists had realised that it could be a source of trouble, but fertile soil, plentiful fish, and nearness to Manila all made the island and the shores of the lake attractive places to settle. Subsequent disasters have done little to diminish its attractiveness.

When the eruption of 1911 occurred, 500 people were living on the island, and all but 15 of them were killed, together with another 800 living around the lake. The column of ash was seen 400 km away.

Exactly what happened on the island can never be known. Certainly there was a rain of scorching mud, which poured through the roofs of the thatched dwellings, while lightning flashed in the cloud above. The mud was not only hot, but impregnated with acids that burned more strongly than the heat. Nine kilometres from the lake the deposits were a metre thick, and a survey party there was blown back five metres by the base-surge. The convulsions of the island raised violent waves in the lake that completed the devastation around its shores.

Half a century later, in 1965, Taal volcano claimed another five hundred victims. The eruption was smaller than the one in 1911, and reports of rising lake temperatures from the small observatory on the island had brought about a limited evacuation; but in half a century the population had more than doubled, and there were too few boats. Once again the lake water gained direct access to the magma, and the resulting phreato-magmatic explosion sent the cloud of steam and ash 20 km into the air. As is often the case with eruptions of this kind, there was a strong base-surge.

This was the first occasion on which the importance of the base-surge had been recognised. Let James G. Moore, the volcanologist responsible, describe it:

"A series of debris-laden eruption-clouds moved out radially from the base of the main explosion column. These clouds carried blocks, lapilli, and ash suspended in water-vapour and gases, and moved with tremendous velocity. They shattered and obliterated all trees within one kilometre of the explosion centre and sandblasted objects up to 8 kilometres distant."

Blocks of lava 50 cm across were carried more than a kilometre.

The effects of the surges are very directional. Up to 10 cm of wood was removed from the near side of trees far enough from the vent to have escaped uprooting or felling, while the far side remained untouched. The centre of the 1965 eruption was near the southwest corner of the island, which largely protected the villages on the far side. Near the vent, a village is reported to lie beneath 12 metres of ash. Along 5 km of the lake shore opposite, the ash is half a metre thick, and it is four metres thick over an area two kilometres across; yet considering the size of the explosion, the total volume is small. One interesting observation concerns the temperature. Neither the base-surge nor the dust-laden steam-clouds reached much above 100°C. This supports the view that the burns reported in 1911 were due to acid, rather than to heat.

The eruption began on September 28, and by September 30 it was over – the briefest of interruptions to the routine of the fishermen and peasant farmers by the lake. Within a week the first families were making their way back, ready to start afresh. There had been eruptions before, and doubtless there would be more when God willed. Meanwhile, life must go on.

Disastrous as these eruptions were, the island in the lake is only one of the possible centres of eruption within the caldera, which is perhaps more accurately classed as a volcano-tectonic depression. Ash-flow deposits show that at intervals ranging from a few hundred to at most a few thousand years, the caldera erupts, an event that would be a hundred times more disastrous than any eruption from a single vent like the one on the island.

The arcuate character of the southern Philippines is very clear, being defined by the very deep Mindanao Trench and the increasingly deep earthquakes beneath the islands to the west, but the group is traversed by a major fault similar to the San Andreas Fault in California, and the Alpine Fault in New Zealand, and this marks a structural division between the features of northern Luzon and those found farther south.

From northern Luzon the line of volcanoes passes by way of several small islands to Taiwan, and on through the Ryukyu Islands to Kyushu, southernmost of the islands of Japan. Although submarine volcanoes lie close to the coast, there are no active volcanoes in Taiwan itself, except possibly for Datun, which has a hydrothermal field at its foot, and may be dormant rather than extinct. Arguments for regarding Taiwan as an active section of the continental margin, rather than as yet another island arc can be based on seismic and structural grounds; but the Ryukyu Islands are clearly an arc, with many active volcanoes.

31—Around the Ring of Fire – IV

…on the margin of the sea
A mountain I discern.
I am come to the land of Nippon,
The land of Nippon.

SEAMI: Haku Rakuten

At the Fossa Magna in Japan the active belts that define the eastern and western margins of the Philippines Plate join and continue northwards as one. It marks a major structural division, and the volcanoes and earthquakes of southern Japan clearly belong to the western belt we have followed through Taiwan and the Ryukyu Islands. In Kyushu the structure is no longer arcuate, and there are no deep-focus earthquakes, but there are several well-known active volcanoes, the most famous of which is Sakurajima (Figure 31.1). It lies only a few kilometres from the city of Kagoshima, on an island in the deep inlet that forms its harbour. The eruption of 1779 has passed into legend, and the historical accounts of it preserve so many vignettes of human behaviour that it would be ungracious to demand more volcanological detail.

For about a day before the mountain exploded there were increasingly frequent and violent earthquakes. It first sent up a column of white smoke that rose for 12 km. Hot lava-bombs began to fall, and houses, trees, and crops caught fire. “A certain dignitary, with whom we must sympathise, hid himself in his well; and another dropped his chop-sticks in terror.” Lightning played within the column. Day was turned to night. Several villages became buried, and pumice floated so thickly upon the water that flight by boat was impossible. Ash fell not only in Nagasaki, 150 km away, but reached Yedo (the modern Tokyo) 1000 km to the north-east. How many were killed can only be guessed, though there are official records putting the number at about 300.

The eruption was to be followed by a long period of false security, but the stories continued to be told, and on January 10, 1914, the people of Kagoshima Bay had little doubt about the meaning of another burst of earthquakes. The army and navy were summoned, and an evacuation followed. The main eruption did not come until two days later, and when it did there was only a small loss of life. Fortunately the prevailing westerly winds carried much of the falling ash away

Figure 31.1 Eruption of Sakurajima volcano viewed from Kagoshima City.

Figure 31.2 An evacuation practice at Hakamagoshi school, on the island of Sakurajima. Children going to and returning from school must wear protective helmets, which saved at least one of them from serious injury when hit by a falling lava bomb.

from the centres of population. Once again, a glassy dust was to reach Tokyo.

By 1914 the Japanese had established themselves as leaders in the field of volcanology, and Professor Fusakichi Omori of the Tokyo Imperial University drew attention to the changes of level that had accompanied the eruption. There was already a chain of survey-marks around the bay, which proved to have fallen by about a metre. He suggested that there had initially been a swelling of the ground, followed by a deflation after more than two cubic kilometres of lava had been discharged during the eruption.

The new lava from Sakurajima covered 25 sq. km, sending a tongue to the east that joined the island to the mainland, and another to the west that had the less acceptable result of reducing the depth of the harbour channel. The evacuation had saved 15,000 lives, but seven of the island's eighteen villages had been totally destroyed, and the value of lost property

Figure 31.4 Showa Shinzan dome on flanks of Mt Usu, Hokkaido, Japan. This dome was formed in 1944-45.

was put at nineteen million US dollars. Evacuation drills are still regularly carried out, and awareness of volcanic hazards has saved many lives (Figure 31.2).

This was not the last of Sakurajima. In 1935 a period of fairly continuous activity began, and in 1946 a larger eruption sent lava-flows across farm-lands, and there were casualties. There was a similar eruption in 1955, and the following year a small lava-lake formed in the crater.

In 1980 a series of ash eruptions began, and were still continuing four years later. They have been troublesome rather than serious. Air-waves from the explosions broke windows in the city, and there was a rain of bombs and lapilli. The ash prevented solar heaters from working, and railway signals and level-crossing barriers were put out of action. More than a hundred motorists ended up with broken windscreens during climaxes of the activity. Some forest fires were started by the incandescent ash.

There are other active volcanoes in Kyushu, of which the most important are Kirishima, Unzen, and Aso. The University of Kyoto maintains an observatory near Mount Aso, which is fairly continuously active, and has more than once killed too venturesome and unwary tourists (Figure 31.3). In 1792 Mount Unzen, on the west coast erupted, producing landslides and

Figure 31.3 Ash fall-out from Mount Aso, 13 October 1990

Figure 31.5 Klyuchevskaya Sopka.

Figure 31.6 Karymsky, a strombolian volcano in Kamchatka.

a tsunami described earlier in the book (see Figure 20.1). Chapter 41 ‘Postscript’ describes the 1990 eruption of Mount Unzen, which occurred after this book was written. These are the last of the volcanoes to the west of the Philippines Plate. There are none in the island of Shikoku, and none in Honshu south of the Fossa Magna.

The northward continuation of the Ring lies along the Japanese Alps, almost at right angles to the trend that we followed from Halmahera to Izu and the Fossa Magna. At the junction is Mount Asama, a complex of three volcanoes about 2,500 metres high, and given to Vulcanian eruption. The Asama Volcano Observatory

Figure 31.7 The eruption cloud from Plosky Tobal’chik, 1975.

is an important centre of research from which the mountain has been watched continuously since 1901.

There have been two great historical eruptions, in 1108 and 1783. The first of these apparently ended a dormant period that had lasted about 220 years. In 1532 a large mud-flow was triggered by melting snow.

It has been claimed that the 1783 eruption produced the greatest volcanic eruption on record, but it is difficult to place such claims in an adequate context, and Tambora, Katmai, and Krakatoa immediately suggest themselves as rivals. We cannot doubt that it was among the most serious disasters in Japanese history.

After about two and a half months of minor explosions pumice explosions began, and covered the eastern slopes to a depth of a metre. Ten days after the last of these the first of two nuées ardentes occurred, and spread a thin sheet of debris over 19 sq. km. On the following day a second and larger one reached the Agatuma River and triggered a secondary flow of hot mud that killed 1,300 people and buried their rice-fields. Immediately afterwards a flow of lava descended the northern slope for five and a half kilometres, and the horror ceased as abruptly as it had begun. The nuées gouged great furrows in the underlying soil and tuffs, and carried blocks of pumice up to 30 metres across. Before it broke, one giant block is supposed to have measured 160 metres.

The eruption of Bandai, 200 km to the north of Asama, in 1888, was neither the largest nor the most destructive of eruptions, nor was the number of deaths a record, yet it caused world-wide dismay and still finds a place in almost every account of the world’s volcanoes. Older descriptions class it as Peléean, and journalists of the day were shocked and impressed by the effects of nuées ardentes and lahars. The dead are likened to victims of a boiler-explosion, hanging from trees, burned and cut to pieces. “Flesh hangs from the branches of trees as paper from London telegraph wires” reads one report. More recent assessments emphasise the massive collapse of the crater wall,

Figure 31.8 Bezymianny (L) before eruption.

Figure 31.9 Eruption of Bezymianny 30 March 1956. Photographed from Kozyrevsk when the eruption cloud had reached a height of 45 kilometres.

which triggered an avalanche of rock that filled an entire valley and buried its villages, accounting from most of the 400 dead.

The line of volcanoes in northern Honshu continues into Hokkaido, and in 1977 the University of Hokkaido established a volcano observatory at Mount Usu. Usu is a composite cone 725 metres high, with a summit caldera a kilometre and a half across, and a melancholy record of destructive eruptions like those of Asama and Bandai. The report that 1,437 horses as well as 103 humans were killed when it erupted in 1822 is unusual. In its long history its activity has taken a variety of forms, its present predilection being to form domes, one of which appeared at the base of the mountain in 1945 and became the site of phreatic eruptions (Figure 31.4). A few months after the observatory was opened an earthquake swarm heralded an upheaval of the summit, an eruption of ash, and the formation of a new dome within the summit caldera.

The Kurile Islands form the central section of a classical island arc that includes Hokkaido and the Peninsula of Kamchatka. There is a trench to the east, and deep-focus earthquakes extend beneath the sea of Okhotsk, following the subducted Pacific Plate to a depth of about 650 km. Possibly because there were enough volcanoes in more populous and accessible parts of their country, Japanese volcanologists rather neglected the Kuriles, but since the political changes of the second World War, Soviet scientists have been active both in observing current activity and in systematising the fragmentary records of the past, and have identified 33 volcanoes that have erupted since the end of the seventeenth century. Many of them have eroded forms that suggest declining activity, but records of recent eruptions are quite numerous.

The snow-covered cones known as sopkas that line the eastern coast of Kamchatka make it a land of impressive scenery. The tallest of them is Klyuchevskaya, rising to 4,850 metres, but others can match its perfect symmetry (Front Cover and Figures 31.5 and 31.6). Several of them are given to fairly frequent Vulcanian eruptions, and there are hydrothermal areas with impressive fumaroles.

Plosky (blunt) Tobal'chik is one of a group of volcanoes that lie within a few tens of kilometres of Klyuchvskaya. It was once a composite cone with a summit caldera about 4 km across. Since the caldera was formed, outpourings of fluid basalt have several times filled it and overflowed down the slope, leading some writers to describe it as a shield, though it has not the typical slope. Before 1975, when a large fissure eruption virtually reconstructed the caldera, it was filled with ice except for a large circular hole with a floor of pahoehoe lava, and containing the active vent. This has been greatly deepened and enlarged to form a new caldera within the old, and about half its diameter. Since it was discovered in the eighteenth century, more than a score of eruptions have been recorded (Figure 31.7)

The volcanoes of the Klyuchevskaya group rise from the ruins of an ancient volcano called Kamen. Among them is – or rather was – a snow-covered cone without a name. No one doubted that it was extinct until 1955, when the first signs that it would shortly be the site of the largest known eruption in Kamchatka were seen. It became known to the world as Bezymianny, the Nameless One (Figure 31.8). The Russian volcanologist G.S. Gorshkov has recorded the story.

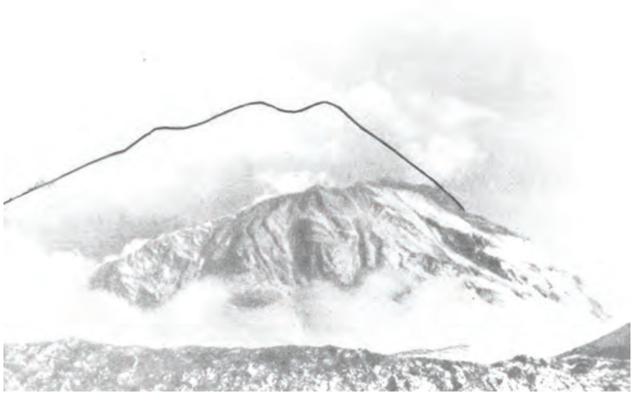


Figure 31.10 The changed outline of Bezymianny before and after the main explosion.

Figure 31.11 Dome in Bezymianny crater after the eruption.of 30 March 1956.

Late in September, the seismographs at Klyuchi, 45 km to the northeast, detected the beginning of an earthquake swarm, and during the next month more than 1200 shocks were recorded. They seemed to be coming from about 40 or 50 km under Bezymianny, but the location of shocks in a disturbed volcanic area can be upset in all kinds of ways, and since Bezymianny was considered extinct, it was decided that magma was trying to open a vent at the foot of Klyuchevskaya, on the south side.

On October 22 puffs of white steam were seen from Klyuchi, and eruptions of ash followed almost at once, but the vent was hidden behind Klyuchevskaya, and the only way to get a look at it would be to go to the upper reaches of the Sukhaya (dry) Khapitsa River. It was winter – a severe one even by Kamchatkan standards – and there were frequent tempestuous storms. The only possible way to travel was by dog-sledge, and the covering of ash upon the snow made even this difficult. The volcanologists' camp was covered by 4 cm of ash, and light falls extended for 130 km. For 60 km around, normal life was completely disrupted, and by mid-November 6 mm of ash had fallen on Klyuchi.

When spring-time came at last, the ash-cover hastened the melting of the glacier ice, and the roads became cut by roaring torrents. Water was undrinkable, and the grass that would normally have supplied feed for horses remained buried under ash. No wonder Gorshkov wrote: "In such difficult and sometimes even dangerous conditions constant observations were impossible, and we did not succeed always to see everything we wanted with sufficient completeness" – yet it is difficult to find fault with his long report and the 39 pages of maps and photographs it contains.

Before the eruption Bezymianny had had a crater about 500 metres across. Its vent was sealed by a dome that contained a smaller crater, also blocked. The eruption came from neither of these, but from a new crater rather below the top of the mountain, on the line of weakness at the edge of the dome. Judging from the size of the column of ash it was about 250 metres across. On November 13 the cloud reached a height of 5 km, lightning played at its base, and rumblings and explosions were frequent. Conditions in Klyuchi had grown worse. Work was at a standstill. Lights were needed all day, and could barely be seen a hundred metres away.

By the end of the month the carpet of ash was 25 mm thick, but activity seemed to be declining. A cloud of vapour still rose from the mountain, but there was much less ash, and on January 25 it became possible to inspect the crater from the air. It had grown to 700 or 800 metres wide. People in Klyuchi began to feel that the worst was over.

March 30 was fine and clear, and every one had a good view of what followed. At ten past five in the afternoon there was a strong earthquake, and a great explosion removed the top of the mountain. There was a blast of air that hurt the ears, and a fan-shaped cloud shot 35 km into the sky, dwarfing Klyuchevskaya and the whole surrounding group of volcanoes. A second explosion sent the cloud another ten kilometres higher (Figure 31.9). Klyuchi lay directly in its path. There was clear sky to east and west, but the cloud was very thick, and seemed almost tangibly heavy. A hail of light-grey pebbles began. Within an hour it had become profoundly dark, and people could not find their way home from work. Lightning flashed, and the thunder became deafening. Telephone bells rang for no apparent reason, and radio-sets gave off sparks. There was a strong smell of sulphur. By 9 pm it was over. Twenty millimetres of ash had fallen, and patches of starlit sky were beginning to show through the cloud.

The next morning, Bezymianny had changed beyond recognition. The whole top of the cone had blown away, and there was a great breach on the southeast side. A caldera had formed, enclosing what remained of the old cone within a semi-circular wall (Figures 31.10 and 31.11). The initial Plinian phase had quickly been succeeded by a Peléean one, and a great pyroclastic flow had filled an 18 km stretch of the Sukhaya Khapitsa with a chaotic mixture of ashes, sand, and lava-blocks dotted with thousands of fumaroles that reminded the volcanologists of the Alaskan "Valley of Ten Thousand Smokes" that we shall describe in due course.

When the explosion occurred, none of the volcanologists were close to the mountain, but their cabin 12 km away was literally blown to bits, and trees 30 cm in diameter were felled at twice that distance. Dead trees were set on fire, and country that had been covered with two metres of snow now lay exposed.

The thick deposits of ash still contained much gas, and remained very mobile, aiding the melt-waters to start lahars. The largest of these came from the lower end of the material filling the Sukhaya Khapitsa, and left deposits of mud up to 20 metres thick along another 18 km of the course of the river. These lahars moved glacial boulders weighing hundreds of tons. The mud was to remain hot right through another winter.

32—Around the Ring of Fire – V

People are in the habit of assuming that uniformity and symmetry are laws of nature.

GEORGE BERNARD SHAW: The Sanity of Art

Most of the island arcs that make up the greater part of the Ring of Fire are convex towards the Pacific. On a map they appear to be "caught up" or "draped" from a series of cusps at which the ring undergoes a sharp change of direction, and follows the ocean margin rather than continuing inland. The Kurile-Kamchatka and Aleutian arcs meet in such a cusp near Klyuchevskaya and Bezymianny.

The Aleutian arc, stretching eastward from Kamchatka through the Komandorsky Islands and the Aleutian chain to the mainland of Alaska, is the largest and most perfectly developed of all the Pacific arcs. It has some forty active volcanoes, but although the ocean trench and shallow earthquakes extend along its whole length, we have to travel for more than a thousand kilometres before we reach the first volcano and its associated deep earthquakes. This is Kiska, in the Rat Islands, which erupted in 1969. Great Sitkin, the "disappearing island" of Bogoslov, and Okmok, on the island of Umnak, are probably better known. Nearly all of them were first recorded during the period of vigorous exploration in the late eighteenth century. The sharp snow-covered peak of Shishaldin, a text-book model of a composite cone 2,857 metres high, frequently displays a plume of gases, but the thirty or so eruptions recorded since its discovery in 1775 have all been modest. It last erupted in 1979.

Katmai is at the eastern end of the Alaska Peninsula, which continues the Aleutian arc to the mainland. In several respects it displays a kind of symmetry with Bezymianny. Before its great eruption in 1912 it was well enough known, but no one seems to have thought it worth a photograph. It was rather less than 2,300 metres high and just one more of a group of composite cones like the many others dotted along the arc. Few people lived within sight of it, the nearest settlements of any size being on Kodiak Island, on the other side of Shelikof Starit.

The beginning of the eruption followed a familiar enough pattern. On June 2 a few slight earthquakes were felt; on June 5 ash-clouds were seen. The next day there were two tremendous explosions, and a third a day later. It would be some time before the full story was known. The nearest witnesses were fishermen camped in Kaflia Bay, 50 kilometres east of Katmai. On June 9 one of them wrote:

"We are waiting death at any moment. A mountain has burst near here. We are covered with ashes, in some places 10 feet (3 metres) and 6 feet deep. All this began June 6. Night and Day we light lanterns. We cannot see the daylight. We have no water. The rivers are just ashes mixed with water. Here are darkness and hell, thunder and noise. I do not know whether it is day or night. The earth is trembling, it lightens every minute. It is terrible. We are praying."

Just after mid-day on June 6 the steamship Dora left Shelikof Strait for the narrowing waters of the Kupreanof Straits, which lead to Kodiak. There was fine clear weather and a strong westerly breeze. At one, the captain noticed a column of smoke astern, and identified its source as Katmai. By three it was overhead. At six he had passed through the narrows, and half an hour later was about five kilometres from the entrance to Kodiak. Suddenly ash began to fall, and within minutes it was dark. Not even the water over the ship's side could be seen. In spite of tightly-closed windows, the helmsman found it difficult to see the compass through the thick dust, and the captain decided to head for open sea. According to the ship's mail-clerk:

"the rain of ashes fell in torrents; it swirled and eddied. Gravity seemed to have nothing to do with the course of its fall. The under side of the decks seemed to catch as much ashes as the sides of the decks under our feet."

The wind increased, and heavy thunder and lightning continued through the night. Helpless sea-birds kept falling to the deck, and even in the engine-room the heat had become noticeable. About 4.40 am next morning, the vessel at last cleared the black smoke of the ash-fall, and to the west and the north the horizon was clear.

The US Coast-Guard cutter Manning was in Kodiak, and more than one writer on volcanoes has published what purport to be verbatim extracts from the ship's log; but while one declares that "deep concern was visible on every countenance, and the advisability of the Manning's getting to sea was discussed", another records that "abject terror took possession of the place". Concern or terror, they agree on dates and times, and the main course of events.

Kodiak is about 160 km from Katmai. Before ash began to fall in the late afternoon of June 6, the only unusual thing that had been noticed was the approach of a curious cloud. By 9 am on June 7, when the fall ceased, 12 cm of ash lay on the decks, and all the streams and wells in the town had been choked. The Manning and a schooner that was also in the harbour were obliged to supply the people with water. At noon ashes began to fall again. Within an hour, visibility was down to 15 metres, and in another hour darkness was total. Static from the cloud made the radio useless.

Sunrise on the 8th brought no daylight. The falling ash had become a yellowish dust that gave off sulphurous fumes, and although they had been cleared the previous day, the decks, lifeboats, and rigging were so loaded that four fire-hoses were directed on to them and the crew kept at work with shovels. When at last it became light, avalanches of ash could be seen sliding down the hills surrounding the port, raising clouds of suffocating dust. In the late afternoon all 500 inhabitants of the town were taken aboard and the ship moved into the outer harbour in readiness for escape. There were further falls of ash. The first was a terra-cotta colour, in striking contrast to the previous grey, and built up another 11 cm of deposit. By six on the evening of June 8 it had again reverted to grey, adding another 4 cm before morning, when it gradually cleared and people returned to their homes.

If this could happen 160 km away, what had happened at closer places? Drifts of ash more than 3 metres thick made houses collapse, acid rains burned skins and clothing, the vapours were suffocating; yet in the darkness nothing could be done but to take shelter and wait. Necessity had joined forces with wisdom, and not a single death was reported. Wildlife, in which the region abounds, was less fortunate. Birds fell from the air, fish died in the ash-choked rivers, small creatures perished in the ash, or became blinded by the acid rains and vapours, and lived only to starve. Large bears, deprived of their normal diet, attacked the surviving domestic cattle. Trees had been felled, and smaller plants and pastures were buried under the thick grey pall.

Piecing together the geological story was to take years, and room for argument still remains. First on the spot was Dr G.C. Martin of the US Geological Survey, who arrived at Katmai in early July with a party organised by the National Geographic Society. This was the first of several expeditions organised by the Society, the later ones being led by Dr R.F. Griggs (Figure 32.1).

Martin's party found Katmai transformed. Fully 300 metres of the peak had gone, and in its place was a crater with almost vertical walls, five kilometres across, and 800 metres deep, already filled with a gleaming blue lake, from which protruded a small island. Recent estimates put the volume of the missing peak at 5.9 cubic km. Where did it go? The obvious answer is "over the countryside", but the ash and the pumice proved to be even more acidic than the andesites of the original mountain.

Not until the 1916 expedition was the full complexity of the event suspected. Before the eruption a broad valley containing the headwaters of the Ukak River had stretched north-westwards from Katmai. In its place, there was now a flat plain four kilometres wide. From its surface rose hundreds of steam-jets. In his caption to a photograph in the National Geographic Magazine Griggs says millions; but in naming it the Valley of the Ten Thousand Smokes he achieved a verbal felicity normally given only to primitive peoples. It was, he said, "as though all the steam-engines of the world had popped their safety-valves at once, and were letting off steam in concert."

The pyroclastic flow that had filled the valley must have happened before the great explosions, for none of the pumice that they generated can be found underneath the flow. Most surprisingly, it did not appear to have come from Katmai, whose slopes on the near side were still covered by glaciers. The extraordinary sequence of events finally pieced together involves movements of magma from one underground chamber to another, over distances as great as eight kilometres.

There is now no way to locate the earthquake-shocks of June 2, 3, and 4 which signalled the beginning of, or possibly even triggered, all that followed. Some time

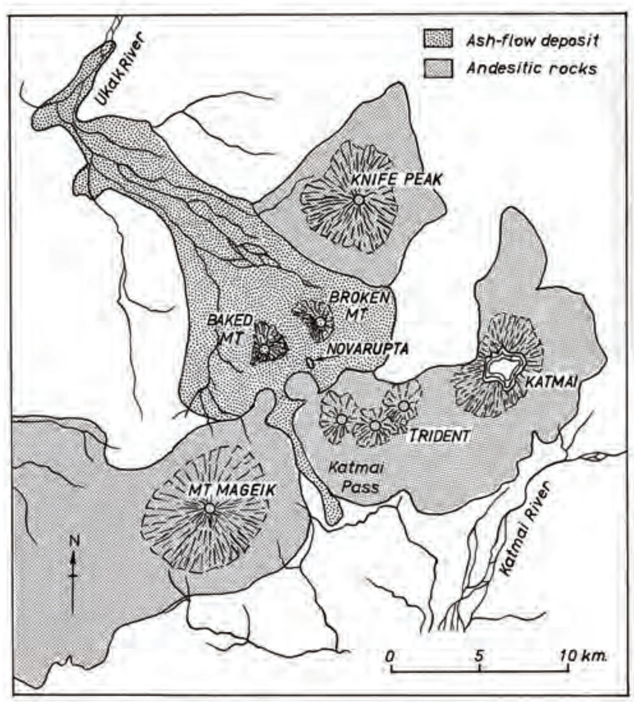


Figure 32.1 Katmai, Novarupta, and the surrounding region. The no-longer active "Valley of the Ten Thousand Smokes" lies in the headwaters of Ukak River.

between then and 1 pm on June 6, a series of fissures opened at the head of the valley, and began to fill it with ignimbrite to a depth of tens of metres. In less than twenty hours more than 11 cubic kilometres were emplaced. A new vent had opened at the southeast end of the valley, 4 km from Katmai. Returning to Latinity, Griggs and his party decided to call it Novarupta, the new break-through. It was probably responsible for the explosions and ash-falls reported from Kodiak. The curious thing is that it seems to have been fed from a magma-chamber beneath Katmai, and that it was a consequent collapse and not an explosion that created the caldera.

Figure 32.2 The perfectly-formed dome that now fills the crater of Novarupta.

Eventually, a dome piled up about the vent of Novarupta, 90 metres high, and nearly 400 metres in diameter (Figure 32.2). It was a final effort, and activity ceased. So too did the spectacular displays in the Valley of Ten Thousand Smokes, when the trapped ground-water had been converted to steam and released. In the early stages many of the steam-vents were highly acid, and Griggs's party, camping in the valley, found that they could not be used for cooking without danger to the pots. Katmai – or if you will, Novarupta – and Bezymianny are among the few historical instances when large quantities of ignimbrites are known to have been erupted. These two eruptions are by far the largest in the present century. Such "great eruptions" are a whole order of magnitude larger than any of the more usual kinds, and are fortunately infrequent.

Figure 32.3 Mt Augustine, an impressive sentinel at the entrance to Cook Inlet, Alaska, but a serious hazard to shipping and oil-drilling activities. Viewed from the M/V Maritime Maid, 27 March, 2006.

It is unlikely that the Katmai story is finished. It has been quiet since 1912, but Novarupta showed minor activity in 1950. Trident volcano, between them, and a few kilometres to the south, remained lively until the middle of 1953, producing lava-flows and ash-falls. Since then it has taken to building small cones in its vent and blowing them to bits again. The area has now become the biggest of the USA's National Parks – not because of any solicitude for volcanoes, but in order to ensure proper protection of the brown bear.

The climax of Katmai does not complete the Aleutian arc, which continues for another 400 km or so to Mount Spurr, active in 1953, and some lesser features nearby. When Augustine, the 1,200-metre island volcano west of the entrance to Cook Inlet (Figure 32.3) erupted in 1976, a nuée ardente destroyed the main research station of the University of Alaska's Geophysical Institute. Since 1812 there have been half-a-dozen eruptions, and drillers on the off-shore oil-rigs have reason to fear a repetition of the events of 1883, when a nuée or a landslide started a tsunami that stranded the fishing-fleet at English Harbour, on the opposite side of the inlet. There have been reports of renewed activity in 1986.

33—Around the Ring of Fire – VI

Survey the WHOLE, nor seek slight faults to find.
Where nature moves …
The whole at once is bold, and regular.

ALEXANDER POPE: Essay on Criticism

From Alaska the Ring of Fire turns southwards to follow the coastal ranges of North America. We are entering a region of major transcurrent faults and large shallow earthquakes. Here the Pacific and American Plates are not being driven together, but moving sideways in opposite directions. There is no ocean trench, and no deep earthquakes. We shall not meet more deep shocks, island arcs, and subduction zones until we reach Central America.

Before we leave Alaska, we should note two volcanoes that lie near the centre of the line from Mount Spurr to the most northerly of the Canadian volcanoes, at opposite ends of the Wrangell Mountains. Mount Wrangell, to the west, was active late last century; and about 1,500 years ago an ill-defined area near White River was the scene of at least two large pumice eruptions. Some minor hydrothermal activity extends farther to the north, and there is a broad and diffuse zone of shallow earthquakes.

None of the claims to have seen a Canadian volcano in full eruption are credible, but Indian traditions of eruptions of Aiyansh (Tseax River) about 250 years ago are confirmed by carbon dating; and basalt erupted from Mount Edziza is less than 500 years old. At least half a dozen other volcanoes in the Canadian Cascade Range are active or dormant. They are part of the same system as their more active neighbours across the US border in Washington and Oregon.

Once across the border, one active volcano follows another. Mount Baker and Mount Rainier both erupted last century, and in 1980 Mount St Helens suddenly bid for world-wide attention. With the exception of Mount Hood, which erupted in 1854, the volcanoes of Oregon are for the present less lively than those of Washington; but the chain continues without a break to Mount Shasta and Lassen Peak in northern California. There has been no eruption of Shasta in the last 200 years, and Lassen has been sleeping since

Figure 33.1 Phreatic eruptions from Mt St Helens started on 27 March 1980.

the 1920s, but the eruptions in 1914-15 have been described as "probably the most violent volcanic activity ever observed by modern man on the United States mainland". That is no longer true.

The 1980 eruption of Mount St Helens was not entirely unexpected. Although the 2,975-metre peak had been quiet since a series of explosive eruptions in the first half of last century, it was not considered extinct. The present activity began in late March with many small earthquakes and phreatic explosions. A team from the US Geological Survey soon established that magma was being intruded into the volcano, and that a bulge had appeared, thrusting the north flank outwards about 100 metres. The main eruption, on May 18, was apparently triggered by a magnitude 5 earthquake, which dislodged a great landslide from the side of the bulge. More than two cubic kilometres of material moved to one side – among the greatest landslides ever observed – releasing the pressure on the rising magma and producing an explosion. Within minutes the whole north side of the mountain was blown away, 550 sq. km of forest were devastated, raging mudflows swept down the rivers, and a column of ash shot into the air, to be carried hundreds of kilometres to the east. Smaller explosions and nuées ardentes continued until October (Figures 33.1, 33.2 and 33.3).

Figure 33.2 The Plinian eruption column from Mt St Helens on 18 May 1980 reached a height of 18 km.

In June, a thick, viscous, dacite lava started to extrude from the vent, forming temporary domes that were blown apart by the explosions. From October onwards a permanent dome was to form, and to go on growing as more lava was thrust from the vent. The process was not continuous, but took place in bursts lasting a few days. By 1985 there had been about 11 of these events, each adding a few million cubic metres to the dome, and it had become possible to predict them with some accuracy. Sometimes there would be bursts of gas and ash, particularly when ground-water reached the hot dome. The explosions melt snow and ice on the crater walls, and the accumulation of water on its floor continues to trigger lahars.

Deaths due to the eruption are thought to total 57, but more than 20 of the bodies have not been recovered. Since this is by far the best observed eruption in recent times, this emphasises how difficult it is to compile reliable statistics. One noteworthy feature of the main explosion at Mount St Helens is its similarity to the one at Bezymianny. In both cases there was a very asymmetrical blast that breached the crater in much the same way, and greatly lowered the height of the volcano.

The US Geological Survey still watches events closely and has established an observatory in Vancouver (a Washington township, not the Canadian city) with a resident staff of about sixty. Known as the David A. Johnston Cascades Volcano Observatory, it has been named after a young volcanologist who died in the May explosion. One of the first members of the team to arrive, he was observing the mountain from a station 9 km away when the blast occurred.

Before leaving the USA it is well to remind ourselves that evidences of hydrothermal activity and of older volcanism are common in the western states. The geysers and hot springs of Yellowstone are the best known, and along with several centres being exploited for geothermal power have been described in earlier chapters. Yellowstone has produced gigantic eruptions of rhyolitic ignimbrite at intervals of the order of half a million years, the last of which was about this long ago.

The Ring continues southwards from Lassen to Mono Lake and Long Valley caldera, and thence through Baja California to southern Mexico, but the volcanoes of this section are dormant. We must not overlook Bárcena and Socorro in the Revillagigedo Islands, both active since 1950, but they are not part of the Ring. They lie on the East Pacific Rise, which separates the minor Cocos and Nazca Plates from the

Figure 33.3 Forest devastated by blast from Mt St Helens eruption on 18 May 1980.

Pacific, where it intersects the Clarion Fracture Zone, one of a series of major transverse fractures of the eastern margin of the Pacific Plate. They are therefore oceanic volcanoes. Bárcena vigorously erupted pumice for two years, building a cinder cone nearly 400 metres high, plugging its vent with a dome, and lapsing into inactivity. Socorro is a basaltic shield.

The region south of Baja California is structurally more complex than at first appears. There is an ocean deep off the west coast of Mexico, vigorous shallow seismicity, deeper activity following the subduction of the Cocos Plate beneath the Caribbean Plate, and a continuous line of volcanoes that extends almost to the Isthmus of Panama. Looked at closely, the "arc" turns out not to be a continuous structure, but a succession of quite short and separate ones; but the greatest problem is posed by the existence of the Caribbean Plate. From the Gulf of Honduras its boundary runs through Jamaica and round the entire Caribbean Arc through Venezuela and Colombia to a complicated junction of four plates south of the Isthmus of Panama (see Figure 5.4). The Cayman and Puerto Rican Trenches extend round the northern boundary, and are paralleled by shallow earthquakes and gravity anomalies; but the only volcanoes lie at the eastern end, where there are also a few earthquakes at intermediate depths. They mark the true division between Atlantic and Pacific, and there are no other volcanoes along the eastern coasts of North and South America.

Most of the islands from Saba (north of St Kitts) are volcanic, with well-preserved cones, though they are usually in a solfataric stage, and only Montserrat (Soufriere Hills), Mont Pelée and La Soufrière on St Vincent have erupted violently in historic times. La Soufrière of Guadeloupe and the submarine volcano Kick-'em-Jenny have experienced several periods of activity, but none of the eruptions has been large.

Many of the volcanoes of Central and South America, like Popocatépetl, the "smoking mountain" of the Aztecs, pass across the pages of history. Its snowy cone rises to 5,452 metres, and dominates the southern skyline of Mexico City. We have already described Parícutin and Jorullo.

Colima, on the west coast (Figure 33.4), whose frequent activity has been known since the late 1500s, erupted again in 1978. El Chichón, until recently catalogued as solfataric, with no known eruptions, resumed activity in 1982 with an outbreak claimed to have been more destructive than the eruption of Mount St Helens. Tens of thousands of people fled their homes, and more than 700 are reported to have been killed. Heavy ash-falls destroyed their crops, no

Figure 33.4 Colima, Mexico.

Figure 33.5 When the Nicaraguan authorities decided that the erupting Mount Momotombo would look well on a postage stamp they could not have dreamt that copies of it sent to U.S. senators would persuade them to route their proposed canal through Panama instead.

grazing for animals was available, and cattle had to be slaughtered. Much ash reached the high stratosphere, and its dispersal has been recorded in unusual satellite pictures. Spectacular sunsets were reported in many parts of the world.

US congressional advocates of a Panama Canal stressed that Panama was the only Central American country without active volcanoes, choosing to overlook Chiriqui, which is close to the Costa Rican border, and last erupted in about 1500 (Figure 33.5). The number of volcanoes in each country of Central America is roughly proportional to the length of its Pacific coast. Guatemala's Fuego has been known since the time of the conquistadors and, even allowing for some confusion with its neighbour Pacaya, is the country's most active volcano. Ever since its devastating eruption in 1902, Santa Maria has been almost continually active, with a long series of lava domes being formed on the flank of the volcano, and destroyed again. El Salvador's Santa Ana and Izalco are another close pair with an impressive historical record, like San Miguel 150 km further to the southeast.

In Costa Rica, Poas and Irazu both have a long record of historic eruptions, but casualties have been few. The eruption of Arenal in 1968, with no previous history of activity, was more serious. Initial phreatic explosions and a thick hail of bombs were succeeded by nuées ardentes that destroyed two villages and killed 78 people, and by long continued flows of andesitic lava.

Coseguina lies on the coast, just within the northern boundary of Nicaragua. It rises only 850 metres above the Pacific, and the walls of its summit caldera, two and a half kilometres across and half a kilometre deep, drop vertically to a clear blue lake. Its eruption in 1835 is usually described as one of the most violent in the western hemisphere; but there are no records of earlier eruptions, and although fumaroles within the crater took some forty years to die out, it has been quiet since. The eruption lasted only four days, during which dense ash-falls affected communities up to 150 km away.

Estimates of the amount of material ejected differ widely, the principal difficulties being in deciding how much of the mountain there was before the eruption, and how much fine material was carried to sea. A commonly accepted figure for the volume of erupted ash is 50 cubic kilometres, and up to three times as much has been suggested; but Professor Howell Williams, after extensive field-studies, and a careful assessment of the historical records, does not believe the amount exceeded 10 cubic kilometres, and could well have been much less. More recent investigators reach similar conclusions.

The course of the eruption does not seem to have been unusual. A few earthquakes were felt, a white plume was seen above the vent, and the ash-falls began. No casualties have been recorded, but the darkness and the booming noises, which travelled to great distances, produced some extreme reactions. At Alancho, it seems the terror of the inhabitants "anticipating the approach of Judgement Day, was so great that three hundred of those who lived in a state of concubinage were married at once". Participants in a penitential procession at La Unión are reported to have been thrown to the ground by an earthquake, but descriptions suggest that an air-wave was responsible. The noises were so like distant cannon that military men were deceived. Colonel Gallindo, camped on the banks of the Polochic River in eastern Guatemala, attributed them to artillery fire from Port Izabal. At Belize, 600 km to the north in British Honduras, the commandant mustered his troops and manned the fort, believing that there was a naval action outside the harbour; and in Guatemala city the local troops prepared for action. Alarm was reported from as far away as Kingston in Jamaica and Bogotá in Colombia.

34—Around the Ring of Fire – VII

Mercy upon me, what a round I have taken!

SAMUEL FOOTE: The Commissary

The western margin of the Nazca Plate is being subducted beneath the South American continent. Ocean trenches follow the coasts, deep earthquakes extend inland, and volcanoes mark the whole length of the Andes. They are high, and many are active, but the record of eruptions is less complete than we might wish, and there has been much confusion between adjacent peaks and craters. There are three main groupings – a northern one in Colombia and Ecuador, a central one stretching from southern Peru to northern Chile, and a southern one that begins in central Chile, the volcanoes becoming more widely spaced towards Cape Horn.

In passing we should note the basaltic shield volcanoes of the Galapagos Islands. They do not of course form part of the Ring of Fire, but lie on the spreading ridge that marks the western boundary of the Cocos and Nazca Plates. Their frequent eruptions are similar to those in Iceland and Hawaii.

In 1985 the 5,321-metre high Nevado del Ruiz in Colombia was responsible for the most destructive lahar on record. Several months of small earthquakes and an increase in fumarolic activity preceded two eruptions from high on the north-east flank of the glacier-clad volcano. They melted part of the ice-cap, and started a mud-flow that buried the town of Armero, 50 kilometres distant, under five metres of mud, and killed 23,000 people. A small flow to the west reached Chinchiná and killed a thousand more.

Purace and Galeras, also in Colombia, have a long history of eruption, and were active as recently as the 1970s; but they are less well known than Ecuador's Cotopaxi and Chimborazo (Figure 34.1). Neither the International Volcanological Association nor the Smithsonian Institution find a place for Chimborazo in their catalogues. It is quite heavily eroded, and the most recent eruptions took place at least ten thousand years ago, but it has an important place in history. Its first appearance in geophysics was in 1736, when Pierre Bouguer noted its gravitational pull on his survey instruments and laid the foundations of gravimetry. He was content to reach the snow-line, but almost fell victim to the treacherous mountain weather. When Alexander von Humboldt tried to climb it in 1802 it was thought to be the world's highest mountain. The Himalayan peaks were not measured for another quarter of a century. He reached a height of 5,840 metres, still 700 metres from the top, before he was defeated by mountain sickness and an impassible fissure. It was not until 1880 that Edward Whymper at last reached the summit. Humboldt was more successful with Cotopaxi and several other cones near Quito, and made some valuable volcanological studies.

Figure 34.1 Chimborazo from Alexander von Humboldt "Vues des Cordillères".

The 5,897 metre Cotopaxi is only 80 kilometres from Quito, and has a bad record of generating lahars like the one from Ruiz, with scarcely less serious consequences. In 1877 one of them travelled 300km at an average speed of 27 km per hour. A thousand people were killed, a village 240 kilometres away was seriously damaged, and many bridges were destroyed. It last erupted in 1942. It is also reported to have thrown a 200-ton block 14 kilometres, a record volcanologists are reluctant to concede.

Figure 34.2 El Misti viewed from Arequipa, Peru.

Both Reventador in the north and Sangay are probably more active than Cotopaxi, though it appears that some early reports of eruptions have been wrongly assigned. Expeditions to Reventador in the 1930s produced controversy about which craters had most recently been active. Sangay is almost constantly active, and in 1976 succeeded in killing two and injuring four members of a British expedition by hurling bombs when they were close to the summit.

Across the border in Peru is El Misti (Figure 34.2), the most recently active of three volcanoes around Arequipa. The city of about two million people is built on nuée and lahar debris from El Misti. It erupted in 1787, and there are fumaroles in the summit caldera to provide it with a plume of steam; its symmetry has gained it an international reputation for beauty. Huaynaputina, a hundred kilometres to the south-east, erupted in 1600 forming a caldera and destroying the town of Omate, but has since been quiet.

Chilean volcanoes are high, numerous, active, in many cases inaccessible, and consequently not well known outside South America. At least a dozen volcanic peaks in Bolivia and northern Chile reach above 6,000 metres. Their only possible rival is in Tibet. Active volcanoes over 5,000 metres high are listed in the Appendix, but it must be remembered that not all the measurements are of high accuracy, and that an eruption can quickly change the order of precedence. Heights of a few non-volcanic peaks are given for comparison. Volcanoes are outclassed.

There are six of these giants over 6000 m in Chile and Argentine, north of the latitude of Santiago, that have been seen to erupt – Llullaillaco (6,723 m), Guallatiri (6,060 m), Pular (6233 m), Antofalla (6100 m), Tupungatito (6000 m) and San Pedro (6,159 m). Ojos del Salado (6,885 m), the present holder of the height record for active peaks, is in a fumarolic stage, and so is Parinacota (6,350 m). Bolivia's Sajama (6,529 m) is older, and shows no signs of continuing activity. San Pedro, which managed to damage a railway-line in 1960 is, for the present, the most energetic member of the group.

The volcanoes of Central Chile are not so tall, but they are more active. Half-a-dozen of them have erupted repeatedly since the early years of last century, and had presumably been doing so long before that, for there are reports stretching back into the seventeenth century and, in the case of Villarrica, to 1558. In 1963-64 an eruption of Villarrica forced 30,000 people from their homes, and there have been several less serious eruptions since. In October 1984 a copious emission of gas accompanied the building of a spatter-cone with a small lava-lake at its foot. This overflowed through an old fissure in the crater wall and started avalanches from the ice-covered slopes. In December the eruption entered a Strombolian phase, and there was a small lahar that destroyed a wooden bridge and damaged houses. Villarrica frequently produces lahars, and casualties were reported in 1949, 1964, 1971 and 1984 (Figure 34.3). In 1932 Quizapu created something of a record for ash eruptions. Six millimetres of ash fell on Rio de Janiero, 1,100 kilometres to the east, and fine dust is reported to have reached New Zealand.

Figure 34.3 Villarrica, showing the path of a lahar in 1984.

The volcanoes of the Central Chilean segment of the Ring systematically decrease in height from the 5,640-metre Tupungatito in the north to Villarrica and Puyehue, little more than 2,000 metres high, in the south, but the height of the land from which they rise decreases correspondingly.

Seismologists instinctively discount reports of volcanic eruptions at the time of major tectonic earthquakes. After the great shock off the Chilean coast in 1960 there was a widely-circulated report that "all the volcanoes of the Andes" were in eruption; which says little for the ability of the press to recognise an absurdity. Yet there was an eruption near Puyehue two days after the earthquake. After an initial eruption of pumice, dacite lava poured from a 14-km long fissure on the north-east side, along which 28 craters were aligned.

The Andes continue to diminish towards the southern tip of the continent, and the volcanoes become less active and more widely spaced. Osorno and Calbuco are the most important members of the South Chilean group, though Osorno has not been active since last century. In the far south, 200 kilometres north-west of Punta Arenas, close to the western entrance to the Straits of Magellan and well-spaced from the rest, is Mount Burney, a fresh-looking and shapely cone 1,758 metres high, the last volcano on the American continent. It has done little to attract attention, the only observed eruption being in 1910.

At the outset of our journey around the Ring of Fire, we noted the Andesite Line separating, often sharply, the basaltic lavas of the oceanic volcanoes from the intermediate and acidic ones of those in the subduction zones. It is natural to expect Andean volcanoes to produce andesite, and if we consider the total volume of erupted products, andesite and still more acid rocks like dacite and rhyolite certainly predominate. If, however, we consider the number of eruptions, we find that a very large proportion produce basalt. This is less surprising if we reflect that while the upper layers of the continental crust are predominantly granitic, basic and ultra-basic materials occur at the deeper levels of the crust, and in the upper mantle everywhere.

35—Around the Ring of Fire – VIII

… in circuit to the uttermost convex of this great Round.

JOHN MILTON: Paradise Lost

The route from South America back to New Zealand takes us through sub-Antarctic seas and the Antarctic continent. Considering the problems of navigation and the hardships of exploration we must expect observations to be incomplete and sporadic, though many nations have established permanent bases and undertaken systematic exploration since the International Geophysical Year in 1957 and 1958.

The shape of the southern tip of South America should prepare us for an initial detour through the islands of the strongly curved Scotia Arc before we reach the continent by way of Graham Land (Palmer Peninsula in American atlases). The similarity of the Scotia Arc to the Caribbean is very striking, with the volcanoes concentrated in the South Sandwich Islands at the eastern end of the Arc; but the only parallel to the line of Central American volcanoes is a gentle swell in the sea floor. The South Sandwich Trench follows the line of subduction of the American Plate. There have been some large shallow earthquakes in this region, and shocks at intermediate depth on the concave side of the arc.

Volcanoes in the Scotia Arc were first reported by the Russian explorer Bellinghausen in 1819, when he found that Zavodovski was sending up a dense cloud of black smoke. (Zavod is Russian for a factory.) Later visitors also found it active, and in 1908 Captain Larsen landed and collected rocks cautiously claimed to be "of andesitic and basaltic affinity". The northern limit of the known activity was extended northwards in 1962, when there was a submarine eruption on the Protector Shoal. Other islands in the group are active, and they have had some attention from whalers, but little scientific information has been gathered since the time of Bellinghausen. In 1956 an Argentinian icebreaker found it prudent to evacuate a party on Thule Island because of the activity of Mount Darnley, on Bristol Island close by. None of the islands rise much higher than 1,000 metres, and several are completely covered by glaciers. Most reports of eruptions are based on little more than the sighting of clouds of steam.

Figure 35.1 On Erebus volcano – This Antarctic fumarole in the Ross Sea Dependency has surrounded itself with a hornito-like chimney of ice.

The volcanoes of Antarctica fall roughly into three groups – in Graham Land, in Marie Byrd Land, and in the Ross Sea. The purist will insist that the volcanoes of Graham Land lie on islands off the coast, but there are fumaroles to be found on the mainland. Here and in the Ross Sea the water in the gases emitted can freeze around the vents and build hornito-like towers, some as high as 20 metres (Figure 35.1). Both the British and Chilean scientific bases on Deception Island have been troubled by eruptions. In 1967 the Chileans' building collapsed under the weight of half a metre of tephra; and in 1969 lahars forced their way between the British huts, pushing down walls and imbedding the generators in an immovable icy mass.

Earlier eruptions are known, from as long ago as 1800. In 1893 Captain Larsen of the whaler "Jason" reported that Lindenberg Island was emitting black smoke from "funnels" in the top and sides. Material had been deposited on the ice, which had melted for some distance around the island.

Antarctica remains a continent of geophysical puzzles, perhaps the greatest of which is the complete absence of tectonic earthquakes, although there are young fold mountains and volcanoes. If we are going to limit membership of the Ring to the andesitic volcanoes of the subduction zones, the Antarctic ones cannot be admitted, for they have more in common with the oceanic rifts. It is unlikely that we have discovered all the volcanoes in the Antarctic, and not to be expected that they will prove to form a continuous system.

At least 1,100 kilometres lie between the volcanoes of Graham Land and the Hudson Mountains in Ellsworth Land, where an eruption may have taken place at Webber Nunatak in 1985. Some 350 kilometres further east is Mount Takahe, in Marie Byrd land, which is known from ice-cores to have been active within the last 10,000 years. In 1959 a US exploration party reported that the high peaks of the Executive Committee Range were basalt, and that one appeared to be a regenerated cone. There were volcanic rocks scattered on the ice at up to 8 km away, and every reason to assume that they had been erupted recently. Since then US and Chilean exploration of the region has been vigorously pursued, and at least five more peaks between here and Black Bay on the Ross Sea are thought to be active – but they have yet to catch one actually erupting.

Ever since James Clark Ross came upon Mounts Erebus and Terror in 1841 and named them after his ships, the idea that there is something paradoxical about volcanoes amidst the Antarctic ice has persisted. Until permanent bases were established in the Ross Sea in 1957 there were few opportunities to study Erebus, though members of the Scott expedition found it lively when they climbed it in 1912. An international research team now keeps it under observation, paying it regular visits during the summer (Figures 35.2 and 35.3). It is a Strombolian volcano, about 3,800 metres high, and more or less continuously active. In recent years the crater has contained a lava lake. Its companion, Mount Terror is 600 metres

Figure 35.2 Mt Erebus, 3794 metres high, is the tallest and most active of the Antarctic volcanoes. This view is from the slopes of Observation Hill, which overlooks Scott's Discovery Hut and the US McMurdo and NZ Scott research bases.

lower, less accessible, less studied, and apparently less active or wholly dormant. Together with Mounts Bird and Terra Nova the cones join at the base to form Ross Island, some 50 kilometres long, rising from the Ross Sea just beyond the northern limit of the permanent ice-shelf (Figure 35.4).

At least seven of the volcanoes in Victoria Land, to the west of the Ross Sea, are considered active; though no eruptions have yet been observed. Traces of former activity are to be found all along the eastern side of the Trans-Antarctic Mountains from the Skelton Glacier to the Balleny Islands. Mount Morning, at seventy eight and a half degrees south, is a possible claimant to the title of World's Southernmost Active Volcano. At Mount Melbourne, on the west coast of McMurdo Sound several hundred kilometres to the north of Erebus, hydrothermal activity can be found.

The wild and inhospitable Balleny Islands, capped thickly with ice and rising abruptly from the stormy Antarctic waters for more than a thousand metres, are indisputably volcanic. Buckle Island has twice been seen in eruption, in 1839 and 1899. From here to southern New Zealand a submarine ridge extends, with an accompanying belt of shallow earthquakes, but it has no deep shocks, and no active volcanoes. Macquarie Island lies on the Ridge, with which it shares its name, and to the east more small islands line the margin of the Campbell Plateau – Campbell, Auckland, and The Snares – and on Macquarie and Campbell Australia and New Zealand maintain weather-stations. The harbour of Campbell is a breached crater, but the weather-men have reported neither smoke nor fire. No special pleading will close the Ring of Fire. In all probability we left it in the South Sandwich Islands.

Figure 35.3 The crater of Mount Erebus which frequently contains a lava lake.

Figure 35.4 Mount Bird, one of the three volcanoes that make up Ross Island.

36—The Mid-Atlantic Ridge

'Twas in the mid-Atlantic,
In the equinoctial gales,
That a young sailor-lad fell overboard
Among the sharks and whales…

TRADITIONAL: Mar-ri-ed to a Mer-ma-id

From a volcanologist's point of view the interesting parts of the Pacific (with some important exceptions) lie around the edge. In the Atlantic they run down the middle; and while in the Pacific most volcanoes we have discussed are products of the destruction of a lithospheric plate, in the Atlantic they accompany the creation of new seafloor (Figure 36.1). We have already noted the vast extent of submarine volcanism, and in this chapter will concentrate on volcanoes that have successfully kept their heads above water – though we must find a corner to note a submarine eruption in 1957 on the Lomonosov Ridge, about 50 km from the North Pole.

Jan Mayen Island is not quite as close to the North Pole as Erebus is to the South, but it lies well within the Arctic Circle, half way between Norway and Greenland, and 600 km north of Iceland. It is covered with snowfields and a score of glaciers, several of which reach to the sea. Beerenberg, an impressive basalt structure 2,277 metres high (Figure 36.2), dominates its northern half, and around its base the waves have cut vertical cliffs up to 500 metres high. On a low saddle between Beerenberg and Sr Jan (Southern Jan) is Olonkinbyen, where the Norwegians maintain a weather-station and a radio navigational-beacon.

Reports of Beerenberg's eruptions are not likely to be complete. It is usually shrouded in low clouds and fog, and for most of its history it has been without inhabitants, yet it makes its first appearance in a book published in Venice in 1558. The book tells of the cloister of St Thomas Zenobium on an island that appears from an accompanying map to be Jan Mayen. The monks, it says, built their cloister with stones "cast glowing hot from the mountain" and very sensibly arranged to heat it by means of channels of natural hot water.

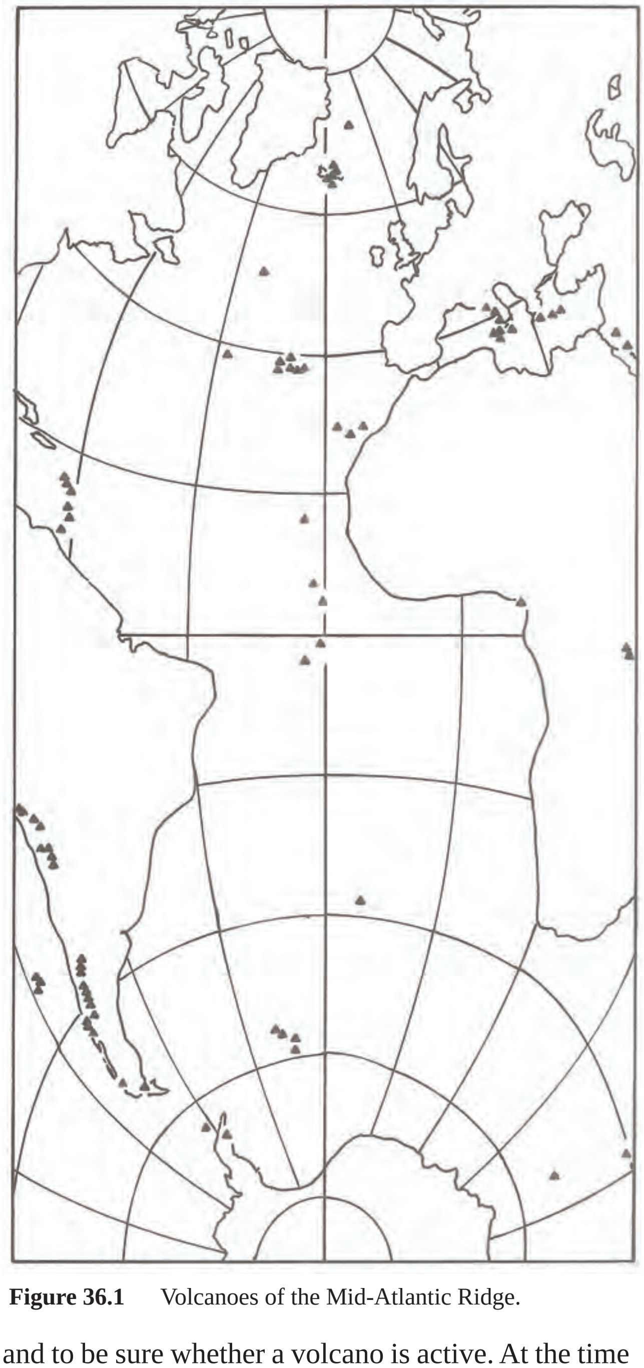


Figure 36.1 Volcanoes of the Mid-Atlantic Ridge.

Several other eruptions were reported before the weather-station was established in about 1920, but volcanologists tended to doubt their accuracy until events in 1970 made them re-examine the evidence. The eruption may have begun on September 18, when the men at Olonkinbyen felt a strong earthquake, but it was not noticed until three days later. The story shows how hard it is to keep a record of eruptions, and to be sure whether a volcano is active. At the time of the earthquake the whole island was covered in impenetrable mist, but on September 20 the pilot of a Japanese aeroplane which had been diverted to a more northerly course than usual reported a high cloud over the island, which he thought looked very like eruption clouds he had seen in Japan. Soon afterwards German

Figure 36.2 Beerenberg, Jan Mayen Island, a large basalt shield north of Iceland, on the Mid-Atlantic Ridge.

and Italian planes reported fire and smoke. It was not until the next day that the eruption could be seen from Olonkinbyen. Norwegian ships and aircraft were sent to investigate, and the 39 people on the island were evacuated. This proved to be a costly and unnecessary exercise, for they were in no danger. From the air, the erupting basalt looked spectacular, but it poured from a fissure 30 km from the station, and ran harmlessly down the cliffs to the sea. A similar, but somewhat smaller eruption took place in 1985.

Volcanologists who want to study the activity of the mid-oceanic ridges must face the same problem that Archimedes did when he wanted to show that his lever could move the Earth – there is no place to stand. Oceanic islands are not only small and difficult to reach, but few are inhabited, and of those that are, few have a long recorded history. Iceland, more than 500 km from east to west and 300 km from north to south, and settled for over eleven centuries by a vigorous and literate people is a striking exception.

Astride the Mid-Atlantic Ridge and entirely the product of its volcanism, it is natural to expect Iceland to provide fine examples of the basaltic fissure-eruptions that are typical of oceanic islands; but the diversity of its activity, which also includes central volcanoes producing intermediate and acid lavas, is perhaps surprising. Not only can most kinds of volcano found elsewhere be found in Iceland, but the activity between 9 and 13 thousand years ago, towards the end of the last glacial period, and its persistence beneath the permanent ice-caps that still cover a large part of the country, have created characteristically Icelandic land-forms and phenomena rarely found elsewhere.

The oldest surface rocks in Iceland are Miocene, about 16 million years old, but Iceland's geological history really begins about 90 million years ago, during the Cretaceous, when the Atlantic Ocean began to open up and to separate Greenland from Scotland and Scandinavia. These movements created a zone of tensional cracks several hundred kilometres wide. Into them, basaltic lavas were injected, filling them

Figure 36.3 Leirhnjúkur Rift, Krafla.

and forming dykes that remained when the activity ceased. The extension of the crust continues, at about a centimetre per year, and the growth of surface cracks can readily be measured (Figure 36.3).

Large increases in the rate at which they grow are sometimes warnings of impending eruptions. This was the case with the major rifting in the Krafla region in 1975. Many fissures have been the site of repeated eruptions, and are marked by prominent central volcanoes. Figure 36.4 shows the sites of the many eruptions in Iceland's long history. Figure 36.5 was taken during a 1980 eruption of Hekla volcano,

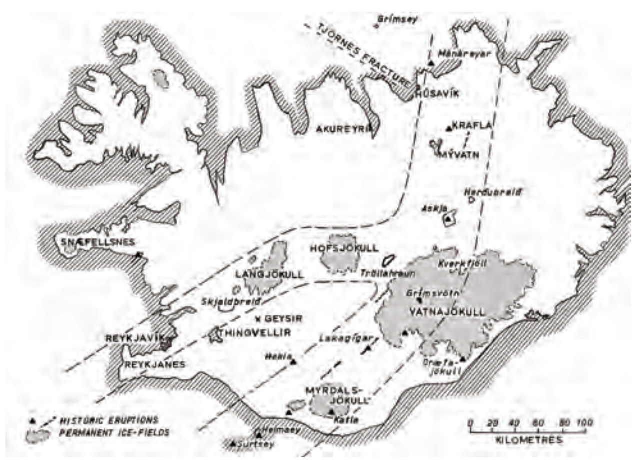


Figure 36.4 Iceland, showing the sites of historical eruptions, and place-names occurring in the text.

Figure 36.5 Mt Hekla in eruption.

Figure 36.6 Krafla Caldera, above the power station.

Figure 36.7 Viti crater, within the Krafla Caldera, was last active in 1724.

Figure 36.8 Lava flow at Krafla, 1984.

while Figures 36.6 to 36.8 show the normal state of the Krafla Caldera, and an eruption there. Present activity is confined to a belt that crosses the country from the Reykjanes Peninsula and Vestmannaeyar in the south to Tjörnes and Mánáreyar in the north, and lies directly over the oceanic ridge; but the boundary between the two plates is not a simple continuous line, and there are two major transverse fracture-zones displacing it to the east. Although the orientation of the swarms of dykes and fissures follows that of the Ridge, it is not so easy to trace in the topography, the clearest expression of its course being provided by the instrumentally-located origins of the associated earthquakes.

Iceland has many small earthquakes. Those that accompany volcanic eruptions are often very numerous; but although history records some damaging shocks few have exceeded magnitude 7, and there seems to be an upper limit of about 7½ for oceanic ridges in general. This can reasonably be attributed to the fact that the rocks involved are not so strong as those of the continental margins. It is possible to make the further generalisation that shocks in active volcanic zones are not so large as those in zones of tectonic fracture.

The southern and larger transverse fracture passes from Snæfellsnes through the northern parts of the Langjökull and Hofsjökull to the western side of Vatnajökull, while the Tjörnes fracture runs out to sea from the Tjörnes Peninsula, parallel to the north coast. On either side of the zone of volcanoes that are still active lie extinct ones that were active in the Tertiary, with still older rocks beyond them. The whole pile of volcanic material that constitutes Iceland now rises 2,000 metres above sea level, and nearly seven kilometres above the ocean floor.

Even when due allowance has been made for the transverse fracture zones, complexities in the pattern of Iceland's volcanoes remain; for while the northward progress of the activity of the Reykjanes Peninsula is clearly interrupted by the easterly displacement north of the Langjökull, the system extending southwards from the Kolbeinsey Ridge (which links Iceland with Jan Mayen) continues to the Vestmannaeyar 15 km off the south coast, and beyond them to Surtsey, another 20 km to the southwest. Vestmannaeyar suffered a disastrous eruption in 1973, while Surtsey first appeared above the Atlantic only ten years before.

At about seven on the morning of November 15, 1963, fishermen off the tiny island of Geirfuglasker noticed an unusual roughness of the sea and a smell of sulphur, and when dawn broke a column of coal-black smoke was rising from the sea. Within twenty-four hours a small island had appeared at its foot, and started to grow. Four days later it was 60 metres high

Figure 36.9 Phreato-magmatic eruption of Surtsey in the Atlantic Ocean.

and 600 metres long. Where it stood the water had been 130 metres deep.

The eruption took place from an elongated fissure, with vents that continually shifted as explosions modified the growing pile of ash. At times, when the sea gained access to hot magma, there were the violent cupressoid explosions that define a Surtseyan eruption; but whenever access to the sea became shut off the pattern changed to a continuous emission of ash and steam, shooting to a height of several kilometres, and accompanied by a loud rumbling (Figure 36.9).

For a time the permanence of the island remained in doubt. The explosions and pounding waves continually changed its shape, and from time to time it was joined by temporary companions. What finally determined its fate was the appearance in April 1964 of a glowing lake of lava which first filled the crater and then overflowed and sealed the sandy beaches. It eventually covered the whole island, whose area had grown to one and a half sq. km. The new addition to Icelandic territory received the name Surtsey, the island of Surt, the legendary guardian of Muspell, a southern land of dancing flames "which none can endure except those born to it".

On June 5, 1967, the last lava-flow was seen, and the eruption was over. It had lasted three years and seven months – but there was more to the history of Surtsey. Gradually heat and moisture hardened the ash to tuff, beaches formed along the shore-lines, and the waves cut cliffs that have become the haunt of nesting birds. Plants took root, seals made it their home, and fish came to its shallow waters. From the beginning, the Icelanders realised that was a unique opportunity to watch the sea at work shaping a new land, and

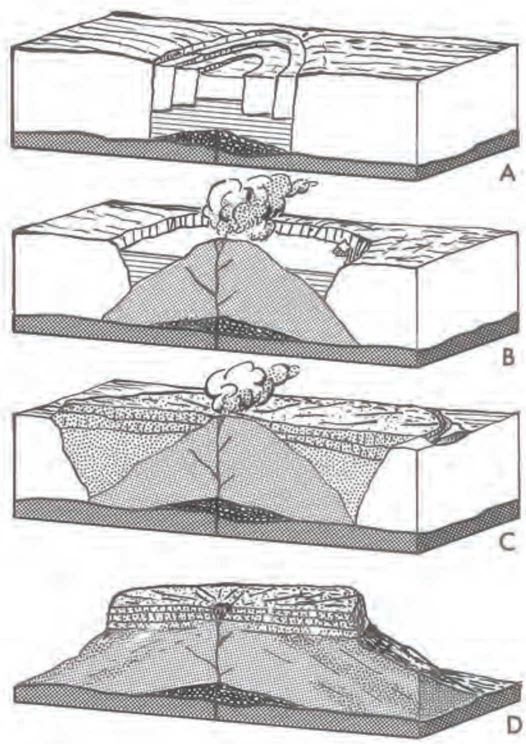


Figure 36.10 Formation of a móberg.

Figure 36.11 Búrfell is a móberg, a typically Icelandic volcanic landform.

to follow the establishment of plant and animal life upon it. They quickly took steps to ensure that it was preserved and studied.

The story of Heimaey, chief island of the Vestmannaeyar, has been told in Chapter 22, and we must now return to the mainland to describe some characteristically Icelandic phenomena. Many Icelandic volcanoes are flat-topped, rather than conical or shield-like, as is more usual elsewhere. At the time of their formation these volcanoes were covered by an ice-sheet. When lava is erupted beneath ice, it melts the bottom and forms a sub-glacial lake into which pillow-lavas are ejected (Figure 36.8). Eventually the lava penetrates the ice and reaches the surface. Explosive activity begins, and the pillows become covered with breccia and tuff. A circular lake now surrounds the pile, in which subsequent lav-flows are cooled, forming a widening cap over the older material. The resulting table mountain is known as a móberg (Figure 36.11).

Since the great majority of these table-mountains date from the last Ice Age, their tops are found to be roughly aligned, thus recording the position of the ice surface during the late Pleistocene. The heights diminish smoothly from about 2,000 metres in the north to rather less than 1,000 metres in the south. Canada has some similar formations in British Columbia, where they are known as tuyas, but they are not on the same scale as those in Iceland.

Today, nearly a sixth of Iceland's total area lies beneath a permanent ice-cap, which covers several volcanoes. The best known are Katla, beneath the Mýrdalsjökull (jökull, which appears in so many Icelandic names, means glacier), and Grimsvötn, beneath the Vatnajökull, largest of the permanent glaciers. Since records began, Katla has erupted every fifty years or so. When one of these volcanoes erupts, one possible consequence is a jökullhlaup (glacier run), among the most devastating of all volcanic phenomena. Great quantities of melt-water accumulate to form lakes that are suddenly released when the surrounding ice can no longer withstand the growing pressure. A full-scale eruption is not essential for the production of a jökullhlaup, which can occur whenever thermal activity has melted sufficient water.

When Grimsvötn erupted in 1934 it released water for over two days at a rate of 100,000 cubic metres per second, while in 1918 Katla produced four times as much. This is roughly ten times the flow of the Mississippi and four times that of the Amazon. Huge boulders are carried by the floods. The Katla eruption carried one seven and a half metres across for 14 kilometres.

South of Iceland the course of the Mid-Atlantic Ridge is marked by a line of submarine volcanoes, but the first to show above the surface are the Azores, a group of ten or more volcanic islands that lie along a fracture zone transverse to the ridge. Here we are at the “triple junction” where the boundaries of the American, Eurasian, and African Plates meet. The axis of the Ridge in fact passes through Corvo and Flores, the westernmost islands of the group, which are probably extinct, and it is possible to regard the active volcanoes to the east as the beginning of the Alpide Belt, of which we shall have more to say.

Some of the world's most hazardous inhabited places are to be found in the Azores. In the past there have been large eruptions of pumice in the form of ignimbrites, and towns have since been built in the calderas. As in other parts of the world it is recognised that the surrounding cones are dangerous, but the greater danger presented by the calderas is unknown, or fatalistically ignored.

Fayal, Pico, and San Jorge form a close group of island volcanoes about 70 km long and 30 km wide, and there have been submarine eruptions between them. Fayal became well known during the eruption of 1957, which was preceded by an unusually vigorous earthquake swarm. Over 450 shocks were felt, and more than 500 houses were destroyed by the larger ones. The volcanic episode began with a submarine explosion just off Cape Capelinhos. An islet formed and joined itself to the mainland with a sandy isthmus, and then began to build a cone. In the early stages there were some severe Vulcanian explosions that sent jets of black cinders up to a thousand metres or more. Within a few months it quietened and produced flows of basaltic lava. They ceased about a year after the eruption began, and a small eruption signalled an outbreak of solfataric activity in the summit caldera. There is a record of a previous eruption in 1672, when extensive lava-flows poured from a fissure on the lower slopes of Fayal, between the summit and Capelinhos.

Pico, which is more than twice the height of Fayal, has a main crater about 500 metres wide with a sharp conelet inside, but the four or five historical eruptions have all been outbursts of basalt from the lower slopes. San Jorge has behaved less typically, producing small nuées ardentes that led to deaths in 1580 and 1808, along with the more usual basalt flows. Rows of cinder cones stand along the active fissures, and the whole island, built over a fissure some 50 km in length, forms a good example of a linear volcano. Like its neighbours it has the useful habit of signalling eruptions with an earthquake swarm, though the burst of 500 shocks in 1964 ended only in reports of a smell of sulphur, but it is possible that there was a submarine eruption.

All the islands of the Azores have features of interest to the volcanologist, and often to the tourist, like the caldera of Graciosa, with active fumaroles and a lava-filled lake 200 metres wide, and the double calderas of Sete-cidades with two lakes, one green and one blue.

No less famous are the Canary Islands, whose great Peak of Tenerife – more properly the Pico de Teide – 3,713 metres high, appears so often in histories of exploration and stories of the age of sail. La Palma and Grand Canary are scarcely less renowned. At the summit of La Palma is the Caldera de Taburiente, about 10 km wide, which induced Leopold von Buch to bring the term “caldera” into geological literature, where it has survived a complete rejection of his theories of caldera formation.

The Canary Islands volcanoes behave in much the same way as those in the Azores. Tenerife had the misfortune to lose its best harbour at Garachico in 1709, when it was filled with lava from Teide. A feature of Teide is the prominence of levees, which border the blows from the summit, and appear almost to be artificial. The last eruption was in 1909, but La Palma was active as recently as 1971.

Fogo in the Cape Verde Islands was active when the Portuguese settled it in about 1500, and remained so more or less continuously, emitting lava from time to time, until the middle of the eighteenth century. Since then there have been half a dozen more eruptions of lava, destroying cultivated land and buildings, and forming spatter-cones around the vents. After 1857 it became relatively quiescent, but there was a further lava-flow in 1951.

The observant reader will by now have noticed that the Canary and Cape Verde Islands lie rather far to the east of the Mid-Atlantic Ridge, and that there are no islands between the Azores and the St Paul Rocks to mark its position. There have, however, been reported eruptions of four submarine volcanoes that can plausibly be associated with known sea mounts, and one has erupted three times. The St Peter and St Paul Rocks are ultra-basic intrusions, and properly described as plutonic rather than volcanic, but Ascension and St Helena are both volcanic, though there are no records of eruptions. The lonely island of Tristan da Cunha is another matter.

Tristan is a tiny conical island about 13 km across, rising some 2,000 metres above the sea, and supporting a population of about 270 people whose main contact with the outside world is a small export of rock-lobsters. Early in August 1961 a swarm of earthquakes of only moderate intensity began bringing down falls of rock upon the settlement and disrupted the water supply. On October 9 a bulge appeared about

Figure 36.12 The impressive dome of Big Ben rises 2745 metres above Heard Island.

250 metres east of the settlement, which is at the northwest corner of the island, and grew within four days into a dome 75 metres high, which then emitted a blocky basalt lava-flow and buried the lobster-canning works. The British government evacuated the population to England, and the Royal Society replaced them with an expedition of volcanologists. After the lava-flow, the summit of the dome collapsed and a small cinder-cone built up. This was to emit two further flows, one on each side of the earlier one. At the same time, a small explosion crater opened on the southern, inland, side of the dome. During February and March of 1962 an elongated dome developed, and grew northeastwards from the crater, in which fumarolic activity was to persist for another year.

The arrival in England of a party of 270 bewildered people, used to living in the manner of a past century, taciturn, and speaking a still older dialect, brought the island forcibly to the attention of a world that scarcely knew its name. Press publicity stressed primitive conditions and isolation amid Antarctic storms, so it is perhaps well to mention that its latitude is much the same as that of Capetown, Buenos Aires, Auckland, and Melbourne.

From Tristan the Ridge continues to Gough Island, and a further 200 km to Bouvet island, close to the northern limit of the Antarctic pack-ice. No eruptions of Bouvet have been seen, but differences between aerial photographs taken before and after 1956 make it reasonably certain that an eruption took place about that time.

In 1825 a Captain Thompson sighted an uncharted island a hundred kilometres or so to the northeast of Bouvet, and made a sketch of it. It was reported again in 1893, but a thorough search by a German oceanographic vessel in 1898 failed to find it, and it has not been seen since. In 1967 two British meteorologists suggested, on the basis of abnormally low temperatures in Chile and New Zealand from 1896 to 1907 and an abnormal northward spread of Antarctic ice, that it had blown up in about 1895 or 96. To produce such an effect an eruption comparable to the 1912 eruption of Katmai would be needed, and there has been a more recent suggestion that volcanoes in Marie Byrd Land might instead have been involved. Sceptics have claimed that Captain Thompson's sketch shows Bouvet Island through fog; but Thompson also produced a picture of Bouvet, and in the same year another captain sketched both islands. That they should both have sketched the same island twice is unlikely, as they both produced a recognisable Bouvet. A submarine eruption in the right place would explain the mystery, and South African oceanographers have charted a suitably-placed bank.

Bouvet is the last island on the Mid-Atlantic Ridge. To the west, shallow earthquakes follow a poorly-defined connection with the southern limb of the Scotia Arc, but there are no volcanoes. To the east, Bouvet is linked by the Atlantic-Indian Ridge to Marion, Prince Edward, and Crozet Islands. Marion produced explosions and a lava-flow in 1980, but there have been no historic eruptions of Prince Edward or Crozet.

The boundary between the African and Antarctic Plates now turns northeastwards along the South-West Indian Ridge, which is again well-marked by earthquakes but without volcanoes, to a triple junction that is unexpectedly far north, almost on the Tropic of Capricorn. Here it meets the Mid-Indian Ridge which (with changes of name) marks the western edge of the Indian Plate, and extends from the triple junction near Macquarie Island south of New Zealand to the Red Sea, connecting the oceanic ridges with the African Rifts. The bathymetry of the western part of the Indian Ocean is complex – as indeed are the Rifts – and other connections can be traced via Mauritius, Réunion, and Madagascar. Piton de la Fournaise, on Réunion, has erupted in 1640, and is the site of an important volcanism. There is no recent volcanism in Mauritius, but some can be found at several places in Madagascar, and the Comoro Islands provide a final link with the African continent. Since reports began in the early 1800s, Karthala, at the northern end of the group, has erupted more than a score of times, usually with explosions and lava-flows, and sometimes with destruction of property and loss of life.

Before we deal with Africa, we shall retrace our steps to the triple junction, and see what lies along the plate boundary to the east. The tiny island of St Paul is reported to have erupted in 1793, and its companion Amsterdam Island is also volcanic. Kerguelen is fumarolic. Early reports of activity on Heard Island came mainly from Antarctic explorers and shipwrecked mariners, but since 1950 the Australian Department of External Affairs has taken an interest in the place, and found it more or less continually

37—Africa

O what a world of vile ill-favoured faults!

WILLIAM SHAKESPEAR: <u>The Merry Wives of Windsor</u>

So far we have been pre-occupied with two kinds of geological structure – spreading ridges and subduction zones. The volcanoes of Africa are rather different. Most of them are to be found near the great system of rift-valleys that run northwards from Mozambique to Ethiopia, the Red Sea, and the Gulf of Aden (Figure 37.1). They have some remarkable similarities and equally surprising differences, and geologists are not at all agreed about how they were formed, though they clearly have much in common with the rifts of the mid-oceanic ridges. Their sides are straight and parallel, and most of them are about the same width, 40 to 50 km. The valley of the Rhine, which is also a rift, varies from 30 to 70 km. The Red Sea, which is two to three hundred kilometres wide and at first appears to be part of the African system is something rather different.

The simple view of the rifts is that the two sides have moved apart, creating two parallel faults and allowing the block between them to subside (Figure 37.2). Volcanism has followed, in some cases flooding the valley floor with lava; but in some of the deepest rifts there has been little or none. In the north, in Ethiopia, volcanoes rise from the floor of the rift, but further south the huge ice-capped massif of Mount Kilirnanjaro, and Mounts Kenya and Meru, lie to the east of the system, although there are many smaller volcanoes within the rifts themselves. The walls of the rifts are seldom equal in height, and though many of them are occupied by lakes whose surfaces are several hundred metres above sea level, their floors may lie an equal distance below it. This is true of Lake Tanganyika, whose surface is 780 metres above sea level and whose floor lies 655 metres below. The sides of the rift rise another thousand metres above the lake. Lake Nyasa, similarly, descends 300 metres below sea level.

It now seems probable that the rifts opened as the result of a great up-warping of the whole region that began in the Miocene some 20 million years ago, first allowing flood basalts to cover most of Ethiopia and south-west Arabia, and then creating the great central volcanoes of Kenya as the rifting extended southwards and became more complex. In Kenya and Uganda, it divides into eastern and western branches, lying on either side of Lake Victoria, which occupies a shallow depression nowhere more than 90 metres deep, unlike the lakes of the rift-valleys. The eastern branch is the older. Mount Kilimanjaro, 5,895 metres high, is now in a solfataric stage; and Mount Kenya (5,200 m) is considered extinct. Meru, west of Kilimanjaro, produced a little lava twice last century, and erupted again in 1910.

From just west of Nairobi the Eastern or Gregory Rift (Figure 37.3) extends southwards into Tanzania. Here great quantities of soda derived from hot springs and fumaroles and leached from the rocks of the surrounding country-side have become concentrated in Lakes Natron and Magadi, which lie within the Rift, and are exploited on a large scale (Figure 37.4). Although the volcanic rocks within the rift system are mainly basalts, they are not quite identical with the oceanic basalts of Iceland and Hawaii, being richer in sodium and potassium (Figure 37.5). These alkaline

Figure 37.1 Volcanoes of the African Rift.

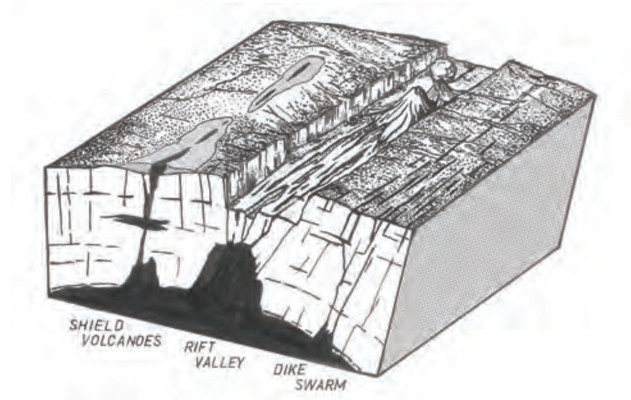


Figure 37.2 Formation of a Rift Valley

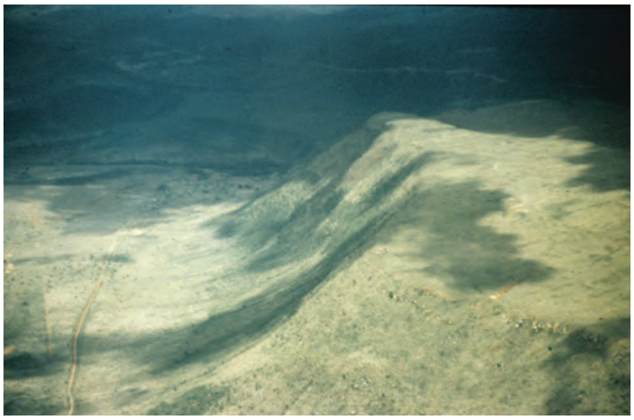


Figure 37.3 Looking northwards along the eastern scarp of the Rift Valley, Kenya.

Figure 37.4 Lake Nakuru is one of the more northerly soda lakes that lie in the African Rift. They are fed by streams that dissolve the salts in the soda-rich ejecta from the neighbouring volcanoes.

Figure 37.5 Eburru is a sulphuritic volcano north of Longonot in Kenya.

Figure 37.6 Ngorongoro caldera in Tanzania is one of the most famous of sanctuaries for Arfican wild-life.

basalts are not unknown in oceanic settings, but they are nowhere so plentiful, and, there is nothing quite like OI Doinyo Lengai, "the Mountain of God", a magnificent cone rising 2,278 metres above Lake Natron and 2,880 metres above sea level. It tends to erupt washing-soda ($Na_2\ CO_3$). Until it was destroyed in the eruption of 1914 a needle 6 metres high and very rich in sodium carbonate stood on the north side of the crater.

Between Lake Natron and Lake Eyasi, another soda lake, lies Ngorongoro, a complex of extinct volcanoes that extends almost the full width of the rift and rises to 3,648 metres. At its summit is an almost exactly circular caldera 19 km across. Abundant clover grows on its almost perfectly flat floor, there is a lake of fresh water six kilometres long, and within its walls, 600 metres high, graze hundreds of thousands of wildebeest, elands, and impalas. There are lions and cheetahs, rhinos and hippos, elephants and baboons, ostriches and quail, and all kinds of waterfowl. In 1959 it was realised that this astonishing animal paradise was imperilled by hunters, and by tribesmen pasturing diseased cattle, and the government acted to declare it a reserve (Figure 37.6).

Mount Elgon, an extinct 4,300-cone to the north-east of Lake Victoria, lies evenly across the border between Uganda and Kenya, separating the eastern and western branches of the rift. The active volcanoes of the western branch, which contains Lakes Albert, Edward, Kivu, and Tanganyika, are concentrated in the Virunga Range which is also divided politically and unequally between Zaire, Uganda and Rwanda. It is composed of eight big volcanic piles more than three thousand metres high, and none of them can be considered extinct. The two most active, Nyamuragira (also known as Nyamlagira) and Nyiragongo, both lie in Zaire. It is a far from accessible region, and the Virunga Mountains first came to European attention in 1861, when they were named by John Speke. (Virunga appears to be the plural of kirunga, the local word for mountain, a linguistic oddity on which we are unqualified to comment.) In 1876 H.M. Stanley saw the three cones of Virunga in the west-north-west, but he does not explicitly declare them volcanic. In 1891 Franz Stuhlman reported an eruption of Visoke. Nyamlagira has some claim to be considered the most active volcano in Africa, but the lively writing of the volcanologist Haroun Tazieff, and his persistence in overcoming the physical and political obstacles in his way, has probably made Nyiragongo better known.

In 1947, Tazieff was a geologist working for the government of what was then the Belgian Congo, with no particular interest in volcanoes, but with a fondness for climbing mountains. From this point of view, Nyiragongo was not greatly interesting. There was even a track to the top , cleared by rangers of the Virunga National Park.

The inside of the summit caldera was another matter. It was over a kilometre and a half in diameter, and from the narrow rim the sides dropped vertically for about 200 metres to a flat floor glimpsed through billowing clouds that poured from a large central pit. Tazieff lay on his stomach gazing through the smoke, and making plans for an eventual descent, which took place a year later. In the meantime, Nyamuragira had decided to erupt, and Tazieff was sent to watch it.

Nyamuragira is a shield volcano 3,056 metres high, with a summit caldera containing several interior terraces that have been greatly modified in the course of successive eruptions, of which there have been more than a score in the present century. In 1948 it was spouting gas and lava from a fissure that extended south-westwards from the summit towards Lake Kivu. Kivu once drained to the north, reaching the Nile via Lake Edward, but this exit had been blocked when the Virunga Mountains were formed, and the water now flows down the Ruzizi River to Lake Tanganyika, and thence via the Congo to the Atlantic. Flows of lava from the two volcanoes continue to reinforce the natural dam.

Tazieff, still new to the habits of volcanoes, expected a spectacular and probably dangerous display of pyrotechnics when the lava reached the lake, but instead it slipped smoothly into the water, giving him an object-lesson on specific heat, thermal conductivity, and change of state. When the lava first met the lake there was indeed a cloud of vapour, and the water came to the boil, cooking a few near-by fish; but the thermal capacity of the lake was very great compared with that of the lava-flow, and the rise of temperature was small except quite locally. Almost at once the surface of the lava cooled and solidified, forming a shell whose low conductivity prevented a rapid supply of further heat from the interior. At the same time, convection carried away the heated water and continued to cool the surface.

As the crow flies, the summits of Nyamuragira and Nyiragongo are perhaps 12 km apart. Tazieff's camp was no more than two kilometres from the crater of Nyiragongo, and he soon became aware that every night a strange reddish glow was lighting the clouds above it. As the months passed, his interest in volcanoes and his determination to look into the pit of Nyiragongo grew steadily. When at last he did he discovered a lake of molten lava, covering about a third of the bottom. Several fumaroles pierced the solid part. Great bubbles up to fifteen metres across agitated the surface of the lake, and uncomfortable surges of heat reached the mouth of the pit (Figures 37.7 and 37.8).

Lava lakes are of particular interest to volcanologists because, as volcanic manifestations go, they are docile and approachable, and long lasting. One of the problems that scientists at volcanoes have is the time they have to wait for the volcano to do something. The most famous lava lake had been Halemaumau, a pit within the caldera of Kilauea, in Hawaii, but that had been destroyed by an eruption in 1924 (Figure 11.30). It still refills at the time of an eruption and can become the site of spectacular lava-fountains, and it may even overflow on to the floor of the caldera but none of this is quite the real thing. Lava lying in a hollow can remain molten for quite a long time, but the heat of a proper lava lake is maintained by continual convection that connects it with the magma in the main conduit of the volcano.

In spite of their long persistence, lava lakes do not last for ever. The one at Nyiragongo probably made its appearance in 1928, when the mountain began to smoke continuously, and the nocturnal glow was first noticed.

It disappeared on January 10, 1977, in the shortest eruption on record, after a life of about half a century. To quote Tazieff:

"The way the lava lake vanished is quite simple: it was drained through a set of perpendicular (N-S and E-W) fissures which broke out at altitudes up to approximately 2,200m. on the northern side of the Nyiragongo complex, 2,400 m on the western side, and 2,700 m on the southern one. The drawing off of the millions of cubic metres of lava contained in the crater has been extremely fast: collected evidence as well as field observation facts show all was over in less than one hour, and it seems that the draining proper was over within less than half that while."

Casualties in the villages on the lower slopes were heavy.

The lake's fifty-year history was marked by violent fluctuations in level. In April 1972 it overflowed the pit and flooded the floor of the caldera. At the time there was an unusually large number of people on the mountain, not only volcanologists and French and American camera teams, but a party of 26 young Americans sponsored by the U.S. National Geographic Society. At one stage, 59 of them were actually within the crater; but most of them had already returned to the rim when it became apparent that not only was the level of lava in the pit rising and falling, but that each rise was higher than the last, and that an overflow was likely. When it came, the volcanologists retreated rapidly, but they soon realised that there would be an exceptional opportunity to take gas and lava samples, and returned to their hazardous duties.

Even before this, Nyiragongo had been – apart from the problem of getting from the crater rim to the caldera floor, which had been solved by specially devised winches and ladders – a more than usually convenient volcano to sample. One of its peculiar conveniences was a floating island of cooled lava that at one stage covered nearly two thirds of the lake.

The many expeditions to Nyiragongo have been particularly fruitful in developing new equipment and techniques, especially protective clothing (Figure 37.9). A lake of molten lava at a temperature of 1,000°C is not readily approached across ground only a few hundred degrees cooler, through clouds of noxious gas. Before the days of space-travel it was necessary to don suits of fire-proof asbestos coated with a heat-reflecting layer of aluminium. They were heavy and hot, but now fortunately space research, in addition to its much-publicised non-stick frying-pans, has produced a heat-resistant synthetic called Nomex, which is light and flexible. Where the ground is not too hot it is possible to wear tramping-boots with plastic soles. They begin to soften and melt at 300° or 400°C, and at higher temperatures shoes with tiny metal cleats that make only limited contact with the ground are used – but it is wise to keep walking. Crash-helmets that are strong enough to resist a rain of ash or a hail of bombs are too heavy to be worn on the head, and must be large enough to be carried by the shoulders, like old-time divers' helmets. The window in front is covered with a heat-reflecting layer of thin, transparent gold.

Before leaving the rifts we must say a little more about the Red Sea. Not only is it much wider than any of the other rifts, but its floor turns out to be oceanic basalt. There is no central ridge, but it seems likely that it is in fact an ocean in the making, and it will eventually acquire one and widen still more, driving Africa and Arabia farther apart. If this is the case, the Red Sea probably started as a rift like those to the south, and they too may eventually widen, creating a new ocean and two new continents. This argument,

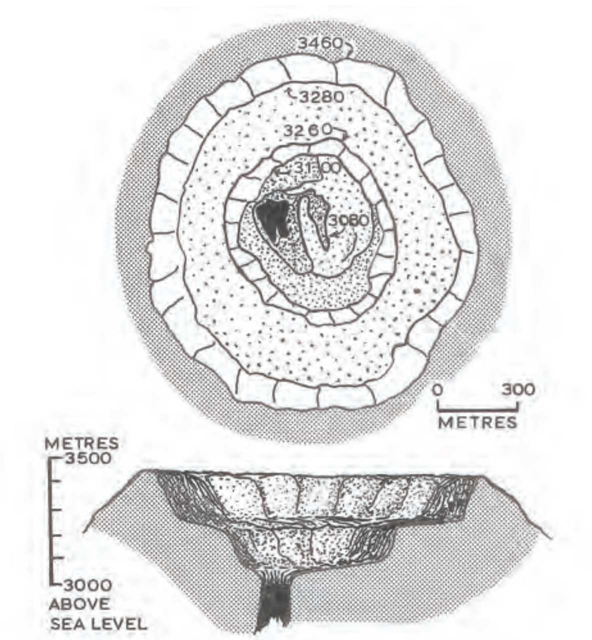


Figure 37.7 Nyiragongo prior to the 1977 eruption.

however, ignores the spreading of the Atlantic, and there are geologists who claim that this is the more powerful, and will eventually close the Red Sea once more.

On the opposite side of Africa, a dead straight line of islands points directly into the angle of the Gulf of Guinea – Annobon, Sâo Thome. Principe, and Fernando Poo. All of them are extinct volcanoes of no great age, and where they meet the coast stands Mount Cameroon, an elliptical basalt formation rising from sea level to 4,070 metres. It is an odd kind of volcano, and an odd place to find one. It is neither on a plate boundary nor on a rift, and like Etna it seems to have had some difficulty in deciding where it would like to be, for the top and sides and the area around the base are pitted with hundreds of craters, some of them simple holes, and others crowned with cones from 10 to 200 metres high. First one and then another has erupted on about a dozen occasions over the last century, most recently in 1959, on that occasion through a fissure in the eastern flank. There are similar fissures filled with congealed basalt, and one of them has formed a basin a kilometre wide at a height of 2,875 metres. Most of them have been sources of large lava-flows.

The most likely explanation of Mount Cameroon is that it marks the present position of a mantle plume or "hot spot" which has gradually migrated eastwards, leaving the chain of islands behind; but it is difficult to understand why such a movement should be so straight, as it must originate at a considerable depth. On the other hand, it is not possible to invoke plate movement over a stationary plume, as the accepted displacement is in the wrong direction.

Figure 37.8 Nyiragongo in Zaire is about 3,500 metres high. In spite of its remote location it is among Africa's best-studied volcanoes.

Figure 37.9 Volcanologist in protective gear as used at Nyiragongo.

38—The Alpide Belt

…the pure subtile, and cleansing fire
Is swiftly carried in a circle even:
Though Vulcan be pronounst by many a lyer,
The onlie halting God that dwells in heaven.

SIR JOHN DAVIES: Orchestra or a Poeme of Dauncing

Our rapid reconnaissance of the Pacific margin and the Mid-Atlantic Ridge illustrated the chief characteristics of constructive and destructive plate boundaries, but by-passed some important concentrations of activity, and a not inconsiderable number of isolated volcanoes that do not readily fit into the simple pattern. Two of these concentrations – the volcanoes of the Mediterranean and of the Sunda Arc – lie at opposite ends of the tectonically active system known as the Alpide Belt, which follows the southern boundary of the Eurasian Plate.

Before we consider the detail of this last major system we shall digress to glance at two regions of older volcanism in Europe. Both are associated with rifting, and characterised by trachytic rocks. Eifel, in the Rhineland, is best known for the occurrence of maars (Chapter 11), probably formed about 8,000 years ago. The Auvergne, in France, active over a lengthier period, greatly influenced the ideas of early volcanologists. Not only are there maars, but breached and symmetrical cones, domes, old tholoids, explosion pits, lava flows and much else (Figure 38.1). These stretch across the Massif Central for about 150 km, in a belt known as the Chaîne des Puys, probably representing an incipient rift that ceased to move apart before it had fully developed.

The best known of the Puys is the Puy de Dôme (1465 m), which dominates the city of Clermont-Ferrand (Figure 38.2), but several other members of the chain are higher. Both the Puy de Sancy and the Plomb de Cantal have a height of 1835 m, and the Puy Mary reaches 1787 m. In Roman times the Puy de Dôme was crowned with a temple of Mercury, and today it carries a television mast. In 1648 Blaise Pascal (who was a native of Clermont) had a barometer carried to the summit, and established

Figure 38.1 The Chaîne des Puys, looking north from the Puy de Dôme.

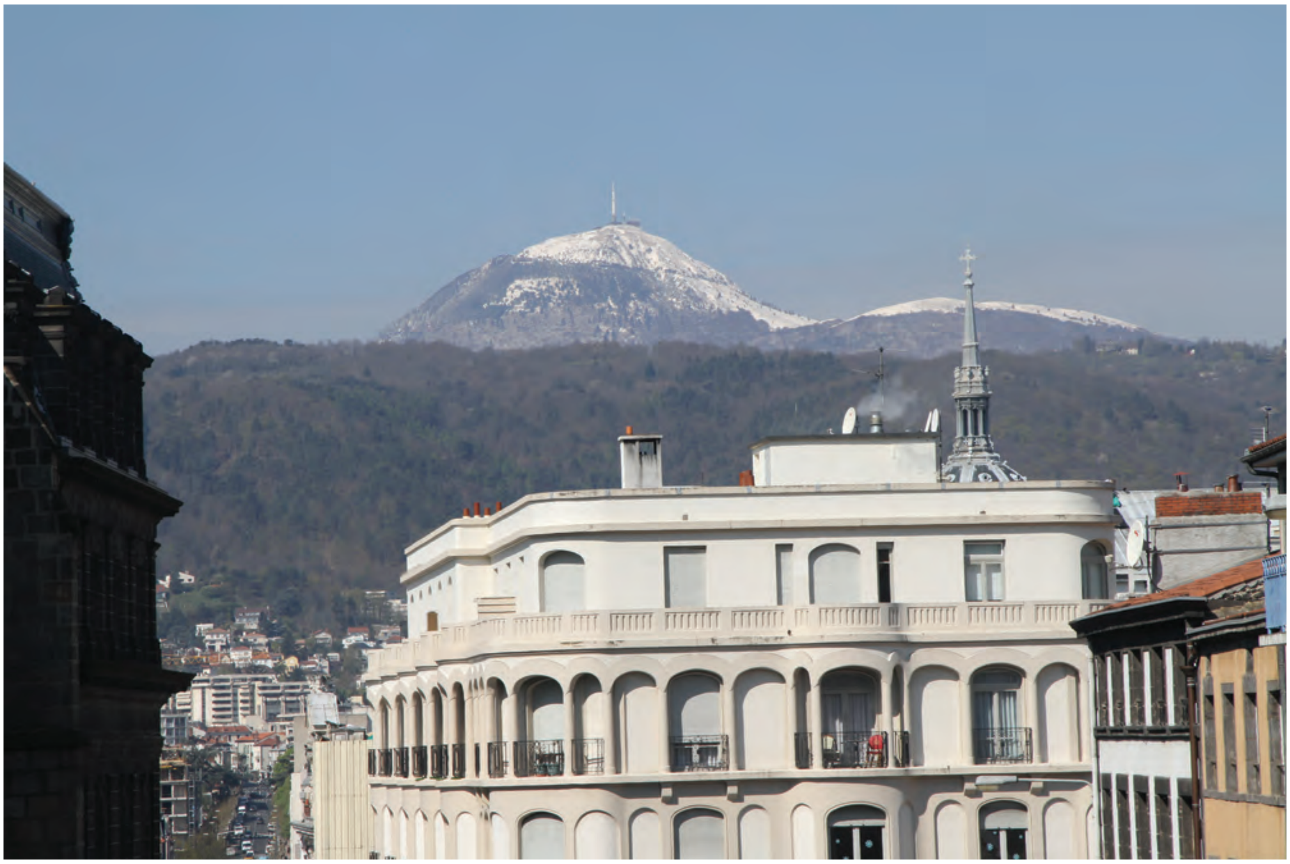


Figure 38.2 The Puy de Dôme dominates the city of Clermont-Ferrand .

Figure 38.3 Puy Griou in the Auvergne.

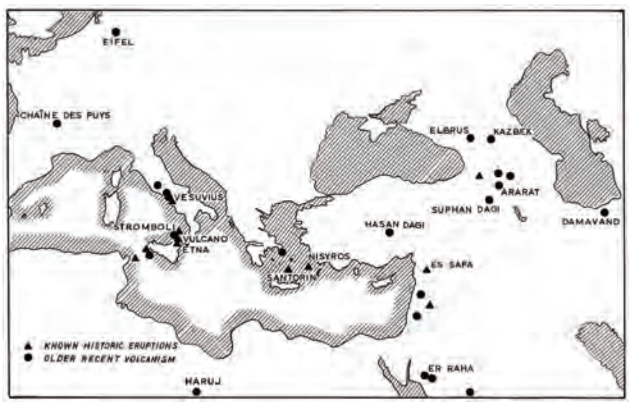


Figure 38.4 The Alpide Belt in the Mediterranean and Near East.

that air had weight; and in 1911 the pioneer aviator Eugene Renaux flew from Paris with a passenger and landed him on top, earning a prize of 100,000 francs.

Most of the Puys were active between 3,000 and 6,000 years ago. An eruption of the Puy de Monteineyre and the explosion that created the Lac Pavin, probably about 1500 B.C., seem to have been the most recent activity in the Massif Central, but volcanism has left its legacy in spas like Vichy, Mont Dore, Royat, and Saint Nectaire; and in the mineral waters of Volvic and Perrier (Figure 38.3).

Figure 38.5 Strombolian activity from the Bocca Nuova, Etna.

The greatest controversy of eighteenth-century geology was settled by evidence found in the Chaîne des Puys. At the end of the century geologists had become divided into two schools – the Neptunists, who held that all rocks had been deposited from a primitive universal ocean; and the Plutonists, who considered granites and basalts to be of volcanic origin. Lavas, the Neptunists contended, were melted by the combustion of coal-seams.

The leader of the Neptunists, Abraham Gottlob Werner, was professor of mineralogy at the influential School of Mines at Freiburg in Saxony, who based his case upon the rocks close to home. It was eventually to be overthrown by his more widely-travelled pupils, most importantly Leopold von Buch, whose doubts began when be visited the active regions of Naples and the Canary Islands, though he was at first reluctant to dispute the views of his distinguished teacher.

In 1802 von Buch visited the Auvergne, apparently unaware that the French geologists J.E. Guettard and Nicholas Demarest had already recognised the volcanic nature of the Chaine des Puys, establishing the relative ages of individual cones, and mapping lava-flows. After he had inspected the Puy de Dôme von Buch's conversion was complete, but it was to lead him to another false doctrine, his theory of 'Craters of elevation', which attributed great volcanic cones like the Mont Dore not to the piling of material around a vent, but to the bulging of material at depth.

The Mediterranean end of the Alpide Belt (Figure 38.4) presents a number of difficulties, some of which arise from the real complexities of a comparatively broad belt of activity, and some from its long accessibility to geologists and geophysicists who are aware of details that refuse to accommodate themselves to large-scale generalisation. Like the Pacific margin, it is a region where lithospheric plates are being forced together; but while in the Pacific they were dissimilar – one oceanic and one continental – here both are continental, except from the Azores to the Straits of Gibraltar, a section of the belt well-defined by earthquakes, but without active volcanoes. From Gibraltar the plate boundary passes along the coast of North Africa, through Morocco, Algeria, and Tunisia, all of which experience large earthquakes, and have high mountains parallel to the coast, but no active volcanoes. The boundary now loops unexpectedly to the north, crossing into Sicily and sweeping around the Adriatic before continuing its eastward course through the islands of Greece and into Turkey. All at once we have reached the familiar volcanoes of classical antiquity – Etna, Vulcano, Stromboli, Vesuvius, and Santorin.

Sicily's Mount Etna is 3,238 metres high. It is the highest volcano in Europe, has been more or less continually active for the last two thousand years, and there are records of eruptions as long ago as 1500 B.C. Both Pindar and Aeschylus knew about it, but Homer, surprisingly, did not, leading classical scholars to argue for an early period of quiescence. In describing the ancient eruptions, poets seem to have found little urge to improve on nature. Pindar writes of

"Snowy Etna, nursing the whole year's length her dazzling snow, from the depths of whose caverns' pure springs are vomited unapproachable fire, with streams of eddying smoke by day, and in the darkness a red stream that sweeps burning rocks into the sea with a roar."

Figure 38.6 Santorin from Thera.

Figure 38.7 Santorin caldera, and Kameni.

Figure 38.8 Santorin. Road to Oia.

Diodorus Siculus tells of a lava-flow in 396 B.C., nearly 40 kilometres long and 3 kilometres wide, that stopped the advance of a Carthaginian army.

Compared with Vesuvius and Stromboli, the slopes of Etna are gentle, in spite of its great height. The base covers about 1,200 sq. km, and has a diameter that ranges from 40 to 50 km, so that in shape it lies somewhere between a cone and a shield. This it owes to its now normal habit of erupting basaltic lavas from radial fissures on the middle and lower slopes, and to changes in the position of the main vent. The result has been a broad and irregular form, with 200 or more parasitic cinder-cones dotting its flanks. The largest of these, Mount Rossi, is 140 metres high. It was the product of the great eruption in 1669, and is quite prominent in its own right. Much of Etna's recent activity has occurred in the Bocca Nuova (Figure 38.5).

The fertile lower slopes of Etna have been cultivated for centuries, and are covered with vineyards, orchards, and gardens. Although the widespread urge to climb mountains is comparatively modern, the accessibility of Etna has long attracted visitors to its summit. Strabo, far from claiming a "first" tells us that in his time it was "commonly ascended" from the south-west. Others who got to the top are Plato and the Emperor Hadrian, who seems to have been more interested in the sunrise than in the mountain, Sir William Hamilton, anxious to compare it with Vesuvius, and Gladstone, probably among the ministers that Disraeli described as "a range of exhausted volcanoes". In recent years, the snow-fields above the villages have been developed into winter-sports playgrounds.

Figure 38.9 Distribution of ash from the Santorin eruption in about 1470 B.C., preserved in sea-bottom sediments.

Lava-flows from Etna. have caused a great deal of damage, for there are many villages, and increasing population is inviting new houses to be sited between old lava-flows which often guide the paths of later eruptions. Of the many large eruptions the most famous was that in 1669, when explosions destroyed the summit cone, and. lava flowing from a flank fissure reached the port of Catania, in spite of the efforts to divert it (Chapter 22). In recent eruptions, new kinds of damage appear. In 1928 the road and railway-lines between Catania and Messina were severed by a lava-flow 30 metres wide, and in 1971 pylons of the cableway that carries skiers and tourists to the summit were brought down and the station terminus destroyed. Also destroyed was a building designed as an astronomical observatory and erected in the 1930s. Strong and persistent volcanic tremor made it impossible to use the telescopes for accurate work, and it ended its days as a rest-house. Lava ran down the eastern slopes from a fissure in the Valle del Bove, cutting some of the high level roads, and permanently ruining some of the best skiing slopes.

It would be hard to find a volcano that has had more written about it than Santorin. The name, a medieval corruption of Sant'Irene, patron saint of Thera, the largest of the surrounding islands, is applied to the southernmost of the island groupings that together make up the Cyclades. About 1470 B.C. a great pumice eruption occurred and a caldera was formed, about 15 km across (Figures 38.6, 38.7 and 38.8). It was breached by the sea, leaving the islands of Thera, Therasia, and Aspronisi to mark its outline. Then for a thousand years history is silent. In about 197 B.C. (historians disagree by a year or two), Hiera, a fourth island, appeared above the waves in the centre of the caldera and began an episode of island-building that lasted for the next two hundred years. Most of the islands, the protruding tops of andesite or dacite domes, proved impermanent, but at the end of the activity the island now known as Palea Kameni remained. Since then Nea Kameni, Georgios, and Dafni have appeared, and small domes and lava-flows continue to alter the configuration of the central group. The cycle of activity from 1939 to 41, renewed in 1950, produced another eight new domes. There is still plenty happening at Santorin, but nothing to match its behaviour in 1470 B.C.

Figure 38.10 The popular Turkish resort of Pamukkale first became a cure centre in about 190 B.C. Its hot springs feed streams that flow through the ruins of ancient hierapolis, destroyed by an earthquake in 1334. Beyond the shallow travertine basins of warm pale-blue water rich in calcium, and the modern motel, lie the walls of the Roman city, enclosing the remains of temples, two theatres, and early christian churches.

Figure 38.11 Mount Popa, Burma.

Figure 38.12 Taunggala Neck near Mount Popa.

There is of course no reason to doubt that a great eruption formed the caldera, and radio-carbon dating has now confirmed earlier attempts to use archeology to find out when. What first aroused public interest was the suggestion that Santorin could be the site of Atlantis. The legend of Atlantis reaches us through the writings of Plato, who says that the story came to him from a politician called Critias, who had heard it from his ninety-year old grandfather, who in turn had got it, 70 years earlier, from Solon. Solon had heard it from priests while in exile in Egypt. The chain of gossip extends across two centuries, and tells of an ancient island empire, ruled by a powerful king, which disappeared beneath the sea in a day and a night.

No matter how inclined we are to dismiss this story, there is a lost civilisation to explain, the Minoan civilisation of Crete, which came to a sudden and apparently mysterious end at about the time of the eruption of Santorin. An Irish scholar, K.Y. Frost, seems to have been first to link the event to the Atlantis story, but the suggestion gained little acceptance until thirty years later, in 1939, when the Greek archaeologist S. Marinatos drew attention to the simultaneous desertion of many Minoan palaces, to deep pits filled with pumice, and rock masses that had seemingly been struck by a giant wave.

Santorin is about 120 km north of Crete, and the kingdom of Minos is not likely to have ended “in a day and a night”, but continued archaeological work has provided further corroborative details. When the Minoan civilisation disappeared from Crete, Mycenean art, described by the Oxford scholar John Boardman as “but a provincial version of the non-Greek Minoan art” made a simultaneous appearance in southern Greece.

The first stage of the convulsion would probably have been a vast eruption of pumice, heralded by frequent and alarming earthquakes that caused the inhabitants to flee. No bodies have been found, and some houses were already destroyed when the pumice fell. Places in the path of the ash could have been plunged into darkness for days, like those around Bezymianny and Katmai in our own time. In 1965 an oceanographic vessel from Lamont Geological Observatory visited the eastern Mediterranean and took cores of sediment from the sea bottom. Many of them contained a layer of ash, which was dated by radio-carbon measurements and found to be otherwise similar to ash known to have come from tho great Santorin eruption. It was detected over an area of 200,000 sq. km, with an axis that passed through Thera and was elongated in the direction of the prevailing winds (Figure 38.9).

The ash covered the whole of Crete and Rhodes, and extends to the mainland of Anatolia, but it did not reach Egypt in sufficient quantity to show up in the cores. It is very fine, and the earliest stages of the eruption would probably have produced an even finer dust that would have travelled to greater distances. Between Santorin and Crete deposits more than two metres thick were found. About 60 cubic kilometres of material were ejected. Collapse followed, and if the evidence of washed-up pumice can be believed, initiated a tsunami. Surviving Minoans could have found persuasive reasons to re-settle in Greece.

Readers inclined to cataclysmic speculation should not be deprived of a note upon the views of Professor G.A. Galanopolous, a respected seismologist from the University of Athens. He notes that the date of the Santorin eruption is much the same as the one that biblical scholars assign to the departure of the Israelites from Egypt. Moses, it will be remembered, impressed Pharaoh with the wisdom of letting them go by stretching forth his hand to heaven and producing thick darkness for three days. Then, too, the behaviour ascribed to the Red Sea is very like that of a tsunami. Unfortunately for the theory, Santorin is in the Mediterranean, butit is possible that the biblical "Red Sea" is the Sea of Reeds, a marshy area east of the Nile Delta.

Not all archaeologists see a volcanic eruption as a solution to their problems. The ash-fall from Thera is real enough, but it has been contended that the disasters in Crete were so much later than the destruction of the settlement on Thera that they cannot have resulted even from a later stage of the "Minoan" eruption. Dr Colin Renfrew of the University of Southampton roundly declares that "There is no archaeological evidence whatever for damage by tsunami in Crete", and attributes most of the destruction to frequent earthquakes.

The volcanoes of Asia Minor cross Turkey (Figure 38.10) from the Greek islands of Cos and Nisyros into the Caucasus and Iran. In most cases there is fumarolic activity or other indications that they are geologically Recent, but historical reports of eruptions are lacking. Just within the eastern border of Turkey is the impressive snow-clad cone of Ararat, 5,165 metres high, and in quite the wrong place to be the mound on which Noah beached his ark.

The Great Caucasus is dominated by several volcanic peaks. Elbrus and Kasbek both exceed 5,000 metres. Elbrus has two summits and two craters, both of which show signs of fumarolic activity, and there are signs that Kasbek has erupted within the last thousand years. Hot springs are found throughout the region, some of which have been developed as health resorts. The best known is Kislovodsk. In the Elbruz Mountains, south of the Caspian Sea, the 5,670 metre Damavand also has active fumaroles.

At this point we run into problems, for active volcanoes become few and far between. Koh-i-Sultan near the Afghan border of Pakistan is a Recent volcano, and Taftan and Bazman, south of it in Iran are both in a solfataric stages. It becomes difficult to continue farther east-wards by following active volcanoes – but we cannot easily overlook the Himalayas. Vigorous seismic activity extends northwards from the Ganges valley, becoming increasingly diffuse beneath the Tibetan plateau, and a tight concentration of deep-focus shocks is to be found in the Hindu Kush. The Ganges valley contains an enormous thickness of sediment, in effect concealing a great trench that fronts a Himalayan arc.

These are the basic ingredients of a subduction zone, but until a few years ago the only reports of volcanic activity north of the Himalayas were hearsay brought back by travellers in the Kun Lun. In 1951 it was confirmed that an active crater, since named Vulkan, existed in Chinese territory at the western end of the range, and in 1973 satellite pictures showed a second volcano in eruption in the east in the region of Bokalik Tagh, near the western boundary of Qinghai.

Tibet is obviously a splendid hideaway for a volcano wishing to escape discovery, but intensified geological exploration by the Chinese has revealed hydrothermal activity along some 2,000 kilometres of the valley of the Tsangpo, between the Himalayas and the Gangdise Shan, and a number of Recent volcanoes in the Gaoling Mountains of Tengchong. At Tagejia, near Sangsang, 400 km west of Lhasa there are several geysers, one claimed to be "the most magnificent on the Eurasian continent". Altogether 1,600 hydrothermal fields in Tibet, Yunnan, and Hengchuan are now known, and several are being exploited for geothermal power.

From Tengchong in Yunnan, the Alpide Belt continues southwards through Burma and the Andaman Islands to Indonesia, and is marked by increasingly vigorous seismicity, though some of the largest shocks have been in northern Burma an beneath the Shan Plateau, where some shocks are deeper than normal. Volcanism is represented by Mount Popa (Figures 38.11 and 38.12). Barren Island, in the Andaman group, is an active volcano. It is less than two kilometres across and only 300 metres high, but there is a somma caldera 1,600 metres across that contains a central cone with recent flows at its base. During the eighteenth and ninetenth centuries four ash eruptions were seen, and solfataric activity has been reported many times. It erupted again in 1991. It has all that can be expected of an andesitic volcano, and prepares us to meet the Sunda Arc.

39—The Sunda Arc

We are arrived among the blessed islands
Where every wind that rises blows perfumes
And every breath of air is like an incense
…
The bowels of the earth swell with the births
Of thousand unknown gems …
We are fire already;
The wealthy magazine of nature sure
Inhabits here.

JOHN FLETCHER : The Island Princess

Sunda Arc is a convenient name for the bold lineation of islands and ocean deeps, gravity anomalies, earthquakes, and volcanoes that sweeps from the Andaman Islands through the whole length of Indonesia to the structural complexities of the Banda Sea and the Moluccas. From northern Sulawesi the line of activity continues into Mindanao and farther north to merge with the systems we have described in Chapter 30.

In the Sunda Arc we at last find a subduction zone that has all the features that text-book writers require of an island arc (Figure 39.1). Only the Aleutian Arc competes with it for size, and nothing comparable can be found outside the Pacific. This so upset the generation of geophysicists who thought up island arcs that they happily re-defined their Pacific to include it, badly upsetting statistics of seismicity and volcanism that are still widely quoted. It remains true that no country can claim more active volcanoes than Indonesia. Over 130 of them have erupted in the last 10,000 years, and history has recorded the eruption of more than 50, some of them many times.

To the south, lying parallel to the line of islands, is the narrow trench that marks the plunge of the Indian Ocean floor beneath the Eurasian Plate. The deepest part, south of Java, descends to more than 7,000 metres. The trench also marks the southern limit of the seismicity. As we go northwards across the arc the depth of the shocks steadily increases, and reaches a maximum of about 600 km beneath the Java Sea. Between the trench and the land there is a narrow belt of negative gravity anomalies, coinciding with a chain of small off-shore islands. This is a feature missing from many island arcs, and there are no islands south of Java, but the Mentawai Islands off Sumatra are an excellent example.

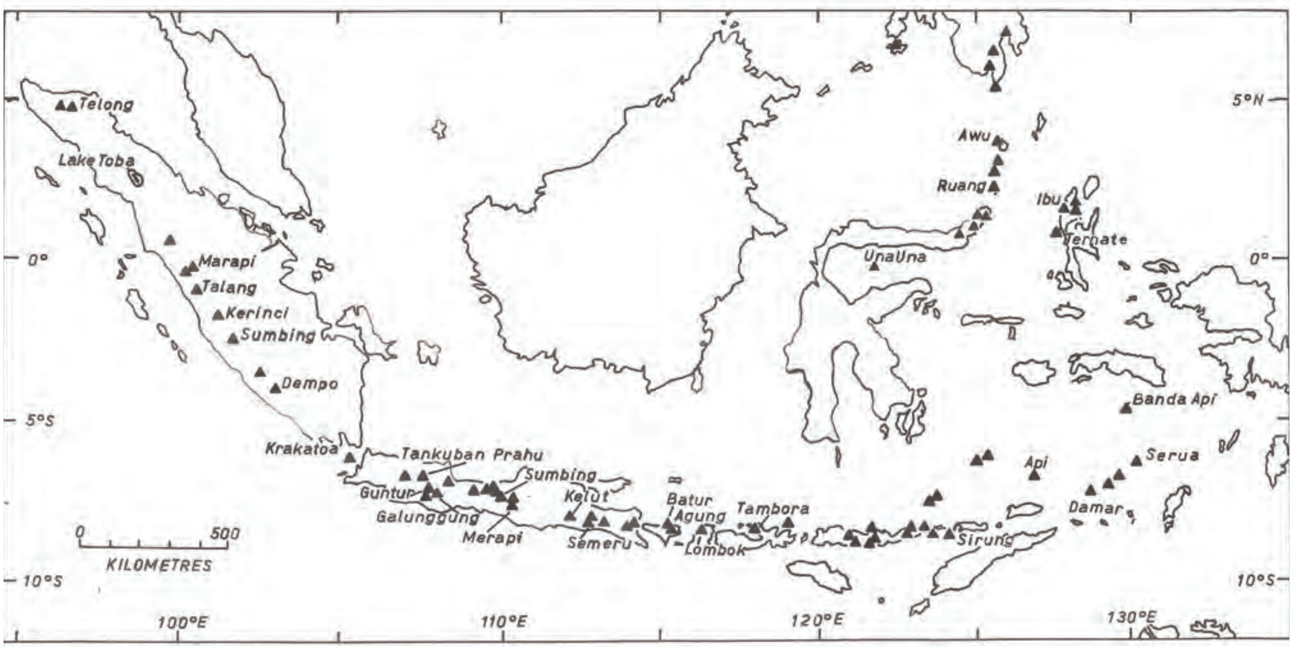


Figure 39.1 Volcanoes of Sunda Arc and Banda Sea, Sulawesi and Halmahera.

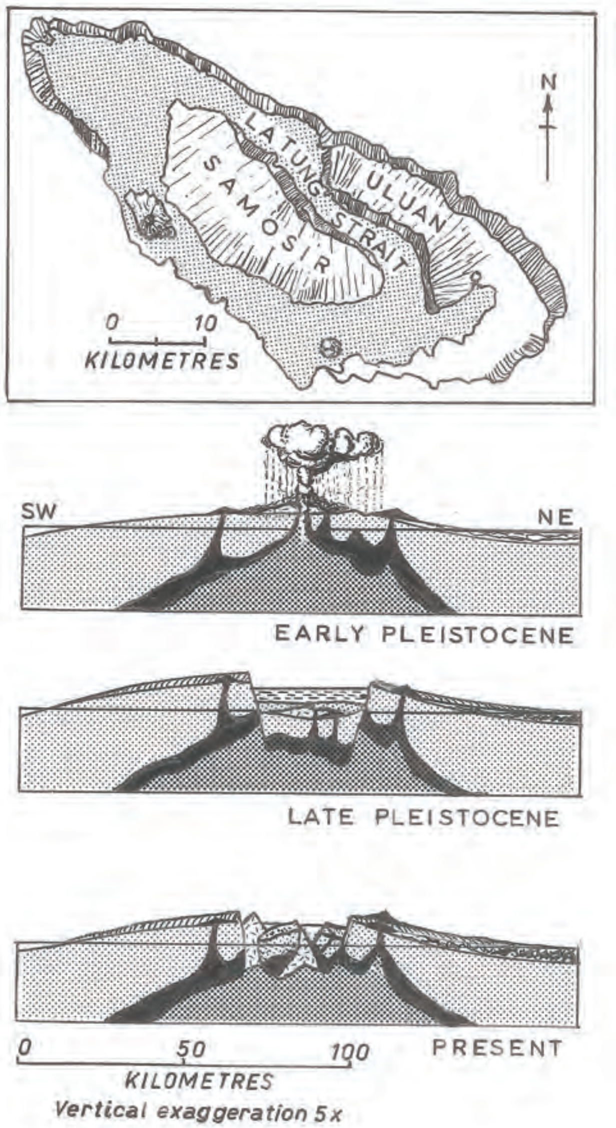


Figure 39.2 Lake Toba, Sumatra. Successive stages of a volcano-tectonic depression.

Figure 39.3 Krakatoa. This photograph was taken by a member of the Schuurman expedition on May 27, 1883, one week after the famous eruption began, and about three months before its awesome culmination. Engravings based on this picture are very common.

Behind the negative anomalies is a complementary belt of positive ones, rather broader, but reaching their maximum before we get to the main volcanic arc. Indonesian gravity studies were pioneered by Professor F.A. Vening-Meinesz who, in the late 1930s, solved the problem of making gravity-measurements at sea by taking his pendulums below the level of the waves in a submarine.

On crossing the coast of the main islands, the volcanoes are almost at once upon us. The line is continuous for the full length of the arc, and as the text-books demand, the earthquakes beneath them have depths of about 120 to 150 kilometres.

So many of the volcanoes of Sumatra have a long history of observed eruptions that only an arbitrary selection is possible; but there is good reason to begin at Lake Toba. It has already been mentioned as an example of the kind of super-caldera called a volcano-tectonic depression (Figure 39.2). The lake is 95 km long and nearly 30 km wide, but much of it is filled with the island of Samosir. On the south-west side hot springs around the cone of Pusuk Bukit attract visitors. Even as volcano-tectonic depressions go, Toba is a little special. Its history has been pieced together by the Dutch geologist R.W. van Bemmelen, and begins with a chain of andesitic volcanoes along the crest of an arch, which collapsed and formed a rift-zone in the early Pleistocene. In the late Pleistocene the floor of the rift fractured, and about 71,500 years ago an enormous eruption of pumice and ignimbrite followed. Some of the ash travelled to Malaysia, India and beyond, but most of the material was erupted as ignimbrite. Between one and two thousand cubic km were produced, and deposited over 20 or 30 sq. km in flows up to 600 metres thick. Collapse followed, along lines of old faults that determined its rectangular shape, and the depression filled to form the lake – but the rise of magma was not complete. A dome appeared on the floor of the lake, and split apart to form the Latung Strait, separating Samosir Island and the Uluan Peninsula, which tilted in opposite directions.

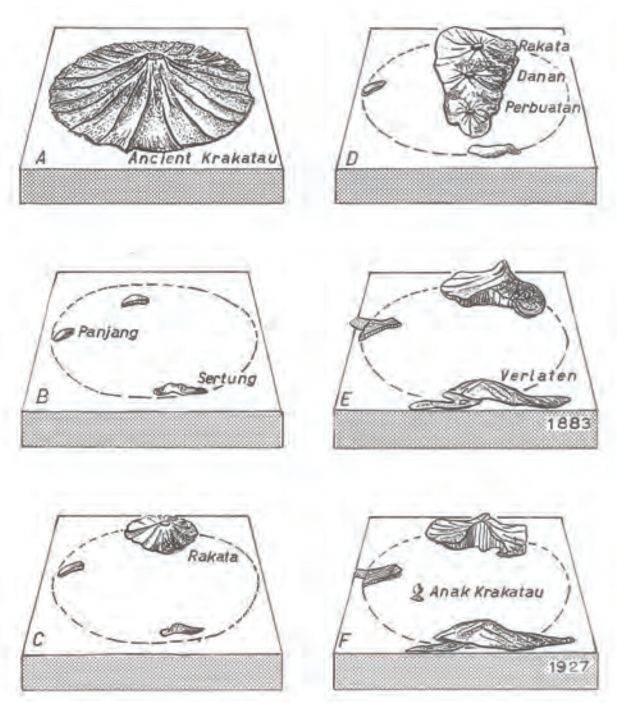


Figure 39.4 Successive stages in the development of Krakatau, looking to the south-east.

Of the active volcanoes of Sumatra, Marapi (not to be confused with Merapi in Java) has the longest record of observed eruptions, having been almost continuously active over the last two centuries. Kerinci and Dempo, both slightly taller at 3,000 metres, rival it closely, the difference lying more in a shorter historic record than in less vigorous activity. In the crater of Kerinci a yellowish-green lake comes and goes.

Krakatoa is by far the best-known Indonesian volcano, if not the most famous of all. Catalogues tend to assign it to Sumatra, but it is in fact an island in the Sunda Strait between Java and Sumatra, and its name is not Krakatoa, but Krakatau. In 1883 it erupted, with enough violence to attract the whole world's attention (Figure 39.3). The Royal Society of London promptly set up a committee to collect and publish all the information it could find, but somewhere on the path to the printer an editorial hand dipped a pen in red ink and neatly altered Krakatau to Krakatoa throughout. Thus the island had appeared on Admiralty charts at least as far back as 1868, and Krakatoa has become the name of the volcano throughout the English-speaking world.

The reader must not expect what follows to be more than the sketchiest outline of its story. The Royal Society's committee produced a volume of 494 pages, only to be outdone by R.D.M. Verbeek, a mining engineer stationed at Buitenzorg (Bogor). His report fills 546 pages, and is accompanied by an album of chromolithographs and an atlas of line drawings. In the bibliography compiled by the Indonesian Volcanological Survey there are 7,500 entries.

Tom Simkin and Richard Fiske, who have edited a remarkable compilation of contemporary accounts for the Smithsonian Institution, suggest that the extraordinary fame of Krakatoa "comes mainly from the fact that its distant effects were observed by such a large part of the world's population at a time when rapid communication and news publication made them aware of the connection between the eruption and their own observation of its effects." Certainly those effects, from air- and sea-waves to temperature changes and coloured sunsets, were widespread and persistent, and there is little doubt of the link between wide publicity and lasting fame. The eruption of Tambora in 1815 – a volcano on Sumbawa at the other end of the Sunda Arc – was by most measures a greater event; but the news travelled slowly, and the world of that day was unreceptive and unready to appreciate it.

The name Krakatoa (or Krakatau), has been used for the volcano that erupted in 1883, the group of islands of which it is part, and the main island of the group. This island is also known as Rakata, and we shall use that name in the interests of clarity. Many geologists have attempted to reconstruct the history of Krakatoa. Most of them give variants on a scheme presented in a series of five diagrams published by B.G. Escher in 1919, to which Dr A. Sudrajat, Director of the Indonesian Volcanological Survey, added another in 1982 (Figure 39.4).

Some time within the last million years Krakatoa was born, and grew to be an andesitic cone some 2,000 metres high. The first lavas seem to have been extruded gently enough, but as time went by it became explosive, and threw out vast quantities of pumice and ash – behaviour that shattered the cone, and led to eventual collapse. A submarine caldera was formed, 40 kilometres across, with three small protruding islets to mark the position of its rim. Still in prehistoric times, basalt was erupted near the largest of these, and built it into the 800-metre high cone of Rakata. By the end of the sixteenth century two other cones had been built within the caldera, and joined themselves to Rakata to form a single, highly forested "pointed island". Some time before this, the source of magma had become more acid and the new cones were andesitic. They were called Danan and Perbuatan.

The islands remained uninhabited, but by the time the Dutch arrived they had gained a place in Javanese folk-lore. It seems that Hanuman, the monkey god, had decided it would be a good idea to fill in the Sunda Straits, and brought a couple of handfuls of earth to start the job. Seeing Rakata, and realising that some one else had been along he flung down the earth in a fury – which accounts for the other islands, but not for Rakata. The Straits soon became a main shipping-lane, but Dutch sailors disliked the island. It was, they claimed, “the home of ghosts who let themselves be heard both night and day by yelling and screaming.” It was also the haunt of pirates.

In January 1681 Johan Wilhelm Vogel, a Sumatran official bound for Batavia (Jakarta) to see a doctor, noticed that: “the island Cracketovv, on my first visit to Sumatra completely green and healthy with trees, lay completely burned and barren ... and that at four locations was throwing up large chunks of fire the ship’s captain told me this had happened in May 1680.”

He had felt an earthquake when about 15 km from the island, and on coming closer found that “Cracketovv had split”. There was a strong smell of sulphur, and the sailors collected floating pumice. The problem is that none of the other vessels that passed by at this time mention the event. The verdict of most later geologists is that there was a real eruption, but that Vogel exaggerated its size.

In 1880 R.D.M. Verbeek, the mining engineer whose report of the eruption three years later was to make him famous, visited Krakatoa, made sketches, and produced topographical and geological maps. He recorded that there were fresh lava-flows on the slopes of Perbuatan, the youngest and smallest of the cones that made up the island. His early geological work had been a spare-time activity, but recognition and an honorary degree had followed work in East Borneo and south-west Sumatra, and made him the obvious man to study the great eruption on behalf of the government; but that is anticipating.

Although it is not the most seismic part of Indonesia, earthquakes are quite often felt in West Java, so it is not possible to be certain that the earthquakes felt in the middle of May in 1883 were connected with the eruption that followed. They were not strong, but two out of the three places from which the shocks were reported felt several within a few days. About the same time passing ships reported smoke and steam coming from Krakatoa, but the people of Anjer, 50 km away, who were used to the island’s habits, were sure there had been only normal cloud.

Early on the morning of May 20, the situation changed. The helmsman of a ship anchored close to Krakatoa noticed activity in the northern crater, and before mid-day Lloyd’s agent in Anjer had telegraphed the news of “a tremendous eruption, with continual shaking and a heavy rain of ashes”. Perbuatan was beginning a Vulcanian eruption. A column of vapour and ash reached upwards for 11 km, and explosions were heard in Jakarta and Bogor 150 km away. Ash-falls continued, at times reaching as far as Bogor, but there were fewer explosions, and on May 27 a party of 86 adventurous passengers boarded the “Gouverneur-Generaal Loudon” for an excursion to the island.

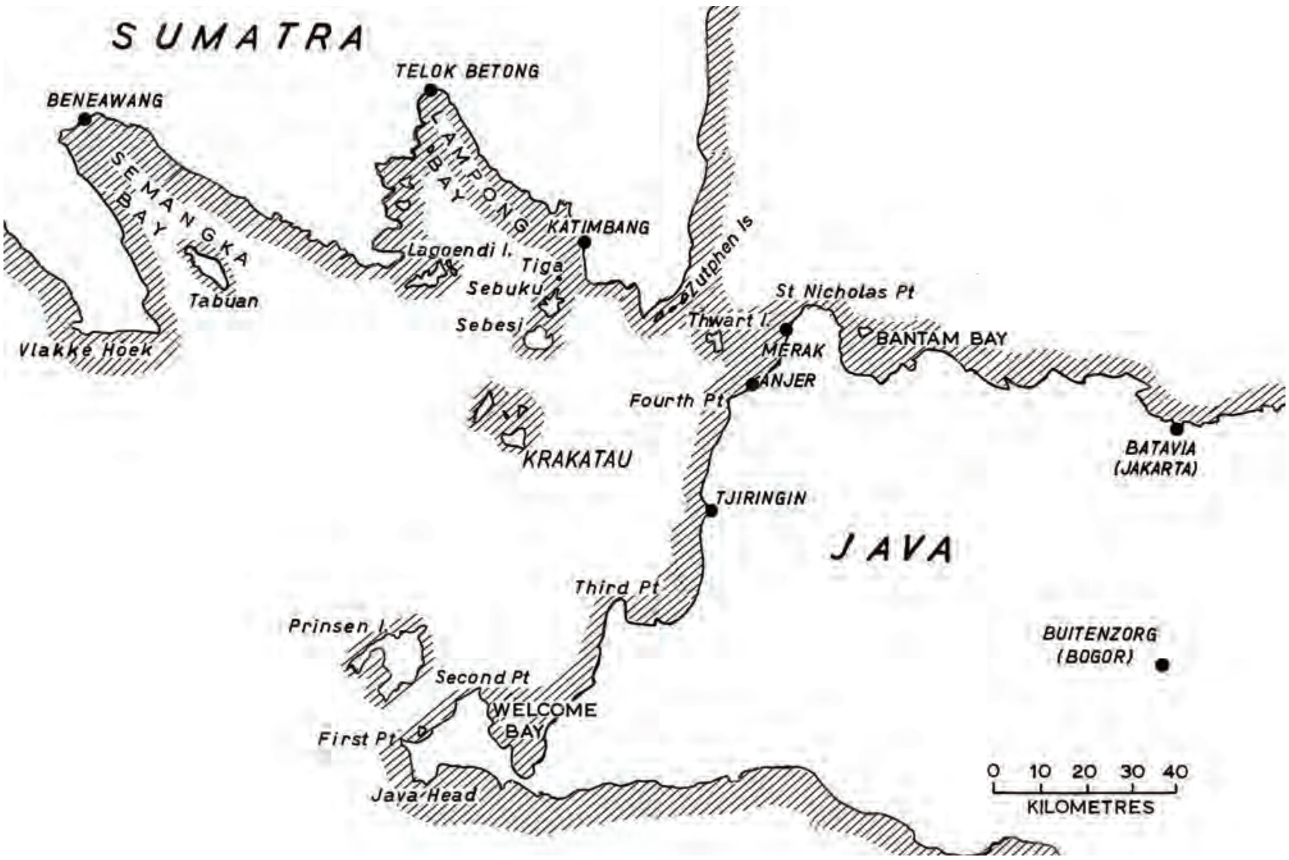


Figure 39.5 Sunda Strait, showing place-names in use at the time of the “Krakatoa” eruption of 1883. Krakatau is shown as it was after the eruption.

Among them was the engineer J. Schuurman, a colleague of Verbeek's, one of the smaller party that went ashore in one of the ship's boats and climbed to the crater. He took photographs and gathered samples of pumice and ash for analysis, reporting that on the beach 60 cm of ash lay on top of 30 cm of pumice, and that the trees on the northern part of the island had been reduced to a few bare stumps.

The rising column of "smoke" came from a vent a few metres across, and widened as it rose with "an incredible beauty and thundering" against a dark backdrop of falling ash carried away from them by the wind. At intervals of five or ten minutes rumbling explosions sent up puffs of darker smoke, and produced a hail of small stones. There was apparently some glowing material in the crater, which was reflected on the clouds, making them appear like flames at night, but no lava-flows were seen.

This hazardous visit fortunately coincided with a decline in activity, and the first part of June was quiet. A naval vessel took soundings and reported that there had been no changes in the sea floor. On June19, explosions were heard at Anjer, but Krakatoa was hidden by cloud.

When it cleared on the 24th two columns of smoke were seen. Throughout July red glows were seen from ships moving through rafts of pumice, but the ash eruptions seemed to be at an end. On August 11 the surveyor H.J.G. Ferzenaar landed to see whether a detailed survey could be made. He reported that it was too risky, but made a most valuable sketch-map showing the active vents and the areas of damaged vegetation. Danan was now as active as Perbuatan, and new vents had opened around its base.

Ferzenaar was to be the last man to walk on the northern part of the island. Soon after he left ash showers began once more. He had mapped three main vents and eleven lesser ones, and a later report claims that more than a dozen vents were erupting simultaneously. There were periods of darkness, showers of ash, sand, and gravel, and displays of lightning. Explosions were heard on ships in the Straits.

August 25th saw the beginning of increased activity that was to climax in the great explosion at ten in the morning on August 27th. Rumblings and detonations were heard on both sides of the Straits, and lightning flashed in the column of smoke that rose above the island. Towards evening fine ash fell at Telok Betong, at the head of Lampong Bay in eastern Sumatra (Figure 39.5). Ships in the Straits reported St Elmo's fire playing about the rigging, and a rain of phosphorescent mud fell on the "Gouverneur-Generaal Loudon", to the north.

Throughout Sunday August 26th explosions grew louder and more frequent and there were heavier falls of ash that spread to Java. At 3.34 p.m. the first of the explosions that would blow Krakatoa apart occurred, and the sound was heard from Sri Lanka and Malaysia to central Australia. That night the noise made it impossible to sleep in Batavia. At about 6 p.m. a small tsunami reached Telok Betong, and boats were thrown on the beach at Katimbang, at the head of the bay.

Establishing the sequence of events on August 27 is not easy. Tsunamis, air-waves, and falls of ash take different times to travel. Many of the places affected are quite far from Krakatoa, a variety of times were in use, and few people had good time-keepers. The best time observations were made almost accidentally, on the tide-gauge at Tanjong Priok, which recorded the tsunamis, and on the pressure-gauge of the Batavia gas-works, which responded to the air-waves. Even so, many places were so badly damaged by the early events that the inhabitants were unable to describe the later ones – they had fled, they were injured, or they were dead.

The tsunami that reached Telok Betong at 6 p.m. on August 26 was apparently due to the eruption at 3.34 p.m., and was succeeded by a second wave a few hours later, which substantially damaged the town. The first damage on the Java coast also occurred that evening, but the most destructive wave was started at 5.46 a.m. the next day, and wiped out Anjer, Merak, Tjiringin and other coastal settlements in west Java. The lighthouse at Fourth Point was also destroyed, the one at Benkoelen damaged, and the outbuildings at

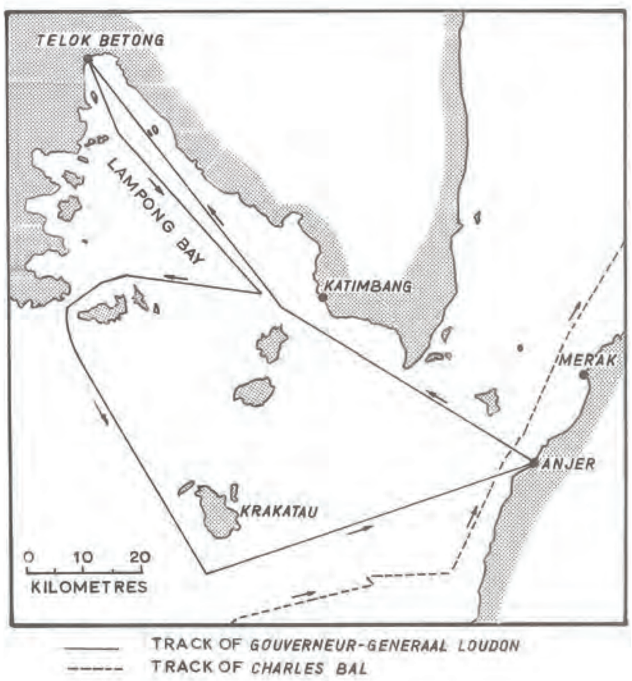


Figure 39.6 Tracks of vessels witnessing early stages of the "Krakatoa" eruption. Krakatau is shown in pre-eruption form.

Vlakke Hoek swept away. The wave that accompanied the climax at 10 a.m. was no doubt bigger, but after the earlier events there was little left to destroy.

The tsunamis destroyed 165 coastal villages, and account for all but a few hundred of a total death-roll of more than 36,400. Places on both sides of the Straits and along the coast of Java as far as Jakarta were affected, particularly around the embayments of Semanka and Lampong on the Sumatran side, and in Pepper Bay and Welcome Bay in western Java.

About a week later a government doctor reached Tjiringin, about 35 km south of Anjer, and gives a horrifying account of what he found:

"As far as the eye can reach, the only thing that remains standing is a solitary tree, a gigantic durian, maimed, branchless, and leafless. It forms the grave-mark of a heap of corpses and carcasses lying under roofs, houses, and trunks of trees … Thousands of corpses of human beings and also animal carcasses still await burial, and make their presence apparent by an indescribable stench. They lie in knots and entangled masses impossible to unravel, and often jammed along with coconut sterns among all that has served these thousands as dwellings, furniture, farming implements, and adornments for houses and compounds."

Tsunamis are seldom of much consequence to shipping unless it is close to land, and ships in the Sunda Straits were more affected by the enormous quantities of floating pumice than by the waves. For ships close to the coast or moored in bays it is another matter. (Figure 39.6).

At eight on the morning of Sunday August 26, the 1,239-ton mail-steamer "Gouverneur-Generaal Loudon" (which had taken the excursion party to Krakatoa back in May) left Batavia. She called at Anjer in the early afternoon, and embarked 111 passengers. As

Figure 39.7 The marooned steamship "Berouw", engraved from a sketch by N. Korthals.

she entered Lampong Bay some time after 3 p.m. they noticed Krakatoa "casting forth enormous columns of smoke", and when she arrived at Telok Betong and anchored in six fathoms of water at about 7:30 p.m. "ashes and small bits of stone' had been falling for over an hour.

To the captain's surprise, midnight came without any communication from the shore, and he sent a boat to investigate, only to find that a strong current and heavy surf made landing impossible. They hailed the small paddle-steamer "Berouw", anchored close to the pier-head, and learned that the pier was under water, and that a boat that had put out from shore had been wrecked. As a safety measure, the "Loudon" steamed out a few ship's lengths. When dawn came on Monday, they saw that a revenue cutter lay foul of a sailing-ship in the roadstead, and that the "Berouw" had stranded.

At seven the major tsunami generated by the 5:46 a.m. explosion swept down the bay. It was obvious that anyone near the shore must have been drowned, and that there was no help any survivor could be given, even if it had been possible to land. The signal beacon was destroyed, the revenue-cutter was aground, and the "Berouw" "high upon the shore among the coconut trees". Later she was to be found almost intact three kilometres up a stream and nine metres above sea-level, presumably carried there by the second great tsunami at ten (Figure 39.7). All aboard were killed. The captain of the "Loudon" decided to head back to Anjer, both because of the danger, and to report the news.

At ten they anchored. The rain of ash and pumice was growing thicker, and within half an hour it had become too dark to see. The wind, a westerly, rose to hurricane force. The deck awnings were carried away, lashings became slack, and everything loose was swept overboard. Lightning repeatedly struck the mast, but did no damage. The rain of pumice changed to mud, and in ten minutes it lay 15 cm. deep. At noon the wind dropped, and the mud changed to light ash, but the darkness continued.

It was half past six on the morning of Tuesday, August 28 when it at last became possible to weigh anchor. They headed for Anjer, following the usual course along the north-eastern side of the bay. When they reached the chain of small islets that stretch between the mainland and Krakatoa they found them joined by a very solid-looking barrier of pumice and tree-trunks that could easily mask some upheaval of the sea floor. The captain took no risks. He altered course to the east, and sought a way out through the Strait of Lagoendie towards the south-east from the month of Lampong Bay. Here too there was a barrier of pumice, but it rose and fell with the waves. It proved to be over two metres thick, but they were through in ten minutes, and at 4 p.m. they reached Anjer. The town was in ruins, and after a short detour to take a rescued official to Bantam Bay on the north coast of Java, the "Loudon" turned back into the Straits and resumed her scheduled trip to the ports of western Sumatra. During the night she passed Krakatoa once again, and reported it quiet.

At the time of the main explosion at about 10 a.m. on August 27, the American barque "W.H. Besse" seems to have been closest to Krakatoa. At daylight there had been a fair wind and the worst of the eruption appeared to be over, but with the great explosion came violent oscillations of the barometer, hurricane winds, falls of ash, lightning, and a current of 10 or 12 knots, though the sea remained smooth. On a sailing ship the ash proved a particularly troublesome problem. As the first officer recorded, "it stuck to the sails, rigging, and masts like glue; so it was weeks before it was all removed, some of it remaining on the wire backstays".

Meanwhile, what had happened at Krakatoa? Falls of ash and darkness continued, and the first to get a close look was the "Loudon" as she headed back to Anjer on August 28.

"As we steamed past Krakatoa we noticed that the middle of the island had disappeared, and that no smoke was to be seen in any direction. However, when we got east of Krakatoa we discovered that between that island and Sebesie a reef had formed, and that various craters planted on that reef were now and then sending volumes of smoke on high."

Considering the importance of the Sunda Straits to shipping, it is not surprising that the ships of several navies were soon on the scene. They included the U.S.S. "Juniata", the U.S.S. "Enterprise", H.M.S. "Magpie", the Spanish "Gravina" and the Dutch "Prins Hendrik". A Mr N. McLeod, who landed from the "Prins Hendrik" on September 6, was the first ashore, and had been one of the last visitors beforehand. He landed on Verlaten and measured temperatures on the surface and below the surface of the mud.

Although too high for his thermometer, which had an upper limit of 155°F (68°C) it was rapidly cooling. Three days earlier the island had been "still boiling hot", appearing to steam from thousands of cracks, especially along the beach. McLeod also traced the effects of the tsunamis, which had reached a height of 36 metres at Telok Betong, and 30 to 40 metres at Merak, reaching places 10 km from the sea.

Although it was possible to get ashore, conditions were far from stable. Small explosions were still continuing, and within a few weeks the sea would wash away a few of the islets that had recently thrust their tops above the waves. Over much of the area between Krakatoa and Sebesie, where there had previously been more than 30 metres of water, a great mass of rock had been emplaced, and the depth was now less than ten metres; but within the caldera that now took the place of Danan and Perbuatan no bottom could be found at 300 metres.

The rest of the world was soon aware that something quite extraordinary had taken place. The air-wave had circled the Earth, and distant tide-gauges had registered the tsunami, though it was not large except in the immediate vicinity of the Sunda Straits. What was puzzling was that it was recorded not only at places to which there was a direct sea path, but in New Zealand, the north Pacific, and even in the English channel. This remained a mystery until 1966, when American geophysicists found that certain waves in the atmosphere travelled at the same speed as tsunamis. What had happened was that these waves, having jumped the continents, set up new waves in the oceans on the far side.

The most lasting and widely-noticed effects, however, were those caused by dust in the high atmosphere. A government official in Ceylon (Sri Lanka) recorded:

"The Sun for the last three days rises in a splendid green when visible; about 10 degrees above the horizon. As he advanced he assumes a beautiful blue, and as he comes farther on looks a brilliant blue resembling burning sulphur … The Moon, now visible in the afternoons, looks also tinged with blue after sunset, and as she descends assumes a very fiery colour 30 degrees from the Earth."

The whole world took to watching the sky. There were reports of brick-red Suns, of purple Suns, of Suns of silver, copper, pink, and lilac. Poets (including Alfred, Lord Tennyson) immortalised "the blood-red eve". Painters strove to reproduce the sunsets in pastel, watercolours, and oil, not without success. From Honolulu the Rev. S.E. Bishop wrote to Nature, describing an "opalescent corona" surrounding the Sun. It was "… a very peculiar corona or halo extending from 20° or 30° from the Sun, which has been visible every day with us, and all day, of whitish

Figure 39.8 The crater of Tangkuban Prahu, near Bandung in central Java. There are usually active fumaroles in the crater floor.

haze, with pinkish tint, shading into lilac or purple against the blue. I have seen no notice of this corona observed elsewhere. It is hardly a conspicuous object."

Others had seen the ring, and it has since been observed in other eruptions. The character of Bishop's Ring, as it is now known, depends upon the size of the particles responsible, and it is not seen at all unless very small ones predominate.

As the months went by, the "Krakatoa sunsets" continued, and the appearance and disappearance of Bishop's Ring enabled the movements of dust, concentrations in the high atmosphere to be followed. The most brilliant sunsets do not seem to have lasted beyond the middle of 1884, but the Royal Society's report notes that "the optical phenomena did not entirely fade from view until the early part of 1886". At first many people in Europe and America were hesitant to link their sunsets with a distant volcano. The scientific world was soon convinced, but the New York Times remained sceptical and continued to print sarcastic remarks about the "feeble suggestions" of "Scientific Persons".

The climatic effects of the eruption proved to be even longer lasting, and at Batavia the effects were noted at once. On August 27, the day of the main eruption, afternoon temperatures were more than 7°C below normal. For the world as a whole, temperatures remained half a degree or more below average all the following year, and did not return to normal until 1888.

Krakatoa was again in the news in 1927. A bathymetric survey in 1919 had revealed the existence of a parasitic cone on the north side of Rakata Island, though no activity had been noticed. It now began to produce a column of steam a few tens of metres high, and a month or two later a small island had shown its head above the water. Like a movie sequel it was called Anak Krakatau – Child of Krakatoa. For a time it indulged in frequent phreatomagmatic eruptions, but eventually the cone grew large enough to seal off the vent from the sea. Basaltic lava-flows began in 1961, consolidating the island and ensuring its continued existence, and there has been further activity since.

By common consent, the 1883 eruption of Krakatoa was among the greatest in recent times; but as we saw in Chapter 19, it is not easy to devise a good measure of size. It is estimated that some 18 cubic kilometres of material were ejected, but it is not necessary to go beyond the Sunda Arc to find possible rivals. The eruption of Tambora in 1815 is believed to have produced about five times the amount of tephra, and even that is small compared with the prehistoric eruption that created Lake Toba. Simkin and Fiske conclude that comparable eruptions occur somewhere about once or twice a century.

After the exuberance of Krakatoa, it is important not to see the volcanoes of Java as an anti-climax. Visitors to Bandung who are not already acquainted with volcanoes are usually taken to have a look at the crater of Tangkuban Prahu (Figure 39.8). The name means "the upturned boat", and fairly describes its appearance from the city. Its elongated nature results from a progressive eastward movement of the vent over about a kilometre, leaving behind the remains of a series of old collapsed crater rims. At present it confines itself to small hydrothermal eruptions, but there are usually one or more vigorously steaming fumaroles on the level crater floor. The gases are mainly sulphuretted hydrogen and carbon monoxide and dioxide, but there are also oxides of sulphur present, and a sudden change of wind can be an unpleasant experience. Accumulations of gas in the summit valleys have sometimes proved lethal. The number of cones visible from the top makes the volcanic nature of Java strikingly apparent.

Java's population of more than 200 people per square kilometre is menaced by volcanic risks to a quite exceptional degree. None of its active volcanoes lies far from a centre of population, and there are many more villages and cultivations on their slopes than there would be in cooler places with winter snows. Lava-flows are not a serious problem, but hundreds of thousands of lives have been claimed by nuées ardentes and lahars.

Two Javan volcanoes particularly associated with lahars are Galunggung, sixty kilometres south-east of Bandung, and Kelut, a hundred kilometres south-west of Surabaya. The eruption of Galunggung in 1822 resulted in over 4,000 deaths, 3,600 of which are attributed to lahars. As a rule, its eruptions do not last long, but very large quantities of ash are emitted, damming streams and water-courses, and providing material for mud-flows that may be delayed until the rainy season. In 1822, 114 villages were destroyed, along with a million and a half coffee plants and nearly a thousand cattle. The crater wall is breached to form

Figure 39.9 Kelut Crater Lake in 1980. Behind is the lava dome of Gunung Kelut.

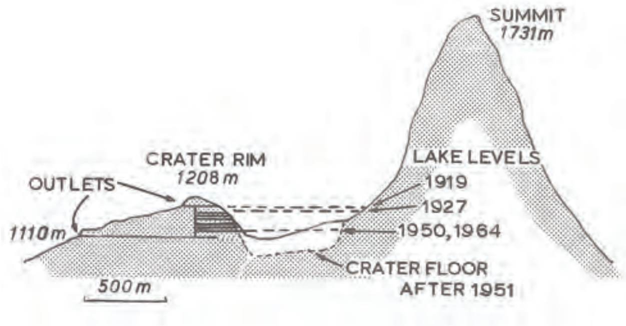


Figure 39.10 The tunnels of Kelut.

an amphitheatre, and the plain below is strewn with hillocks of lahar debris. They cover an area of about 250 sq. km, and are known as the Ten Thousand Hills of Tasik Malaha. An Australian geomorphologist, unimpressed by poetry, notes that there are in fact fewer than four thousand, ranging in height from 3 to 70 metres. They are similar to the mounds at the foot of Mount Egmont in New Zealand.

Further small eruptions occurred in 1894 and 1918, but Galunggung then remained relatively quiet until the major eruption of 1982. Some 75,000 people were evacuated, but not without some casualties from road-accidents. Efforts to resettle people from the endangered locations, in Sumatra and the Riau Islands, have been only partially successful. This eruption had some unexpected consequences. The destruction of bird-life encouraged the reappearance of the malarial mosquito, which it was thought had been eradicated, and there was an epidemic of malaria in which 31 people died.

Figure 39.11 Merapi, central Java. lava is spilling from the crater, following the path of past nuées ardentes.

Figure 39.12 Path of a nuée ardente during the eruption of Merapi in 1961. The picture was taken about 10 km from the crater, here hidden by cloud.

This eruption also revealed a new kind of volcanic hazard. Within less than a month two passenger jet-planes, bound for Australia at heights of over 9,000

Figure 39.13 Nearer Merapi the destruction was almost complete. Jungle was cleared from a path almost a kilometre wide and more than a dozen villages were destroyed. Most of the inhabitants had been evacuated and there was only a small loss of life.

metres, unwittingly flew into fine dust erupted from the volcano. In the first instance, all four engines stalled and the plane dropped 7,500 metres in the sixteen minutes before the pilot could persuade them to start again. He landed his 230 passengers safely at Jakarta, on three engines. On the second occasion, three engines stalled, and after dropping 2,400 metres only one could be re-started, but once again 240 people were safely landed. Later in the year, the windows of another plane were cracked by lapilli from the Japanese volcano Sakurajima. Scratched and broken windows are not uncommon.

Columns of erupting tephra are a serious problem for jet aircraft. They deposit a layer of glassy material on the turbine blades, and completely disrupt the pattern of the airflow through the engine. Volcanoes are so numerous and so close to cities with major airports that it is impossible to avoid them, and any one of them may become a danger within minutes. Very fine dust of the kind emitted by Galunggung does not show up on air-borne radar, and is not readily detected from satellites.

Kelut has found its way into almost every book that deals with volcanic risks, because of the efforts made to control its lahars. Historical records going back well into the 1300s show that on the average there has been one about every 20 years. Kelut's particularly dangerous nature is due to the size of its crater lake, which once contained 38 million cubic metres of water, all of which was liable to be thrown out during an eruption, only to refill once more as soon as the eruption was over (Figure 39.9). Records show that out of 56 lahars on sixteen Indonesian volcanoes, 45 have involved a crater lake.

The first attempts to do something about Kelut were made in 1905, when a wall was built across a ravine that had been the path of past lahars; but it proved unequal to the major eruption in 1919 when 104 villages were destroyed, and 5,110 people were killed by hot mud up to 25 metres thick. The authorities decided to drain the lake, and cut a series of shafts and tunnels through the crater wall (Figure 39.10). These dropped the level of the water by 65 metres, and reduced the volume of the lake to a twentieth of its old capacity. In 1951 an eruption deepened and widened the crater, but there were no lahars. Two of the seven casualties were volcanologists trapped while inspecting the tunnels, which were damaged, and left above the level of the larger and deeper lake. An additional tunnel was made, relying upon seepage, but although its inadequacies had been pointed out by Indonesian volcanologists there were 40 million cubic metres of water in the lake in 1966, when the next eruption killed 210 people and destroyed railway bridges. A new drainage system has since been built, and dams have been thrown up to hold back

Figure 39.14 Looking westwards across the crater of Batur, on the island of Bali. This caldera is claimed to be "one of the largest and finest in the world".

mud-flows until the water has drained out. A similar system of dams and sand-pockets has been built on Galunggung, involving the largest collection of earth-moving machinery ever assembled in Indonesia. Kawah Idjen, in the extreme east of Java, faces the additional problem that the water of its crater-lake is strongly acid.

The behaviour of Merapi, a 2,911-metre cone only 35 km from Jogjakarta (and not to be confused with Marapi in Sumatra) is rather different (Figure 39.11). It usually generates Nuées ardentes but a lahar usually follows if the nuée encounters a stream. Containing-pockets have been built. It has been claimed that an eruption in 1006 A.D. prompted the Hindu rajah to move to Bali (at the foot of the equally lively Mount Agung), thus allowing the final conversion of Java to Islam.

The nuées of Merapi are not quite like those of Mont Pelée, as they are more often sent on their way when the pressure of liquid lava shatters the viscous front of a flow that has reached the top of a steep slope than by the collapse of summit domes and spines or explosions in the crater. When one of us visited Merapi during the eruption in 1961, a dam would form at the edge of the crater, only to be shattered every few minutes or so to release a cascade of molten material that rushed down the slope, liberating clouds of gas as it went (Figures 39.12 and 39.13).

The line of Indonesian volcanoes continues eastwards through Bali and the Lesser Sunda Islands, Lombok, Sumbawa, and Flores, to Sirung on the island of Pantar which, so far as volcanoes are concerned, marks the end of the Sunda Arc. A highly curved arc of volcanoes follows the southern and eastern margins of the Banda Sea, and activity continues into Sulawesi and along the Minahassa Peninsula to the Sangihe Islands. The oppositely curved arc of Halmahera faces this part of the system across the narrow Molucca Straits, but it is part of the Pacific system already described.

Before leaving the Sunda Arc two other eruptions deserve mention. The small and justly celebrated tourist island of Bali has two active cones, the 3,000-metre Agung, and the less impressive but more frequently active Batur (Figure 39.14), which the Dutch geologist van Bemmelen has called “one of the largest and finest calderas in the world”. It is from 10 to 14 km across, with a rim that varies in height from 1,200 to 2,150 metres. In its centre is a smaller caldera, 7 km across, with a floor about 300 metres lower, and containing a lake.

In 1963 Agung erupted for the first time in over a century. The effects on the densely-populated island were severe, and international relief efforts were largely nullified by current political unrest, the bulk of the supplies finding their way to the black markets of Jakarta and Surabaya. The eruption began in mid-February, and continued until January of the following year. Over 1,100 people were killed, 90,000 rendered homeless, a third of the arable land was lost, along with over 18,000 cattle, and nearly every bridge on the island was destroyed. Most of the deaths were due to nuées, but the coming of the rains caused delayed lahars and further casualties and swept away bridges that had been repaired or replaced, in some cases several times over.

The 1815 eruption of Tambora, on the island of Sumbawa, surpassed even the Krakatoa eruption of 1883 in violence and destructiveness. Paroxysmal explosions spread ash from south-east Sumatra to Timor, and to parts of Kalimantan and Sulawesi. On the island of Madura, 500 km to the west, darkness lasted three days, and was also reported from Makassar, 400 km to the north. As in the case of Krakatoa, the dust spread to the northern hemisphere, and in Europe and America 1816 became known as “the year without a summer”. The explosions were heard at great distances, and it seems probable that “earthquakes” reported from Surabaya and elsewhere in eastern Java, if not independent events, should be attributed to the arrival of air-waves.

The twin peaks of the mountain, which had reached to over 4,000 metres before the eruption, were destroyed, reducing the height by 1,400 metres, and forming a caldera 12 km across. A small tsunami, probably the result of coastal subsidence or a pyroclastic flow entering the sea, has been credited with over 4,000 of the 10,000 deaths that directly resulted from the eruption – but this was a small matter compared with the 38,000 on Sumbawa and 44,000 on Lombok who died from the starvation and disease that followed. The total death-toll must have been at least 92,000.

The quantities of pumice and ash erupted were enormous. Early writers put it as high as 150 cubic kilometres; but even the 30 cubic kilometres of the lowest recent estimate far exceeds the 18 cubic kilometres attributed to Krakatoa. Pumice rafts were reported for as long as six years after the event. Recent calculations of the energy released put Tambora ahead of Sakurajima, Bezymianny, and Krakatoa combined! (see Figure 19.1). For most of this century it has been quiet.

The volcanoes of the Banda Sea are active enough, but since most of them are submarine and not given to producing large tsunamis, they tend to escape publicity. Tectonically their interest is very great, as they are close to the “triple junction” of the Pacific, Indian, and Eurasian Plates, whose complexities are the subject of continuing geophysical debate. The interesting points are that the line of volcanoes has moved to the northern side of the Sunda Arc, the very sharp curvature of the Banda Arc, the short but very deep trench, and the very deep earthquakes that dip westwards under the Banda Sea. There is a belt of negative gravity anomalies on the convex side of the arc, and of positive ones inside it. The volcanoes lie between the trench and the positive anomalies. The problems arise from the bathymetry. To the east, where we might expect to find ocean, we find the shallow Arafura Sea, which really belongs to the Australian continent. The Banda Sea, inside the arc, where we might expect to find land, is not deep enough to be real ocean, but much more like one than the Arafura Sea. The islands of Tanimbar, Kai, and Ceram are no help in forming a classical pattern. Since a popular book is no place to push personal views, the matter will be, as mathematical text books are apt to say when one is most lost, “left as exercise for the reader”.

40—Worlds Apart

Each change of many—coloured life he drew,
Exhausted worlds, and then imagined new.

SAMUEL JOHNSON : Prologue at the opening of the theatre in Drury Lane

Long before Galileo turned his telescope to the skies in 1610, reported the existence of mountains on the Moon, and tried – not altogether successfully – to measure their heights, the idea that other heavenly bodies had landscapes like the Earth's, and probably inhabitants as well, was common enough. After Fontenelle's Entretiens sur la pluralité des mondes became a best-seller in 1686 the idea grew not merely acceptable, but fashionable. In 1647 Johann Helwecke of Danzig engraved the first satisfactory map of the Moon, bestowing names on its features that echoed those on Earth. Few of them are still in use, and the prominent crater we now know as Copernicus bore the name "Mount Etna" (Figure 40.1).

Whether Helwecke (better known as Hevelius) considered his Etna a volcano or not, astronomers turned increasingly to the view that the Moon was a dead world, and even before 1834, when F.W. Bessel showed convincingly that it had no atmosphere, William Herschel's claim to have observed lunar volcanoes in eruption met with scepticism. Nevertheless, the idea that the Moon's craters were extinct volcanoes gained ground – but a major objection was their size. The largest terrestrial calderas do not greatly exceed 20 km in diameter, and while it is usual to call any lunar depression more than 50 km across a walled plain rather than a crater, we cannot overlook Grimaldi's 190 km diameter, or Bailly's 290 km.

With some bizarre exceptions, most astronomers who remained doubtful whether a volcano could produce anything as impressive as a lunar crater began to invoke a bombardment of meteors, and by about 1930 this had become the generally accepted view. A falling meteorite, unimpeded by an atmosphere, possessed enormous kinetic energy, and explosion on impact can be shown theoretically and experimentally

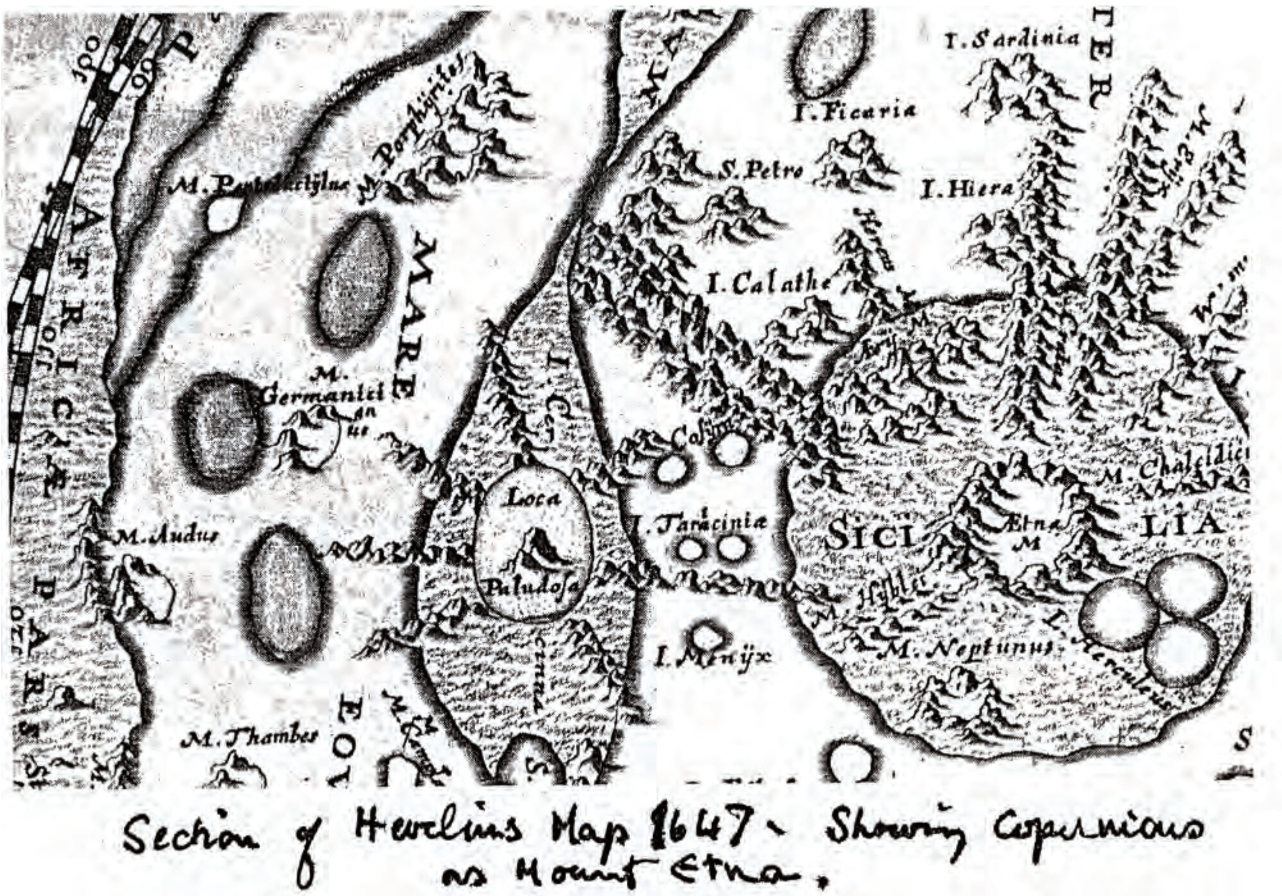


Figure 40.1 Detail of the 1647 lunar map of Hevelius, with the crater Copernicus captioned "Etna", and its surroundings "Sicilia".

Figure 40.2 Craters on the Moon. The two large walled plains are Alphonsus (above, with a central peak) and Ptolomeus. Alpetragius (top centre) appears to contain a dome. To the right of it the picture includes part of the margin of Mare Nubium. The prominent crater below Ptolomeus is Herschel.

to produce both the outer wall and the central peak typical of a lunar crater. Large meteorite impacts have left their imprint on the surface of the Earth, but our atmosphere protects us from all but the largest, and erosion and other geological processes have destroyed most of the surviving evidence.

Lunar craters are very numerous. On the visible side of the Moon alone there are more than 300,000 more than a kilometre across. Nearly all the lunar features, including the great plains known as maria (Latin, seas; singular mare), are accurately circular, and although a few are simple pits, and others appear to have been filled to the level of their outer walls, many of them contain an accurately–positioned central peak (Figure 40.2).

The heights of both the walls and the peaks reach 6,000 metres or more. Considering that the Moon's radius is only a quarter of the Earth's, this is high even in the context of lessened gravitation, yet the plains are so vast that the curvature of the lunar surface would prevent an astronaut standing at the foot of a central peak from seeing the surrounding wall.

Depressions in the summits of some peaks have been interpreted as vents from which both the central mountains and the surrounding walls were erupted. With a handful of exceptions, none of the peaks are well-shaped cones, and none can match the size of Fuji or Vesuvius. If they are indeed extinct volcanoes, they cannot ever have matched the vigour of the volcanoes on Earth.

It is now generally accepted that most of the circular lunar formations are the result of meteorite impacts at an early stage of the Moon's history, but that the bombardment was followed by the extrusion of basalt lavas, smoothing the floors of the great seas, and sometimes filling craters to the brim. Many features of terrestrial volcanism have lunar counterparts, from lava-flows to calderas; but lessened gravity and the absence of an atmosphere have produced subtle modifications, and it is unwise to assume identity from close outward resemblances. Pyroclastics would be thrown higher and further, and would form squatter cones. A few of them have been tentatively identified, from dark haloes surmised to be ash. In the absence of winds, they are quite circular. More familiar in form are the swellings scattered on the plains, and attributed to the extrusion of viscous lavas.

If we accept that igneous processes have taken place on the Moon, it is reasonable to ask whether any astronomer has seen an eruption. Volcanoes can function quite well without an atmosphere. All that is needed is a solid crust, and enough internal heat to bring deeper material to melting-point. Since William Herschel, many astronomers have reported changes of one kind or another. Most of them are best attributed to fluorescence excited by radiation from solar flares, but there are two events that deserve a closer look.

In 1866 Julius Schmidt, one of the greatest of lunar observers, announced that the crater Linne, which he had mapped several times between 1841 and 1843, had disappeared. Others confirmed his observation. There is little doubt that Linne once existed, and exists no more. Pictures of the area taken from spacecraft show some small craters, but no trace of the conspicuous marking 9 km across that once appeared on maps of the Moon. Neither volcanic eruption nor the impact of meteorites seems to offer an adequate explanation of so complete an obliteration.

Reports of luminescence have become fairly common in recent years, since larger telescopes have been turned on the Moon, and the methods of confirming its reality have improved. The study of "transient lunar phenomena" has become a respectable part of astronomy. In 1958 Nicholas Kozyrev of the Crimean Astrophysical Observatory decided to concentrate his attention upon the crater Alphonsus, where an American colleague had reported an "obscuration".

Figure 40.3 Mercury seen from the space-craft Mariner-10, at a distance of 75,000 kilometres. Resemblance to the lunar surface is striking, but there is less evidence of basaltic extrusion after the craters were formed.

On November 3 he noticed changes in the central peak, which first appeared reddish, and then became unusually bright. During the brightening he photographed a spectrum. As a rule, the Moon's light is just reflected sunlight, but this spectrum showed emission lines from carbon, similar to those in the spectrum of a comet. They came from a cloud that seemed to have been erupted from the peak. Kozyrev described it as "very similar to a normal volcanic process".

During the following year he took twelve more spectra, all quite normal, but on October 23 he again observed what he considered to be evidence of thermal radiation. Not surprisingly, his results have been questioned, but they are the best indication we have that the Moon's volcanoes are not quite extinct.

Pictures of the far side of the Moon show it to be much the same as the one we have always been able to look at, with one difference. No one expected the Mare Orientale, a huge triple-walled circular basin 850 km across. Whatever landed here must have been more like an asteroid than a meteorite of normal size. The innermost part, about 200 km in diameter, is like the floor of a walled plain or sea. There are two views about the great surrounding scarps. Either they were thrown up by shock-waves at the time of the impact, or they are collapse features, following the extrusion of the material that covers the central plain. If that is the case, Mare Orientale holds an indisputable record for calderas.

The rocks gathered from the floor of the lunar "seas" turn out to be basalts, much like those on Earth "Down to the last phenocryst and vesicle", protested one disappointed petrologist, but there are important differences, both from terrestrial rocks, and from different lunar sites. Although the rocks are igneous, it is most unlikely that they are volcanic, or that the floors of the lunar seas had their origin in spreading ridges; but just as the maria show a certain analogy with the terrestrial oceans, so are lunar highlands similar to continental crust, and consist of plagioclase feldspars.

Before the days of space-probes, the Moon was considered something of an oddity. We knew that the giant outer planets were largely gaseous, but we expected the inner ones, and perhaps the larger satellites to be more like the Earth than the Moon, making due allowances for temperature, and atmospheric composition. Surprise was to follow surprise after the first pictures of Mars showed markings like the Moon's, and so did the pictures of Mercury.

The craters of the Moon are very old. Radiometric dating of the rocks brought by astronauts shows that the floor of Mare Tranquillitatis solidified between 3,000 and 4,000 million years ago, though the Oceanus Procellarum is perhaps I,000 million years younger. The smaller chips of material found at each landing site proved to be still older – about 4,000 million years which is roughly the same age as the oldest meteoritic material that has been dated. Geological processes have continually rejuvenated the surface of the Earth, comparatively little of which is more than a few hundred million years old, but the surface of the Moon has preserved a record of the earliest condition of the Solar System.

At some time, all the bodies that would eventually become the Solar System must have been involved in a mutual bombardment. The evidences of this period

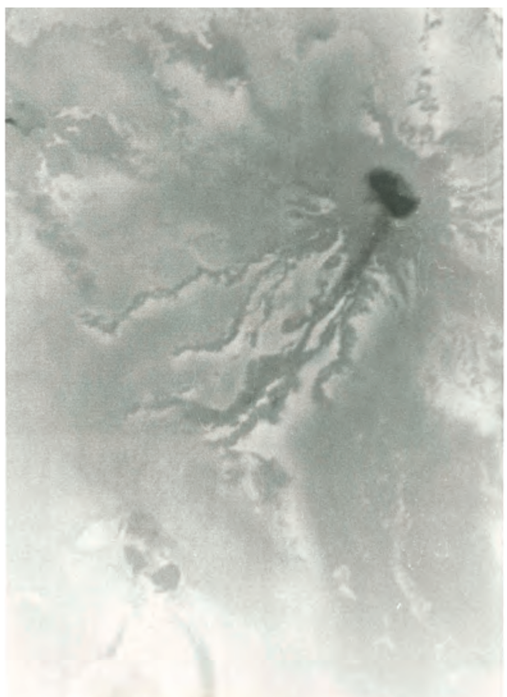


Figure 40.4 The surface of Io shows what are interpretted as flows of sulphur from a dark crater some 70 kilometres across.

have been most clearly preserved on the surface of planets and satellites small enough to have become solid, but not large enough to have retained an atmospheric shield. The Moon is the most accessible example, but the planets Mercury and Mars and the larger moons of Jupiter and Saturn carry scars inflicted at this time (Figure 40.3). Even quite small objects like Deimos and Phobos, the moons of Mars, are pitted with craters. The oddly shaped Phobos, only 27 km long and 19 km wide has a crater 11 km in diameter, which could not possibly be volcanic. The floors of the craters on these small bodies are comparatively irregular, presumably because there is no source of molten basalt that could have flooded and levelled them like the walled plains of the Moon.

Successive space-probes have shown that it is usual for bodies in the Solar System to have craters, and that hardly any of them are primarily volcanic, though many have been modified by igneous activity of some kind. At the time of the great meteoritic bombardment, perhaps 4,500 million years ago, their outer surfaces must have cooled below the melting-point of rock, but not so far that radioactive heating or the release of pressure when the crust was fractured by a colliding body would be unable to cause melting and the formation of magma.

The problem of working out the origin and distribution of the Earth's internal heat is among the most intractable in geophysics, and speculations about thermal conditions on remote planets and satellites are easy to dismiss. There is only one way to be completely certain that a formation is volcanic, and that is to see it erupt. Considering the frequency of eruptions on Earth, this is not an unreasonable expectation, but the conditions that produce an eruption involve a rather delicate balance of heat, melting-point, and confining pressure. Even if these conditions once existed, what are the chances that they still do?

Jupiter, the largest of the planets, is attended by 13 moons. Two of them are as big as Mercury, and two more about the size of our Moon. The two larger ones are not very dense, and are thought to be covered in a thick mantle of ice; but Io and Europa are much the same density as the Moon. In 1979 the space-craft Voyager I and Voyager II took 171 photographs of lo, the closer of the two to the planet, and found eight erupting volcanoes. Seven of them were erupting during both visits, several months apart. It is possible to find resemblances between the surfaces of Europa and Mars, but no other body looks quite like Io. Its predominant colours are reds and yellows, blended together in a variegated pattern upon which darker spots are scattered. A volcanologist is at once reminded of the sulphur deposits around fumaroles, and it is possible that this is more than a superficial resemblance (Figure 40.4).

The volcanoes of Io are not fired either by radioactivity or by residual heat from a remote past, but by tidal energy. The giant Jupiter exerts an enormous tidal pull that distorts the whole satellite, and the work done becomes transformed into sufficient heat to melt the interior. The structure of the outer parts is a matter of debate, but the prevalent view is that there is a solid crust about 20 km thick containing large amounts of sulphur. When magma rises from the interior of Io, the sulphur is vaporized and helps to propel the eruptions. Material is ejected at speeds up to a kilometre per second (about twice that attained on Earth), and the plumes reach heights of more than 200 km, compared with about 80 km for the highest terrestrial plumes.

Apart from the fumaroles, which must have formed very recently, there are no crater-like markings on Io, although one structure has been interpreted as a caldera. Assuming that Io shared in the early bombardment, traces of which remain on Ganymede and Europa, and even more plainly on Callisto, whatever remains of the ancient craters must lie beneath the present surface. Close-up pictures of "lava-flows" that extend for several hundred kilometres from the larger vents presumably show molten sulphur. Quite marked changes in the shapes of major features occurred between the two Voyager missions.

Saturn has at least sixteen moons in addition to the multitude of small fragments that make up the rings. Some of them have the now-familiar cratered surfaces, and others do not, but most of them are still objects of mystery. Of the half dozen whose densities have been measured none is much denser than water, and there have been no signs of erupting volcanoes. As yet we are largely ignorant of conditions on the outer planets and their satellites. The latest probe has revealed new satellites of Uranus, some apparently cratered and possible sites for volcanoes. Observations of Neptune can soon be expected, but it would be wise to wait until the excitement of discovery gives way to calm appraisal before claiming sound knowledge.

We have still to consider the two planets most like the Earth. Mars is 6,794 km in diameter, a little more than half that of Earth. From time to time movement about the Sun brings Earth-bound astronomers within 80 million kilometres of Mars, and gives them their best view of a sister world. Venus indeed comes closer, to a mere 42 million kilometres; but when she does, her face is in darkness, and her surface is always veiled in cloud.

Viewed through a telescope, Mars is a world with two white polar caps, a surface that changes colour from reddish to greenish and back again as the seasons change, and the spectroscope shows that its atmosphere holds oxygen and water-vapour. Cautious astronomers carpeted it with mosses and lichens, and

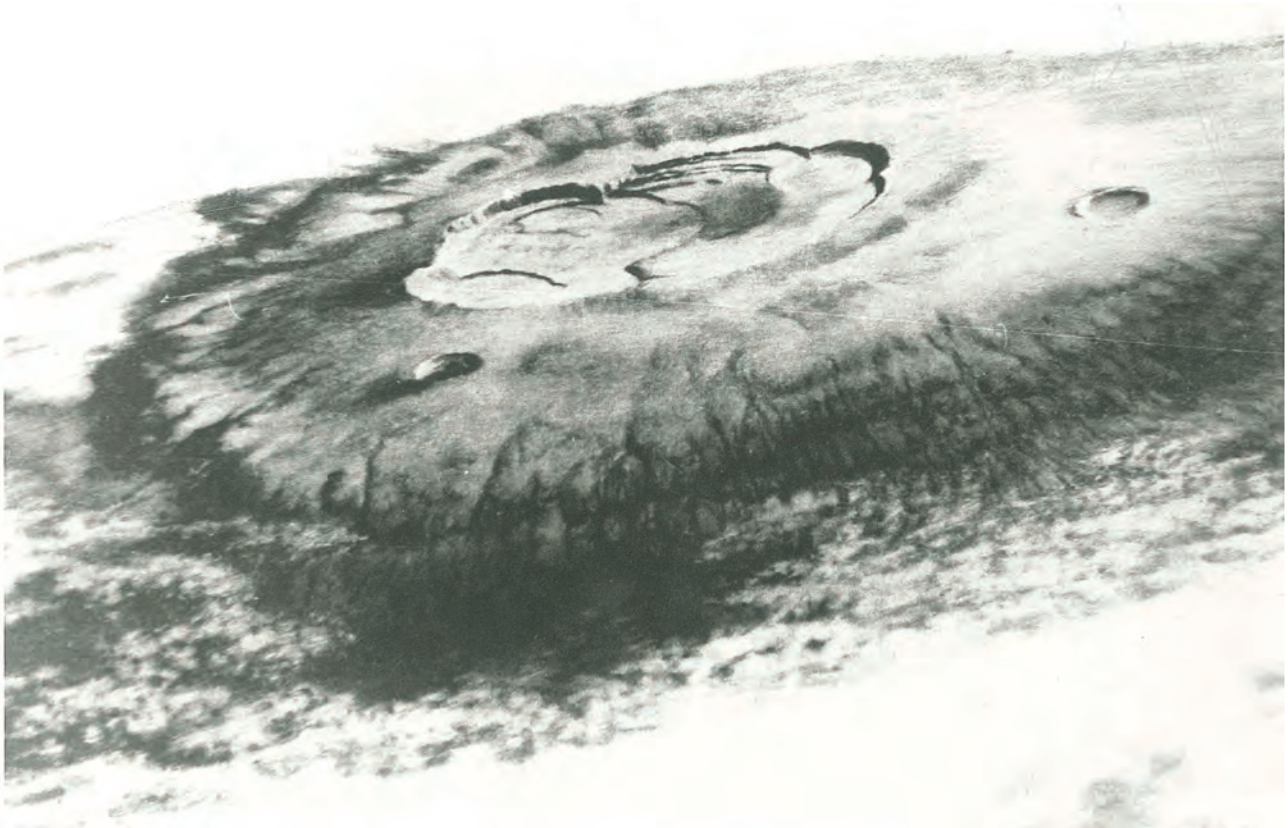


Figure 40.5 Olympus Mons, a Martian shield volcano 26.4 km high and 600 km in diameter. The summit caldera, a system of nested craters, is about 90 kilometres across.

the dreamers peopled it with cities of canal-builders. In 1965 a space–craft was sent to take a close look. On July 14 it came within 10,000 km and sent 19 pictures back to Earth. Those pictures showed terrain cratered like the Moon.

Observers with telescopes had produced maps of what they saw, and named a great many Martian features. Identifying these with what could be seen on the photographs was not always easy, and many of the names proved sadly inappropriate. More and more pictures were taken, and eventually space-craft landed on the surface. They showed no canals, no lichens, and no mosses, but there were dust-storms, and signs of volcanism and erosion by water in the past. No “marsquakes” or active volcanism has been detected.

The old telescopic maps showed a bright circular spot familiar to observers as Nix Olympica, the Olympian Snows. It was photographed in 1969, and described as “a large white-rimmed crater about 300 miles (480 km) in diameter.” Realisation of its real nature did not come at once. When the Mariner 9 space-craft flew past in November 1971, Mars was recovering from a dust-storm that had covered the whole planet, and the first pictures were disappointing. One of the first things to appear out of the dust was the summit caldera of Nix Olympica, a complex nest of craters 90 km across. By the time it finally settled, Nix Olympica had become “the giant volcano Olympus Mons”. Later pictures show it to be a giant indeed (Figure 40.5). It is almost three times the height of Mount Everest, and covers an area of nearly three million sq. km, with an average slope of about four degrees. It is a classical shield volcano, with lava-flows extending radially from the summit, but it has two puzzling features not paralleled in terrestrial volcanoes. Its base does not grade smoothly into the surrounding plain, but ends abruptly in a nearly circular scarp 5 to 10 km high, and accurately centred about the crater. Geologists cannot agree how it was formed: there are those who explain it by faulting, those who attribute it to some unspecified “modification” of the lava deposit, and those who invoke landslides.

The plain beyond it is covered by an “aureole”, less symmetrical than the scarp, and extending for another 600 to 1,000 km. Its appearance in photographs has been likened to wrinkled elephant-hide. The explanations so far offered range from pyroclastic flows to erosion by ancient ice-sheets, and it is wiser not to return a verdict.

A more basic question is: “How did the mountain become so big?” Mauna Loa, the largest shield volcano on Earth, is a mere baby beside it (Figure 40.6). It is not the only large shield in that part of Mars. Pavonis Lacus and Ascraeus Lacus (now no longer lakes, but mountains!) are also huge, and much the same height.

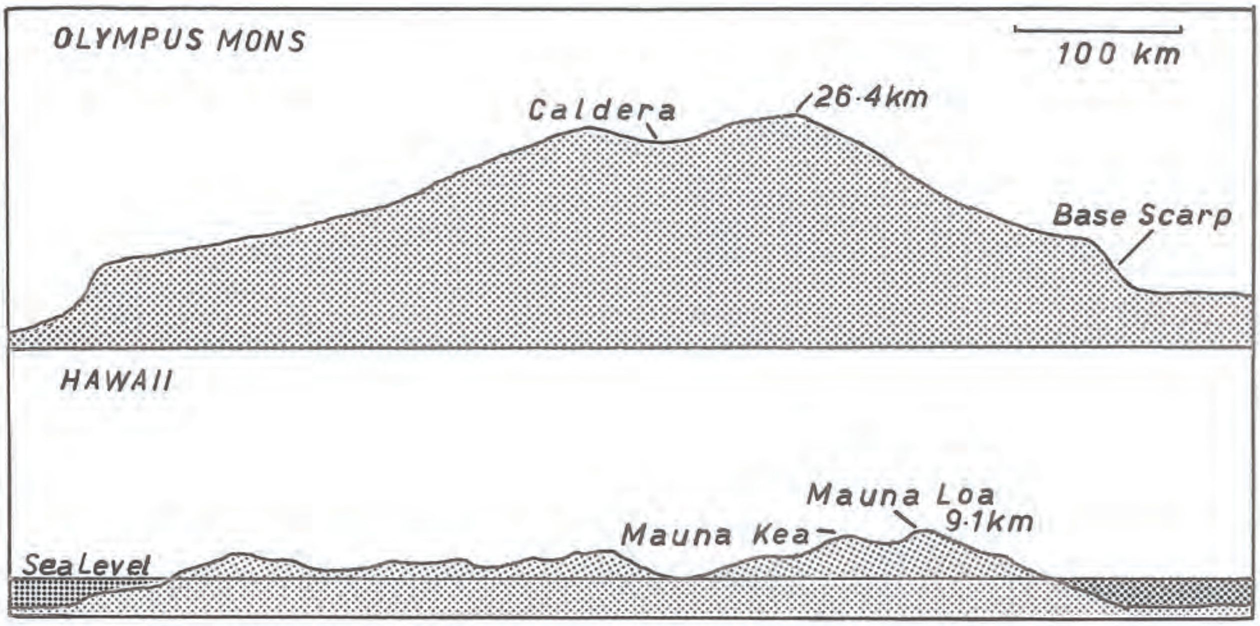


Figure 40.6 Cross-sections of Olympus Mons and Mauna Loa compared. The vertical scale is five times the horizontal.

This is unlikely to be coincidence. The maximum height to which a volcano can rise depends upon the depth of the source, and the densities of the magma and the crustal rocks.

Are they extinct? The usual way of dating is based on the frequency of impact-craters, and it becomes very uncertain on rough ground. There are few craters on the slopes of Mount Olympus, and the most recent lava-flows certainly occurred within the last 100 million years. Signs of activity would not surprise a geologist.

Venus is much the same size as the Earth – a little smaller and a little less dense, with a cloud-filled atmosphere – but there the resemblances end. The atmosphere is mainly carbon dioxide, with a little water and ammonia. The clouds rain sulphuric acid, and the surface temperature is about 480°C. The Russian space-ship that landed in 1969 sent back two pictures of a rock-strewn landscape, and a few more were secured in 1982. These and earlier probes secured chemical and temperature measurements, and sampled the radioactivity, but none of them survived the conditions for more than an hour. In spite of this hostility, radar has succeeded in penetrating the clouds, and we have detailed maps of the surface, and measurement of differences in height.

Compared with the Earth's, Venusian topography is smooth, but the planet is not without mountains. Maxwell Montes stands 11 km above the average height of the surface. Several astronomers have argued strongly that there are volcanoes on Venus, and that this is one of them. The images that radar techniques can now produce show that Maxwell Montes has slopes ribbed with rifts or fractures, and is topped with a dark circle provisionally called Cleopatra Patera. Patera is Latin for a shallow dish, appropriate enough for a summit caldera. Arguments based on the density of the planet and measurements made by the probes suggest that Venus originally received much the same allocation of radioactive elements as the Earth. The heat they generate must escape, but there is no evidence for the kind of orderly convection responsible for terrestrial plate-tectonics. The most likely way of losing the heat would be through volcanoes. There are certainly features that look like volcanoes, and have the size and shape of shields. Appropriate gravity-anomalies are associated with them. Russian geochemists consider that measurements of X-ray fluorescence, taken together with radioactivity data, allow them to identify specific types of rock, and that the Venusian samples analysed were basalts.

The comment of one Russian, considering whether flow-like markings near Beta Regio could possibly be lavas, that "We don't know that it's not still erupting", like the suggestions of an American colleague that the lightning storms over the Venusian highlands were discharges in ash-clouds rising from volcanic vents, may be premature enthusiasm; but the evidence for volcanism on Venus is strong. Volcanoes are so common a planetary phenomenon that the chance of our space-explorers observing more eruptions seems high.

41—Postscript

Of the making of books there is no end, and much study brings weariness of the flesh.

Ecclesiastes 12: 12

Fear of the accusation that one does not know where to stop is no excuse for depriving readers of an account of one of the largest eruptions this century, that of Mount Pinatubo in the northern Philippines, in 1991. Early in April a phreatic explosion followed by a series of earthquakes and accompanied by ground deformation and the emission of small ash plumes marked the end of a 600-year period of quiescence. The eruption built up gradually, and on June 16 a series of strong explosions culminated in the eruption of a column of tephra thirty kilometres high, a series of pyroclastic flows, and the formation of a small summit caldera. By the end of the month dust from the eruption had fallen some 11,000 km from the mountain.

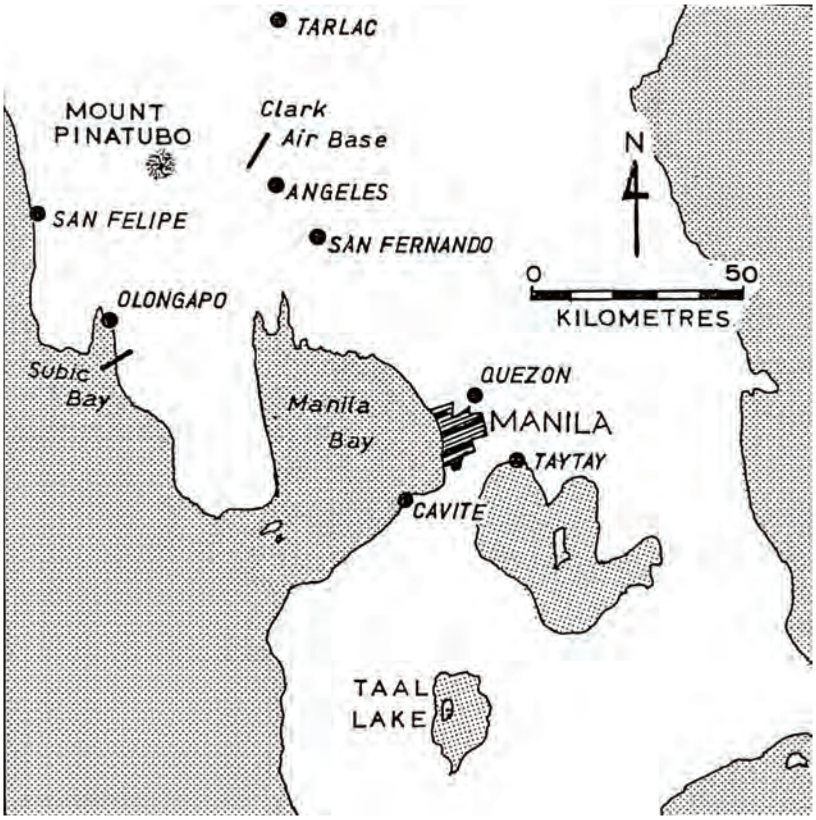


Figure 41.1 Sketch map of central Luzon, showing Mount Pinatubo and places affected by the eruption in 1991.

The 1,745-metre high Mount Pinatubo is a complex andesitic-dacitic dome lying about 100 km north-west of Manila (Figure 41.1). A kilometre and a half to the north-west of the summit is an area of geothermal activity that has recently been prospected for possible power generation.

The April explosions devastated a square kilometre of forest, and caused the evacuation of some 2,000 people living within a radius of about 10 km from the crater. Continuing gas emissions from new fumaroles drove another 5,000 inhabitants from an area on the west flank of the mountain, but although these evacuations saved many lives, the coincidence of the climax of the eruption with typhoon Yunya brought heavy rains that caused large lahars and resulted in more than 300 deaths.

Eventually 79,000 people were evacuated, 15,000 of them from the United States Clark Air Base, which was rendered permanently inoperative by a deposit of ash more than 30 cm thick. Operations at Subic Naval Base and Manila Airport were also disrupted, and light falls of ash were reported from as far away as Singapore, Sabah, Sarawak, and the Mekong delta.

At about the same time as the events at Mount Pinatubo, Mount Unzen in Kyushu also erupted. The eruption of Unzen in 1792, which has already been described in an earlier section of this book (caption of Figure 20.1), is among the best known of Japanese historical eruptions. The present eruption began in November 1990, and the following May a lava dome 100 metres in diameter and about 50 metres high was extruded above the crater rim. Periodic collapses sent large blocks down the steep outer slopes. On June 3 a pyroclastic flow moved rapidly down the eastern flank, killing 41 people, destroying 56 houses, and covering parts of Shimabara with wet ash. A larger flow on June 8 destroyed an additional 73 houses at Shimabara and Pukae, but without further injuries. An explosion three days later carried ash 250 km to the north-east. All the fatalities occurred within a “forbidden zone” from which residents had been evacuated. They included 15 reporters and photographers, four taxi-drivers, three distinguished volcanologists, Maurice and Katia Krafft, and Harry Glicken, and members of the police and fire-brigades. Ten died later in hospital, from burns.

Appendix—Facts and Figures

Did you ever have the measles, and if so, how many?

ARTEMUS WARD : The Census

This final section of the book brings together some tables of figures and lists of events that the reader may care to have for reference. There is also a little more guidance through the thickets of igneous petrology, and a list of books that should help in finding more information on specialised topics, and of periodicals that can be expected to cover future events.

The size of the Earth

More than two hundred years ago French scientists began a battle to establish an international standard of length based on the size of the Earth. The metre was to be one ten-millionth part of the distance from the equator to the pole, and was established by a heroic series of geodetic measurements carried out between about 1790 and 1820.

International agreement to adopt the metre and its associated standard of mass, the kilogram, has now been reached, and most countries have either made the change to the units of' the Systeme International, or are in the course of doing so. S.I. units have therefore been used throughout this book, but the recommendations concerning preferred multiples (which would deprive us of so useful a unit as the centimetre) have been passed over whenever popular usage seemed likely to part company from official edict. Our most wilful offence has been to use 'ton' to mean metric ton throughout. When tons avoirdupois no longer appear in the problems of school arithmetics and short tons and long tons have vanished from commerce, the form tonne should become as rare in English as gramme is now.

Geophysicists, who saw no reason to express densities in four figures when they needed only two or three have decided to adopt the allowed unit megagrams per cubic metre (Mg m^{-3}), which yields exactly the same numbers as their accustomed grams per cubic centimetre. Thus, honour is preserved on both sides, and the old advantage that densities and specific gravities taking water as 1 are expressed by the same numbers is still retained.

Polar diameter of the Earth	12 714 km
Equatorial diameter	12 757
Mean radius	6 371
Radius of the core	3 473
Radius of the inner core	1 250
Depth to the core	2 898
Depth to the inner core	5 121
Mass of the Earth	5.98×10^{24} kg
Volume of the Earth	1.083×10^{21} m^3
Mean density of the Earth	5.517 Mg m^{-3}

The Geological Column

Years Ago	Era	Period	Duration (Years)
	Quaternary	Recent Pleistocene	10 000 2 m
2 million	Tertiary or Cainozoic	Pliocene Miocene Oligocene Eocene Palaeocene	3 m 18 m 11 m 22 m 10 m
65 million	Secondary or Mesozoic	Cretaceous Jurassic Triassic	80 m 54 m 53 m
252 million	Primary or Palaeozoic	Permian Carboniferous Devonian Silurian Ordovician Cambrian	48 m 60 m 57 m 28 m 45 m 54 m
542 million	Pre-Cambrian or Eozoic	Proterozoic Archaean	
	Age of the Earth's crust: 4500 million years Age of the Earth: 4600 million years		

The Recent period began with the ending of the last Ice Age. It was not simultaneous everywhere, but in round numbers occurred 10,000 years ago. Geologists concerned about possible confusion between common and scientific usage often prefer the term Holocene (Greek holos, whole; kainos, recent).

http://en.wikipedia.org/wiki/Geologic_time_scale

Classification of the igneous rocks

The chief difficulty in classifying igneous rocks is to find a way of relating at least three different properties simultaneously. First comes the grain-size, which depends upon the rate at which the rock has coo1ed and hence tells us whether it is Volcanic, Hypabyssal, or Plutonic. Next comes the silica content, which determines not only whether it is chemically acid, basic, or intermediate between the two, but also governs important physical properties like viscosity, which affects both its behaviour when erupted and its ability to intrude between other rocks at depth. Lastly, there is the content of minerals other than silica, most importantly the feldspars. Once again, it is usual to distinguish three groups – the Alkali Series, the Monzonite Series, and the Calc-Alkali Series, in order of increasing calcium. Since we cannot show a three-dimensional arrangement on a flat page, we must present three groupings in two dimensions. There are three possible ways to do it, and no special merit beyond convenience in the way we have chosen.

Let us begin with the acid rocks, which contain more than 66 per cent silica, put the volcanic rocks at the top, and the Alkali Series (which are more than two-thirds alkali-feldspar) on the left, the Calc-Alkali Series (with more than two-thirds plagioclase) on the right, and the Monzonite Series in the middle, thus:

The rocks that occur most commonly are not always the ones that fit most neatly into such tables, and names marked with an asterisk are not in frequent use. There are no sharp boundaries between rocks in successive lines or adjacent columns, or between those in corresponding positions in successive tables.

It is instructive to compare this classification with one based upon chemical composition, which brings out the essential similarity between the coarse-grained plutonic rocks and their fine-grained volcanic relatives, the product of more rapid cooling.

Acid Igneous Rocks

	Alkali Series	**Monzonite Series**	**Calc-Alkali Series**
Volcanic	Alkali Rhyolites	Toscanites*	Rhyolites Dacites
Hypabyssal	Quartz Porphyry		Porphyrite*
Plutonic	Alkali Granites	Adamellites	Granodiorites

Similar schemes can be drawn up for the intermediate and basic rocks:

Intermediate Igneous Rocks

	Alkali Series	**Monzonite Series**	**Calc-Alkali Series**
Volcanic	Trachytes	Trachyandesites	Andesites
Hypabyssal	Porphyry		Porphyrite
Plutonic	Syenites	Monzonites	Diorities

Basic Igneous Rocks

	Alkali Series	**Monzonite Series**	**Calc-Alkali Series**
Volcanic	Alkali Basalt	Ciminite* (Shoshonite)	Basalt
Hypabyssal	Mugearite-Teschenite		Dolerite*
Plutonic	Alkali Gabbro	Kentallenite	Gabbro

Compositions of some common Igneous rocks

The analyses given are the averages for a characteristic sample of the plutonic rocks listed. The volcanic rocks whose names are given in brackets have broadly similar compositions.

Nepheline Syenite and Phonolite did not appear in our original classification. Along with Ijolite they belong to a group of sodic rocks, which contain 7 per cent or more of Na_2O.

A glance at the hundreds of names of rocks and minerals that appear in the index of any book on igneous petrology will give the reader an idea of how much had to be discarded to keep the number mentioned in the text down to about thirty. Other writers on volcanoes will choose differently, so we append a short glossary of names likely to crop up in other books, or appearing in the tables and not explained in the text.

ADAMELLITE. An acid plutonic rock intermediate between typical granites and granodiorite. It takes its name from Adamello, in Italy.

AMPHIBOLES. A family of minerals, the commonest of which is hornblende. They are mainly silicates of magnesium, calcium, and iron. The name is from the Greek amphibolos ambiguous, as they are easily mistaken for other minerals.

BIOTITE. A mineral common in very many types of igneous and metamorphic rocks. In its wider sense the term includes all the ferromagnesian micas.

DUNITE. A dense ultra-basic rock, essentially composed of olivine, and widely considered to be a principal constituent of the upper mantle. The name derives from Dun Mountain, close to the city of Nelson in the northern part of the South Island of New Zealand.

ECLOGITE. A rock composed of garnet and olivine, and considered, like dunite, to be a possible constituent of the upper mantle. It lacks most of the normal gabbroic minerals, and many petrologists regard it as lying uncertainly between the igneous and the metamorphic rocks. The name (Greek ekloge, a selection) refers to its unusual mineral composition.

EPIDIORITE. A metamorphic rock rich in hornblende, and common among the sills of the Grampian Highlands of Scotland. Elsewhere the term has largely dropped out of use. The modern equivalent is amphibolite.

MIGMATITE. The rock that forms when a cooling magma has become mixed with rock it been able to metamorphose, but not to melt. (Greek migma, a mixture).

MUSCOVITE. White mica, a mineral characteristic of most acid igneous rocks, but also commonly found in many metamorphic and sedimentary ones.

NORITE. A form of the rock gabbro.

PHONOLITE. A very alkaline trachyte. The rock owes its name to the very characteristic ring it gives when a slab of it is hit with a hammer. Early German geologists called it Klingstein (clink stone), but later generations decided that Greek was essential to petrological respectability.

SERPENTINE. The alteration of minerals rich in magnesium, like olivine or pyroxene, can result in a greenish or reddish mineral with a soapy feel. It can sometimes form rock masses called serpentinite. The name arises from the presence of markings similar to those of snake skin.

SPILITE. Sea floor basalts, especially in the form of pillow lavas, may take up sodium from wet sediments and become transformed into spilites rich in the sodium feldspar albite, and spotted with vesicles of calcite or zeolite. (Greek spilos, a spot).

If all other paths to understanding fail, try grouping all the coarse-grained acid plutonics together as “granites and all the fine-grained acid volcanics as “rhyolites”. The basic rocks can be treated similarly, by calling all the coarse ones “gabbros” and the fine ones ‘basalts’. Intermediate rocks can be called “diorites” if coarse and “andesites” if fine-grained, without violating the truth too much, and finer distinctions can be made as the need arises.

Some great eruptions compared

Energies are based on data published by I. Yokoyama, H. Tsuya, P. Hédervári, and others. Volumes of ejecta and explosivities (VEI) are taken from the Smithsonian catalogue “Volcanoes of the World”.

Volcano	Date of Eruption	Energy (joules)	Volume of Ejecta (cubic km)		VEI
			Lava	Tephra	
Santorin	c1628B.C.	1.0×10^{20}		10	6
Laki	1783	8.6×10^{19}	10	1	4
Tambora	1815	8.4×10^{19}		100?	7
Coseguina	1835	4.8×10^{19}?		1	5
Katmai (Novarupta)	1912	2.0×10^{19}		10	6
Sakurajima	1914	4.6×10^{18}	1	0.1	4
Surtsey	1963	3.8×10^{18}	0.1	0.1	3
Etna	1669	3.4×10^{18}	0.1	0.1	3?
Bezymianny	1956	2.2×10^{18}		1	5
Mauna Loa	1950	1.4×10^{18}	0.1		0
Krakatoa	1883	c.1.0×10^{18}		10	6
Asama	1783	8.8×10^{17}	0.1	0.1	4
Hekla	1970	7.3×10^{17}	0.1	0.01	3
Fuji	1707	7.1×10^{17}		0.1	4
Sakurajima	1946	2.1×10^{17}	0.1		2
Torishima	1939	9.7×10^{16}	0.01		2
Komagatake	1929	5.6×10^{16}		0.1	4
Asama	1935	4.8×10^{16}	-	-	3
Bandai	1888	c.1.0×10^{16}		0.1	4
Taal	1965	1.0×10^{16}		0.01	4
Mount St Helens	1980	1.3×10^{18}		1	5

Causes of Death

This table includes all eruptions between 1700 and 1985 believed to have caused 1,000 or more deaths. The data are based on information issued by UNESCO, sources cited by R.J. Blong, and the SEAN Bulletin. Most figures are subject to large uncertainties. The total fatalities during the period are unlikely to have been less than 250,000.

Volcano	Area	Date	Pyroclastic Flow	Lahar and Collapse	Tsunami	Famine
Awu	Sangihe Is	1711		3,000		
Oshima-o-Shima	Hokkaido	1741			1 ,475	
Cotopaxi	Ecuador	1742		1 ,000		
Makian	Halmahera	1760		2,000		
Papandajan	Java	1772	2,950			
Laki	Iceland	1783				9,350
Asama	Honshu	1783	820	550		
Unzen	Kyushu	1792		10,000	4,300	
Mayon	Luzon	1815	500	720		
Tambora	Sumbawa	1815	10,000		4,600	80,000
Galunggung	Java	1822	400	3,600		
Mayon	Luzon	1875		1,500		
Awu	Sangihe Is	1856		1,530		
Cotopaxi	Ecuador	1877		1,000		
Krakatoa	Sunda Str	1883	3,600?		33,000	
Ritter	Bismarck S	1888			3,000+	
Awu	Sangihe Is	1892		1,530		
Soufrière	St Vincent	1902	1,680			
Mont Pelée	Martinique	1902	29,000	30+		
Santa Maria	Guatemala	1902	6,000			
Taal	Luzon	1911	1,335			
Kelut	Java	1919		5,500		
Merapi	Java	1930	1,300			
Lamington	Papua N.G.	1951	2,940			
Hibok-Hibok	Camiguin	1951	2,000			
Agung	Bali	1963	1,200	200		
El Chichón	Mexico	1982	1,000?			
Nevado del Ruiz	Colombia	1985		20,000		

Active Volcanoes over 5,000 metres high

Height above M.S.L. metres	F = Fumarolic	S=Solfataric	Last known eruption
6887	Ojos del Salado	N. Chile	F
6739	Llullaillaco	N. Chile	1877
6377	Coropuna	Peru	S
6348	Parinacota	N. Chile	F
6145	Aucanquilcha	N. Chile	1960?, S
6176	San Pedro	N. Chile	S
6052	Guillatiri	N. Chile	S
6071	Copiapo	N. Chile	1985
6051	Socompa	N. Chile	F 5250B.C.
6008	Uturunco	Bolivia	S
5808	Tacora	Tibet	1951
5980	Vulkan Ka-er-daxi	N. Chile	F1937?
5911	Cotopaxi	Ecuador	1942
5895	Kilimanjaro	Tanzania	S
5890	Putana	N. Chile	1972
5868	Ollague	N. Chile	S 1903?
5808	San Jose	N. Chile	S
5856	Tocorpuri	C. Chile	1960
5822	El Misti	Peru	1870?
5815	Taapaca (= Nevado de Putre)	N. Chile	F
5815	Sabancaya	Peru	1902
5967	Tutupaca	Peru	S 1930
5787	Chupiquina S.V. of Tacora	N. Chile	S
5760	Puquintica S. V. of Arintica	N. Chile	S
5365	Antisana	Colombia	S 1555
5753	Huila	Colombia	1801
5697	Lastarria	N. Chile	S
5610	Pico de Orizaba	Mexico	1687
5672	Ubinas	Peru	1969
5670	Damavand	Iran	F
5592	Tupungatito	N. Chile	1993
6000	Lascar	C. Chile	1986
5633	Elbrus	Georgia (USSR)	50 B.C.
5597	Arintica .	N. Chile	S
5590	Herrera	Ecuador	F
5050	Isluga	N. Chile	1960
5550	Yucamani	Peru	1787
5465	Popocatepetl	Mexico	1947
5321	Ruiz	Colombia	1991
5407	Olca	N. Chile	1867
5264	Maipo	C. Chile	1912
5240	Sangay	Ecuador	1993
5200	Tolirna	Colombia	1943
5400	Un-named in KunLun Shan	Tibet	1973
5163	Irruputuncu	N. Chile	S F 1489>
5050	Kasbek	Georgia (USSR)	750 B.C.
5023	Tungurahua	Ecuador	1944

The reality of the eruptions of San Pedro in 1960 and El Misti in 1870 has been questioned. Also doubtful are the eruptions of Tacora in 1951, Ollague in 1903, the un-named volcano in the KunLun Shan in 1973, and Irruptuncu in 1989. The dates of the eruptions of Elbrus and Kasbek were established by tephro-chronology, with uncertainties of about 50 years. Sangay displays almost continuous activity of a Strombolian character.

Heights of Non-Volcanic Mountains

The heights of some well-known volcanic mountains are listed for reference and comparison:

		Metres
Mount Everest	Tibet	8848
Kanchenjunga	Nepal	8586
Annapurna	Nepal	8091
Pik Kornmunizma	Tadzhikstan	7495
Pik Lenina	Tadzhikstan	7134
Aconcagua	Argentina	6959
Mt McKinley	Alaska	6594
Mont Blanc	France	4808
Matterhorn	Switzerland	4478
Mt Whitney	California	4418
Mt Elbert	Colorado	4398
Mt Cook	New Zealand	3754
Kosciusco	New South Wa1es	2229
Ben Nevis	Scotland	1344
Snowdon	Wales	1085

Active and Dormant New Zealand Volcanoes

The volcanoes included in this list are known to have erupted within the last 35,000 years. The date of the last major eruption, and known fatalities are given. Dates before European settlement began in about 1840 are based upon radio-carbon measurements.

Bay of Islands – Kaikohe Volcanic Field	15,000 B.C.
Whangarei Volcanic Field	32,000 B.C.
Auckland Volcanic Field	A.D. 1725
Mayor Island	A.D. 1000
Whale Island	20,000 B.C.
Haroharo	A.D. 700
Maroa-Mangakino Volcanic Centre	12,000 B.C.
Lake Taupo (Horomatangi Reef)	A.D. 100-200
Mount Egmont	A.D. 1750

Historical New Zealand Eruptions

Rumble III		1986 July
White Island	10 deaths	1914 Sept 10
Tarawera	153 deaths	1886 June 10
Waimangu	4 deaths	1903 Aug 31
	10 deaths	1917 Apr 4
Tongariro (Te Mari Crater)		1896 Dec 15
Ngauruhoe		1975 Feb 19
Ruapehu		1945 Mar
		1975 Apr 24

No eruption accompanied the lahar in 1953 which caused a railway disaster in which 152 people were killed. (See Chapter 12)

Books, Journals, Catalogues

The literature that deals with volcanoes is vast, and the reader in search of further information deserves some help in finding it. The most accessible and up-to-date catalogue of volcanoes and eruptions is Volcanoes of the World compiled by an international group of volcanologists for the Smithsonian Institution in 1981, and distributed through the Academic Press. The information covers volcanoes known to have erupted in the last 10,000 years, and is listed geographically, chronologically, and alphabetically. There is an informative introduction, and a short but very useful bibliography.

More detailed information, including photographs and maps, petrographic analyses, and bibliographies, appears in the International Association of Volcanology's Catalogue of the Active Volcanoes of the world including Solfataric Fields. There are over twenty volumes, arranged by geographical regions, and a visit to a specialised library will probably be needed to find a set. The volcanoes on Alaska and Iceland have still to come, and the quality of the information already presented is rather variable; but it is quite indispensable to the professional volcanologist.

The information in the Smithsonian volume ends in 1993, but the data are stored in a computer file that it regularly up-dated, and addenda are published annually. The Institution also issues the monthly SEAN Bulletin. SEAN is not Irish, but stands for the Scientific Event Alert Network, which organises the rapid collection of information about earthquakes, fireballs, and other phenomena as well as about volcanoes, but eruptions usually claim most of the space in the bulletin. A similarly unpretentious publication is Volcano News which offers "an informal exchange of information", and originates in the Geology Department of the Michigan Technical University.

Those who 'write about volcanoes are singularly agreed about appropriate titles. One of the best general treatments is Volcanoes by Gordon A. Macdonald (Prentice Hall, 1972), which contains a better map and catalogue than most, but is no longer fully up-to-date. Fred M. Bullard's Volcanoes of the Earth (Univ. of Texas Press, 1962) has very clear photographs and locality maps. He concentrates upon volcanoes with which he is personally familiar, without attempting comprehensiveness, but gaining in detail. Volcanoes by Peter Francis (Penguin Books, 1976) is a lively treatment that does not attempt geographical completeness. Volcanoes by A.L. Rittmann (Orbis, 1976) has an unequalled world coverage of large colour photographs. Volcanoes by Robert and Barbara Decker (W.H. Freeman and Co., 1981) has excellent photographs in black and white, and a good introductory text.

Kent Wilcoxson's Volcanoes (Cassel, 1967) should perhaps have been called Eruptions, but contains some good eye-witness accounts, and adequately summarises more technical matters. Haroun Tazieff's Volcanoes (Prentice-Hall, 1962) is a leading volcanologist's personal apologia, and its appeal should not be limited to those who would consider themselves "interested in science'? There are splendid illustrations, almost equally divided between modern photographs and historical prints and woodcuts.

Volcanology by Howel Williams and Alexander McBirney (Freeman Cooper and Co., 1 979) is a more technical work, placing an emphasis upon physics and chemistry that is regrettably absent from most other treatments. Unfortunately there is an abundance of misprinted place-names. Cliff Ollier's Volcanoes (Basil Blackwell, 1988) considers them primarily as landforms, and some of his statements on other aspects of the subject could be questioned; but he is excellent in his field, and includes some little-known Australian examples that are not to be found in other books.

Few accounts of individual volcanoes are as comprehensive as Tom Simkin and Richard Fiske's Krakatau 1883 (Smithsonian Institution Press, 1983), which reprints and translates historical material that has long been hard to obtain, and brings together modern studies.

The original account of the Birth and Development of Parícutin Volcano Mexico, by W.P. Foshag and J. Gonzalez R. (U.S. Geological Survey Bulletin 965-D, 1956) is still good reading, and Haroun Tazieff, surely the liveliest and most literate of all writers on matters volcanic, has recorded his long fascination with Nyiragongo, the Forbidden Volcano (Cassel, 1975), which includes particularly good accounts of the operations of a volcanologist in the field, and of the special clothing and equipment used.

Icelanders have developed a particular skill in photographing eruptions. Surtsey by Sigurdur Thorarinsson (Viking Press, 1967) has an excellent text, and Volcano by Arní Gunnarson (Iceland Review Books, 1973) is a fine account of the Heimaey eruption and its effect upon the island community.

Many New Zealand writers have found inspiration in the eruption of Mount Tarawera in 1886, but the definitive work is Tarawera – the Volcanic Eruption of 10 June 1886 by R.F. Keam of the Physics Department of Auckland University, who has had a life-long interest in the mountain. The handsome quarto volume contains over 170 illustrations and 470 pages of text in addition to maps, plans, and diagrams, and was published by the author in 1988. It is not primarily a geological treatise, but a record of the individual and community responses of nineteenth century New Zealand to a vast natural event. The author plans two companion volumes, a description of the region before the eruption, and one bringing the story up to the present day.

Two journalists have published non-scientific accounts of the eruption – Tarawera by E. and V. Grayland (Hodder and Stoughton, 1971) and Tarawera by Geoff Conly (Grantham House, 1985). The latter is more fully illustrated, but both have good selections of the justly celebrated photographs taken by the Burton Brothers.

Island Volcano by W.T. Parham (Collins, 1973) treats White Island from many angles, giving not only an account of the geology, but telling the history of the ill-fated attempts to exploit the island commercially, and describing the fauna and fauna. E.J. Searle's City of Volcanoes (2nd ed., revised by R.D. Mayhill. Longman Paul, 1988) is a geology of Auckland by a professor in its university, who successfully communicates the results of his studies in plain language. There are few comparable accounts of a volcanic field, and not only his fellow-citizens should find it interesting.

Anyone who proposes to visit a volcano should be on the look-out for guide-books prepared by local geologists, which are usually much better value than the glossier material designed to catch the eye of the tourist. The Geological Society of New Zealand has sponsored guides to some of the most important volcanic areas of the country, including Auckland and Banks Peninsula, as well as the Central Volcanic Region.

In France, the Auvergne is well covered in material issued from the Maison des Volcans in Aurillac, and comparable publications are available in other parts of world.

Among more specialised books we should mention Volcanic Activity and Hunan Ecology by P.D. Sheets and D.K. Grayson (Academic Press, 1973), R.J. Blong's Volcanic Hazards (Academic Press, 1984) which contains useful statistical tables, and Forecasting Volcanic Events (Elsevier, 1983), a collection of papers on the present state of the art edited by Haroun Tazieff and J-C. Sabroux. G.A. Eiby's Earthquakes, (Heinemann Reed, revised ed., 1989) is clear, comprehensive, and up-to-date. A great deal has now been published about the use of geothermal heat. H.C. Armstead's Geothermal Energy (E.F. and F.N. Spon, 1978) is a good survey of the field. Unfortunately there is little about igneous rocks or volcanic soils likely to commend itself to the general reader, and we are not aware of any good modern treatment of balneology, either from the historical or from the strictly medical point of view.

A number of useful handbooks have been issued by UNESCO, including The survei1lance and prediction of volcanic activity (1972), Source-book for volcanic hazards zonation (1984), and Volcanic Emergency Management 1985). The texts are generally clear and authoratative, but some of the statistics have been combined in inadmissable ways, and dates and casualty figures in the tables are in need of checking.

A good deal of volcanological research finds its way to more general geological and geophysical journals, but two specialised periodicals must be mentioned. The older one is the International Association of Volcanology's Bulletin Volcanologique, long a multi-lingual journal edited and printed in Italy, but recently reorganised as the Bulletin of Volcanology, with all papers in English, and published in Germany. Similarly high standards of content and presentation apply to the Journal of Volcanology and Geothermal Research.

Finally, anyone adrift in the sea of geological nomenclature should be aware of John Challinor's A Dictionary of Geology (University of Wales Press, 3rd. ed. 1967), which is literate and scholarly, and greatly to be preferred to most works of more pretentious bulk and appearance.

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