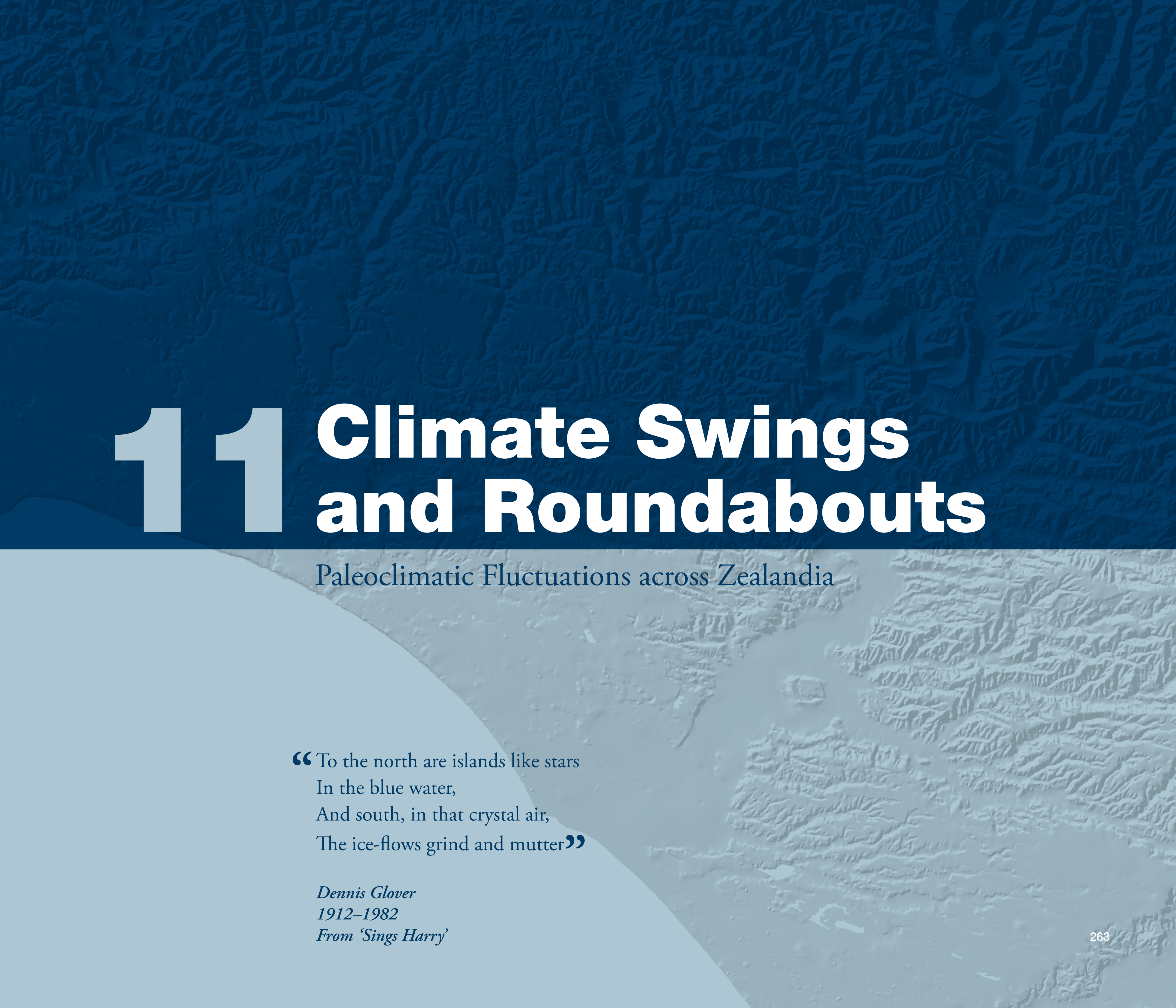


11

Climate Swings and Roundabouts

Paleoclimatic Fluctuations across Zealandia

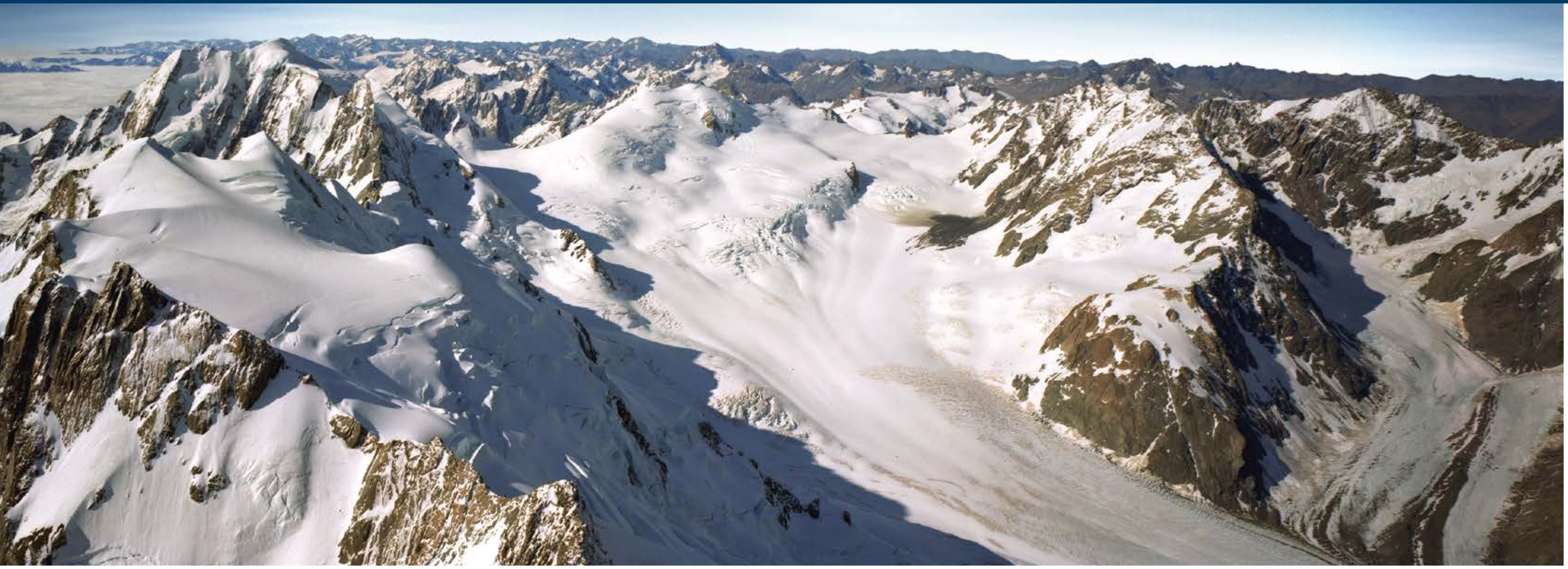
“To the north are islands like stars
In the blue water,
And south, in that crystal air,
The ice-flows grind and mutter”

Dennis Glover
1912–1982
From ‘Sings Harry’

Overview

Bob Carter

Zealandia's sedimentary deposits, rocks and their fossil record provide an outstanding archive of mid-latitude climate change for the past 66 million years, including details of the c. 50 major, worldwide, glacial–interglacial cycles that occurred during Quaternary time (the past 2.6 million years).



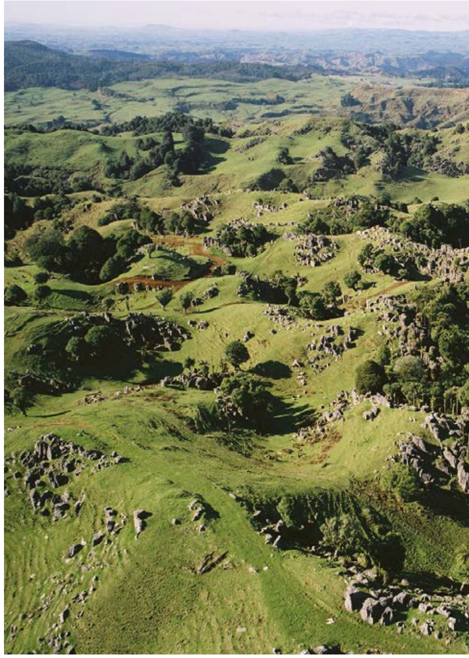
◀The Tasman Glacier snakes down ~~the flank of New Zealand's highest mountain, Aoraki-Mt Cook.~~ The terminus of this, and several other glaciers within the Southern Alps, lie at heights of only a few hundred metres above sea level, despite their occurrence at mid-latitudes.

Earth receives more solar radiation per unit area at the equator than at the poles. The resulting imbalance in heat energy results in a vigorous fluid circulation in both the atmosphere and oceans, redistributing the heat around the planet. Heat is transferred via the atmosphere, which mixes globally on a one-year timeframe, and via ocean circulation, which mixes globally on a thousand-year timeframe. Natural climate change, therefore, needs to be considered over timeframes of at least several thousand years. The longest useful series of instrumental weather measurements, the Central England Temperature Index, is just over 350 years long, so researchers into past climate change must look to long-term geological records which, fortunately, Zealandia has in abundance.

The main islands of New Zealand extend over 14 degrees of latitude, whereas the submerged parts of Zealandia to the north and south straddle more than 20 degrees of latitude. Northern parts are in the warm subtropics, whereas southern parts such as the Campbell Plateau are bathed in cold subantarctic waters [see page 224]. Zealandia thus lies athwart both subtropical and subantarctic wind and ocean water belts, which are separated by a dynamic oceanographic boundary, the Subtropical Front. Zealandia is also cut by the active tectonic boundary between the Pacific and Australian plates, which controls the locations of mountains and plains on land and water depths at sea. These factors all have marked effects on the distribution of today's plants and animals and were also influential in past times.

As climate and tectonic activity change through time, so too do the positions of wind belts, snowlines, weather fronts, water masses and sedimentary basins. The mid-latitudes of the South Pacific Ocean are a major corridor for cross-latitudinal circulation of heat, ensuring that Zealandia's climate is constantly changing.

New Zealand's 19th century pioneer geologists appreciated that the abundant fossils they collected from the younger sedimentary rocks had environmental and climatic significance. For example, Frederick Hutton in 1899 commented that the abundant molluscan fossils found in South Island Miocene sediments "*... give the fauna quite*



▲The coastal cliffs at Okehu Bluff, 20 km north of Whanganui city, contain one of the world’s best on-land records of climate change during mid-Pleistocene time (c. 1.0–0.35 Ma). Cyclic alternations of siltstones (Upper Okehu Siltstone and Lower Kai-iwi Siltstone) and sandstones (Kaimatira Pumice Sandstone) are overlain by younger terrace sands (Rapanui Formation), which formed during an interglacial period c. 125,000 years ago.

a tropical appearance”. As fossil collections increased in size, and became more closely studied, the accuracy of past climatic and environmental inferences grew.

Charles Fleming’s 1949 paper *The Geological History of New Zealand*, and papers presented at a 1968 climate symposium in Wellington city, were pivotal steps towards defining a curve showing temperature changes for Zealandia over the past 66 million years [see page 267]. This curve depicted Eocene warming (c. 55–40 Ma), Early Oligocene cooling (c. 34–29 Ma), Early Miocene warming (c. 17 Ma), and strong Pliocene–Pleistocene cooling (c. 5–0 Ma). In 1968 this fossil-based climate history was reinforced by Ian Devereux’s quantitative temperature curve based on the then-new oxygen isotope method for determining past seawater temperatures. This curve captured what later proved to be the major features of worldwide Cenozoic isotope-based temperature reconstructions.

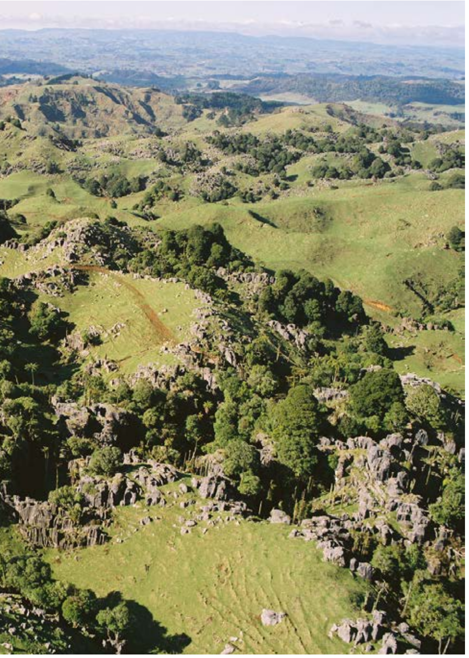
By the turn of the 21st century, geoscientists had available to them many sophisticated methods with which to extract and analyse the climate records contained in sedimentary deposits. Foremost amongst these are detailed oxygen isotope records, which accurately display both long-term temperature trends and, at higher resolution, the intricacies of climate cycling down to thousand year or shorter timeframes. The temperature history over the past 66 million years is recorded in great detail in the Cenozoic sedimentary basins of New Zealand. As the articles in this chapter show, studies of this record reveal commonalities with the global record, as well as crucial differences that are consistent with Zealandia’s unique location.

In *Core Beliefs*, the evidence for changing environmental conditions gathered from oceanic seafloor drilling, particularly legs 90 and 181 of the Ocean Drilling Program [see page 44], is discussed. The long-term temperature pattern that oceanic drill cores have yielded matches a similar pattern established from cores drilled in the Ross Sea, Antarctica, as is discussed in *Unlocking the Icehouse.* The higher global temperatures that characterise Eocene and earlier Cretaceous times (55–40 and 100–80 Ma), when atmospheric greenhouse gases are thought to have been 3 to 5 times higher than in the early 21st century, introduced a tropical flora and fauna into Zealandia, as described in *Life in a Greenhouse.*

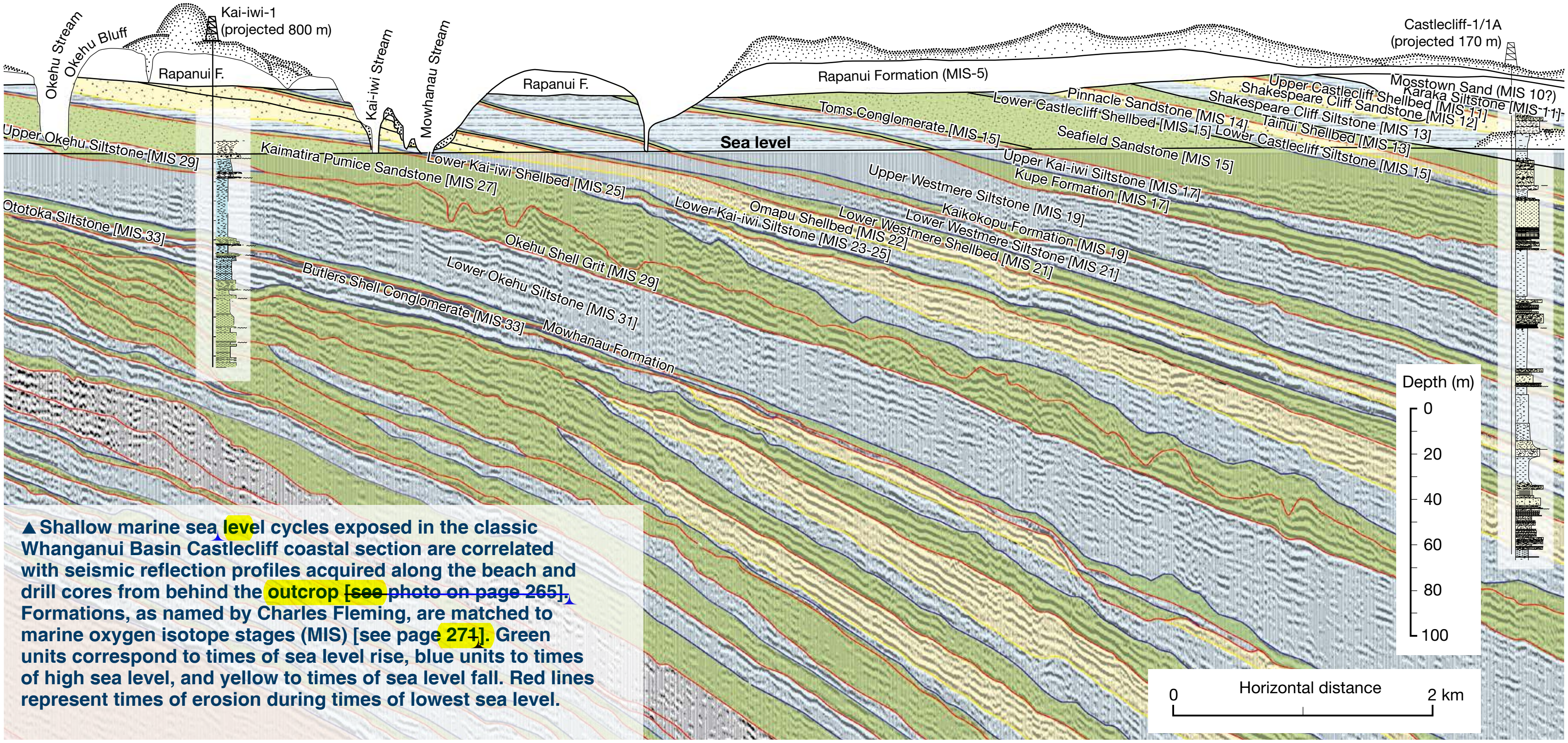
The remaining articles are concerned with the very young, high-resolution record of Zealandia’s environment during the Quaternary ice age, a time of marked cycling of glacial and interglacial periods. *Fleming’s Legacy* explains the significance of the ~~Whanganui~~ Basin sedimentary succession, first described by Charles Fleming and now established as a world standard reference site for paleoclimate studies. *Feeling the Cold* looks at the variety of evidence for climate change during the most recent glacial period c. 71,000 to 11,700 years ago, describing the setting of the most recent period of refrigeration (now known to be punctuated by periods of relative warmth) and its effects on New Zealand’s flora and fauna from c. 30,000 to 18,000 years ago. *Dusty Horizons* discusses the climate record contained in loess deposits and their associated soils. In *Nature’s Vaults*, we venture into the depths of New Zealand’s limestone caves, where there are remarkably detailed records of temperature fluctuations. In *Cold Comfort*, we learn the significance of the climate signals preserved in ice cores, including the concentrations of the ‘greenhouse’ gases carbon dioxide and methane in past atmospheres.

Finally, ~~*Adapting*~~ *to Climate Change* examines how society can mitigate the effects of climate change ~~and even benefit from it through adapting our lifestyles and farming methods~~.

Paleoclimate studies of Zealandia, of which only a selection are presented here, provide vital insights into the nature of climate change in mid-latitudes of the Southern Hemisphere. The New Zealand paleoclimate record, and the many geoscientists who have helped interpret it, stand second to none on the world stage.



◀Polygonal karst topography west of Waitomo Caves as described in *Nature’s Vaults*. Dolines pock the landscape, producing a polygonal pattern of adjoining depressions. Rocky limestone outcrops form residual ~~hills~~ on ridges between the incising dolines.

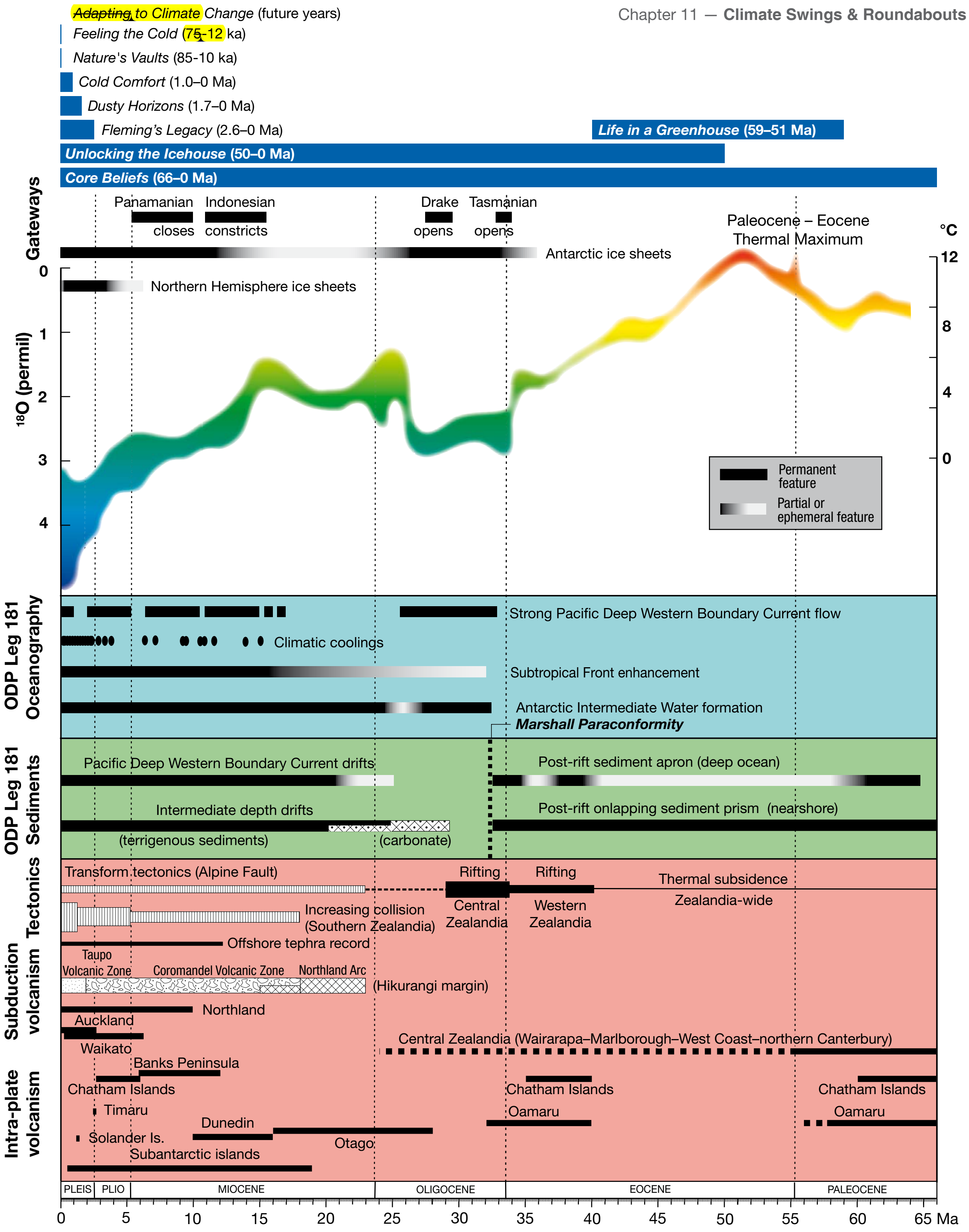


▲ **Shallow marine sea level cycles exposed in the classic Whanganui Basin Castlecliff coastal section are correlated with seismic reflection profiles acquired along the beach and drill cores from behind the outcrop ~~[see photo on page 265].~~ Formations, as named by Charles Fleming, are matched to marine oxygen isotope stages (MIS) [see page 27~~1~~]. Green units correspond to times of sea level rise, blue units to times of high sea level, and yellow to times of sea level fall. Red lines represent times of erosion during times of lowest sea level.**

Past Temperatures Revealed

Foraminifera, microscopic single celled (protisoan) marine animals that occur in vast numbers in the modern ocean, have a rich fossil record extending back to Cambrian time, c. 500 million years ago. Their calcareous shells contain an archive of changes in oceanic chemistry that can be used to infer seawater temperatures, ice volumes and oceanic productivity (the generation of organic matter). Moreover, because foraminifera range from planktic (free swimming) to benthic (seafloor dwelling), their shells can be used to deduce seawater conditions for the full range of oceanic depths. Other important microfossil groups, including nannofossils, diatoms and radiolaria, can similarly be employed. The primary chemical tools used to measure past oceanographic conditions are the naturally occurring isotopes of oxygen (^{16}O and ^{18}O), and carbon (^{12}C and ^{13}C). The ratio of ^{18}O to ^{16}O (written as $\delta^{18}O$) is preserved in foraminifera shells and reflects two natural processes. First, rainfall, snow and ice sheets are enriched in the lighter isotope ^{16}O, because they are formed from ocean vapour in which ^{16}O has been concentrated by evaporation. At the same time, the ocean, from whence most of the water is evaporated, is left relatively enriched in ^{18}O. Second, foraminifera tend to include more ^{18}O in their shells as seawater temperatures decrease. Thus, as ice sheets grow and seawater temperatures fall, the amount of $\delta^{18}O$ in foraminifera shells increases, reflecting changes in the oceans in which they live. During the life of a micro-organism, the lighter isotope of carbon, ^{12}C, tends to be preferentially absorbed into soft tissues or cellulose. An increase in the ratio of ^{13}C to ^{12}C (written as $\delta^{13}C$) in foraminifera shells thus suggests an increase in oceanic productivity or burial of organic matter. A marked decrease in $\delta^{13}C$ — a 'negative excursion' — may have many causes. For example, a negative excursion has been observed at the K/T boundary 66 million years ago — the notorious end of the 'age of the dinosaurs' — and is inferred to record the collapse of the oceanic ecosystem for hundreds to thousands of years. An even more pronounced negative excursion at the Paleocene–Eocene boundary 56 million years ago [see *Life in a Greenhouse*] is best explained by a massive injection of ^{12}C-enriched carbon into the oceans. Gas hydrates [see *Future Bounty*] are good candidates for a source for this carbon, since they occur in vast quantities — around 10,000 billion tonnes in the modern ocean — within continental shelf sediments.

▶ The 66 million years of Zealandia's history, since its split from Gondwana, is packed with incident. Here, the major geological events are summarised in relation to an averaged global oxygen isotope–paleotemperature curve, based on historical studies by Ian Devereux, and James Zachos and colleagues. The curve relates to the temperature of ~~average global~~ oceanic bottom water, which is c. 10°C colder than the ~~average~~ sea-surface temperature. Information from deep-sea cores east of New Zealand, drilled during ODP Leg 181, is used to infer changes in climate, ocean currents, and sediments deposited at various depths. Major ocean water flows reaching New Zealand are affected by gateways created and closed by tectonic activity in other parts of the globe. Also summarised are on-land records of volcanic and tectonic activity. The time periods covered by the chapter articles are shown at the top of the diagram.

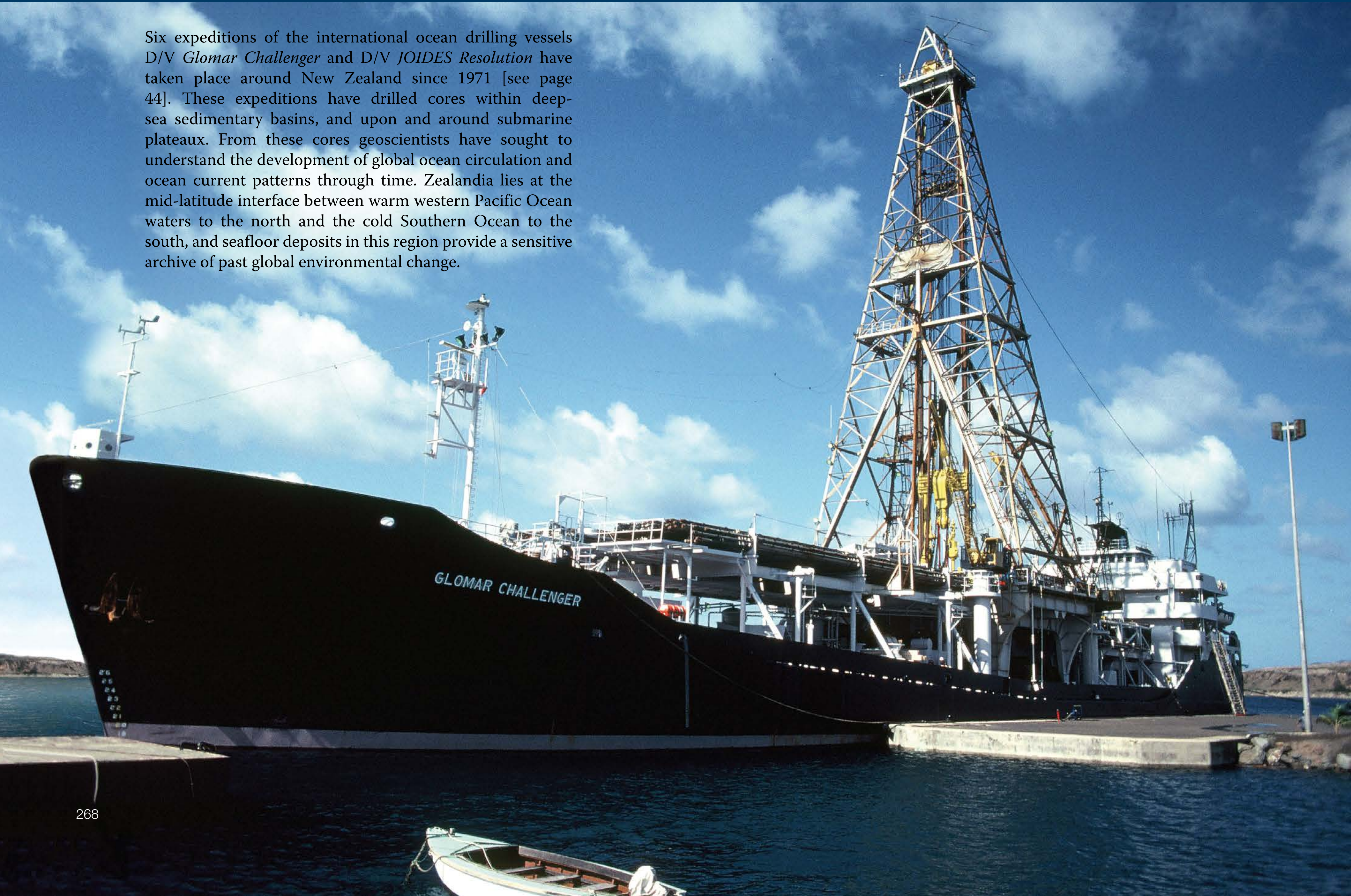


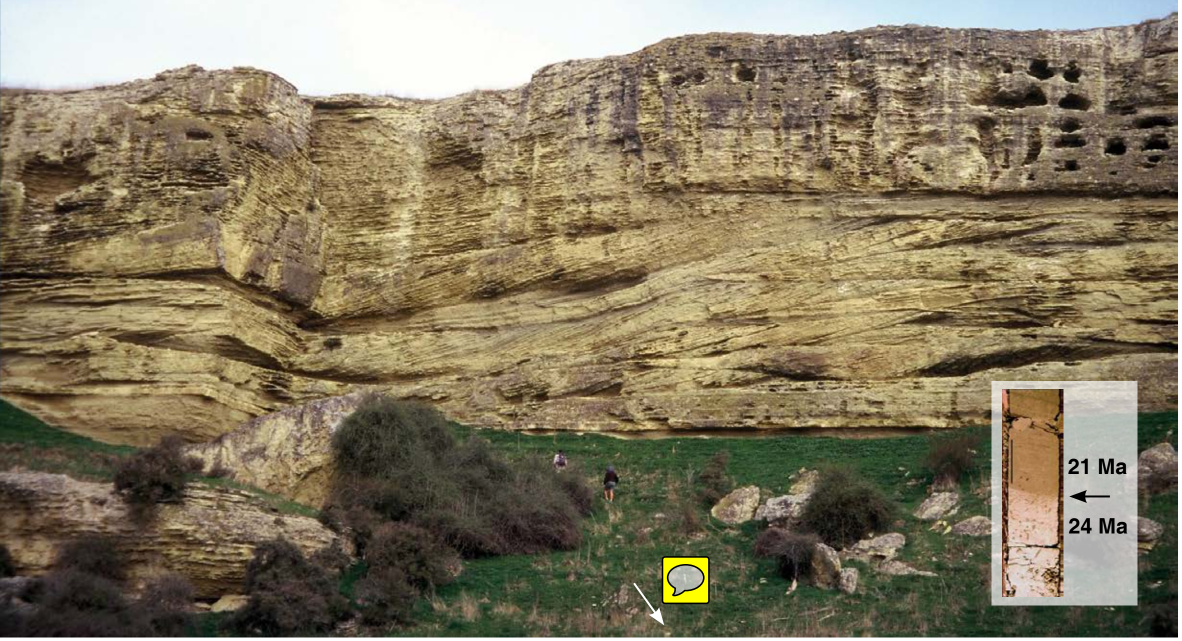
Core Beliefs

Cam Nelson
Bob Carter

Drilling into seafloor sediments in and around Zealandia has revealed a history of dynamic changes in oceanic circulation, climate and biota over the past c. 66 million years.

Six expeditions of the international ocean drilling vessels D/V *Glomar Challenger* and D/V *JOIDES Resolution* have taken place around New Zealand since 1971 [see page 44]. These expeditions have drilled cores within deep-sea sedimentary basins, and upon and around submarine plateaux. From these cores geoscientists have sought to understand the development of global ocean circulation and ocean current patterns through time. Zealandia lies at the mid-latitude interface between warm western Pacific Ocean waters to the north and the cold Southern Ocean to the south, and seafloor deposits in this region provide a sensitive archive of past global environmental change.





▲Banks of shelly debris on the seafloor formed the cross-bedded drifts seen preserved in the Weka Pass Limestone above the Marshall Paraconformity (~~arrowed~~) at Waihao Forks in southern Canterbury. The inset shows the Marshall Paraconformity in a core from ODP 181, Site 1124, drilled in 3967 m water depth on the northern flank of the Chatham Rise.

▼Deep-sea core laid out and labelled after extraction is carefully assessed prior to cataloging, and subsequent analysis by geoscientists.

The core records from in and around Zealandia exhibit a range of sediment types, from deep-ocean marine biogenic oozes to shallow water terrigenous (land-derived) sands and muds. The distribution in space and time of these different sediment types and their physical, biological and chemical properties allow oceanographic conditions to be reconstructed for the South Pacific Ocean and Southern Ocean, from north of New Zealand to Antarctica. For example, the oxygen isotope compositions of microfossils [see page 266] provide information on past seawater composition, global ice volume, seawater temperature, and nutrient levels. The Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) expeditions to New Zealand waters have generated a wealth of new knowledge and resulted in oceanographic discoveries of global significance.

Paleomagnetic measurements and other studies of sediment cores record the tectonic history of Zealandia after it separated from the eastern margin of Gondwana [see *Leaving Gondwana Behind*]. The intra-continental rifting between Australia–Zealandia and Antarctica that led to the creation of the Southern Ocean was apparent by latest Jurassic time (c. 150 Ma), but marine conditions became widespread only with the commencement of seafloor spreading during Late Cretaceous to Early Eocene time (c. 83–53 Ma) between Antarctica and Australia and between Antarctica and Zealandia. It was during this time also that the Tasman Sea mainly formed. The final separation of Tasmania from Antarctica in latest Eocene time (c. 34 Ma) opened up a deep-water passage between the Indian Ocean and Pacific Ocean and led to the establishment of a major current — the Antarctic Circumpolar Current [see page 225].

Waning of the Antarctic ‘Greenhouse’

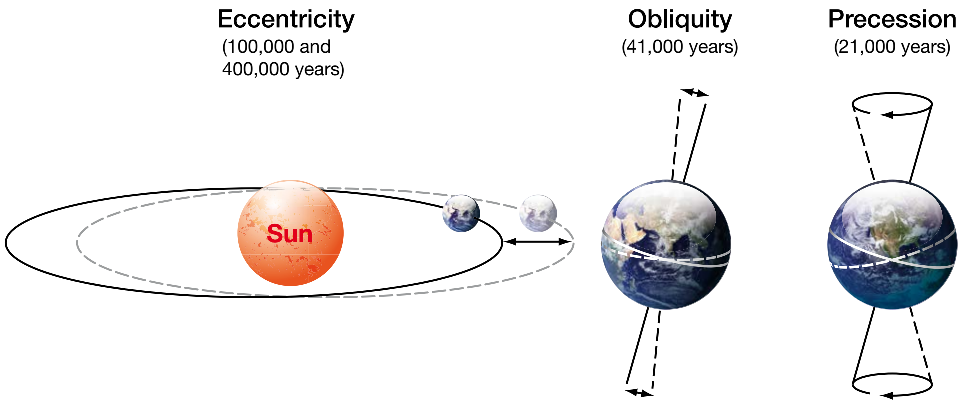
During Eocene time, warm subtropical waters bathed the coastlines of Antarctica and Zealandia. As the Southern Ocean opened, ~~the increasing thermal isolation of Antarctica, perhaps aided by~~ a long-term decline in atmospheric carbon dioxide, resulted in cooler temperatures and the growth of Antarctic glaciers. By latest Eocene time some of these glaciers had reached sea level. This timing is critical because, as Southern Ocean surface waters were dramatically chilled, they sank to initiate the Thermohaline Circulation, a global system of deep-ocean current flows that persists to this day [see page 220]. At the same time, oceanic circulation patterns became more energetic as the Earth shifted out of its greenhouse climate mode into an icehouse one, with the first southern polar ice sheets in latest Eocene time waxing and waning, but becoming persistent from Middle Miocene time (c. 14 Ma) onwards [see *Unlocking the Icehouse*].

As the climate cooled, the Southern Ocean developed thermally distinct water masses, separated by three major oceanic fronts — the Subtropical Front, the Subantarctic Front, and the Antarctic Polar Front [see page 224]. Tracing the evolutionary history of the latitudinal water belts between the fronts has been possible only by using the sediment records from deep-sea cores. Today, these water masses and the fronts play a major role in controlling regional climate patterns, and this has also been true for changes in past climate. For the past few million years, the sediment cores have recorded short-term migrations of the oceanic fronts as a result of alternating cold glacial and warm interglacial climatic periods, with associated consequences for the terrestrial New Zealand environment.

Deep-ocean thermohaline currents, such as the Pacific Deep Western Boundary Current that flows northwards along eastern Zealandia, may locally erode the seafloor, resulting in gaps in the sedimentary record of up to a few million years in duration. A spectacular example occurs in Oligocene time (c. 33–28 Ma) — the Marshall Paraconformity. This hiatus appears also in the shallow-water rocks from on-land New Zealand, and suggests that an especially vigorous current circulation existed at the time. As indicated by sediments younger than Late Oligocene (c. 25 Ma) in eastern Zealandia, the Thermohaline Circulation later slowed, resulting in the deposition of voluminous mounds of deep-sea mud or shell material known as 'sediment drifts'. These drifts preserve evidence that past deep-ocean current speeds were coupled to the global climate system in a c. 41,000-year cycle. This demonstration of the truly dynamic nature of past 'hidden' deep-ocean currents is but one of many unanticipated outcomes of deep-sea drilling around Zealandia.

Orbital Dynamics

Superimposed on a long-term record of global cooling over the past c. 50 million years have been much shorter-term fluctuations in temperature associated with the waxing and waning of ice sheets in Antarctica and in parts of high northern latitudes. One consequence of these changes in ice-volume has been cyclical rises and falls of sea level of typically 25 to 130 m. Substantial glacial–interglacial variations have probably characterised Earth history for at least the past 25 million years, driven mainly by orbital irregularities. These include the c. 19,000-23,000 year cycle of change in the wobble of Earth's spin axis (precession), the 41,000-year cycle of change in the tilt of the Earth's axis (obliquity) and, over the past 700,000 years, the 100,000-year cycle of change in the elliptical shape of the Earth's orbit around the sun (eccentricity). These three periodic variations, caused by the gravitational influence of other Solar System planets on Earth's orbit, control the distribution of the solar radiation received over the Earth's surface — and hence climate. The periodic changes are termed 'Milankovitch cycles', after the Serbian mathematician who was the first to systematically calculate how patterns of solar insolation changed with variations in the Earth's orbit.

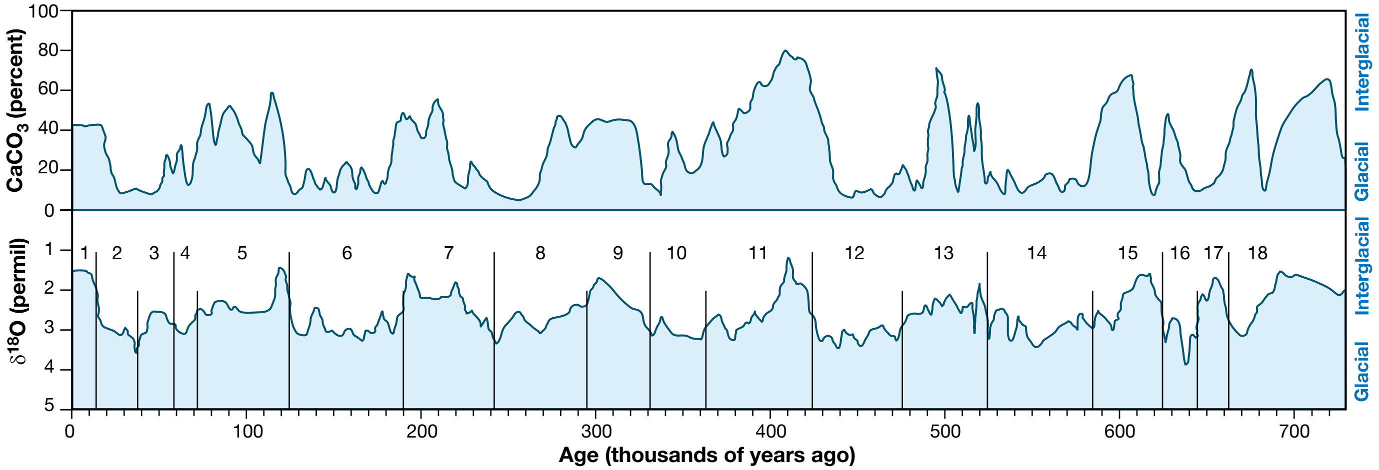


▲ As the Earth orbits around the Sun it experiences three orbital irregularities: eccentricity, obliquity and precession, each on different timeframes, and caused by the fluctuating gravitational pulls of the other planets of the solar system.

The fluctuations in ice volume and sea level have been accompanied by changes in oceanic conditions such as current velocities, nutrient levels, water chemistry and biological activity, all of which manifest themselves by changing properties in the deep-ocean sedimentary record.

A key question in global climate research is whether climate changes affected the Southern and Northern hemispheres everywhere in the same way and at the same time. DSDP 90, Site 594, drilled at 1204 m water depth on the southwestern flank of the Chatham Rise, c. 300 km east of the South Island, provided the first Southern Hemisphere climate record back to mid-Pleistocene time (0.75 Ma), in which the details of the 41,000 and 100,000 year Milankovitch cycles match closely with comparable cycles described from Northern Hemisphere deep-sea cores.

Nearby ODP 181, Site 1119, drilled closer to shore in 395 m water depth, confirmed this pattern, indicating that Southern Hemisphere climate cycles matched the established



◀ The upper 100 m of sediment core from DSDP 90, Site 594, shows more or less in-phase changes in the oxygen isotope composition (δ^{18}O) of planktic foraminifera and in the calcium carbonate content (percent CaCO$_3$) of bulk sediment samples. The changes are related to cyclical fluctuations in climate over the past c. 720,000 years. 'Marine oxygen isotope stages' (MIS) are also shown on the oxygen isotope plot (numbered 1 to 18) — odd-numbered stages correspond to warm interglacial periods and even-numbered stages to cooler glacial periods.

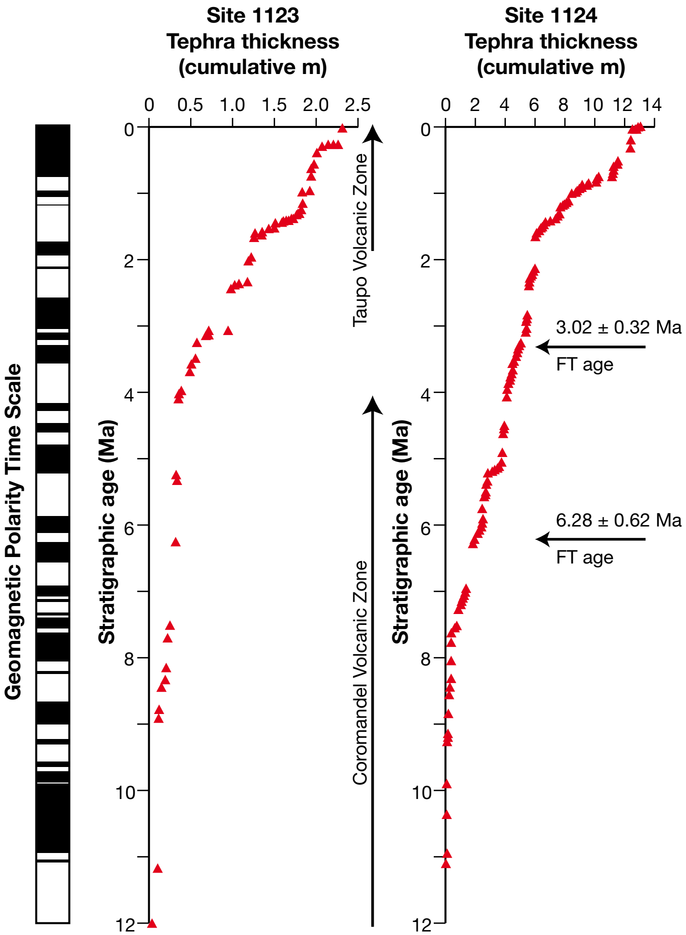
‘global’ (but mainly Northern Hemisphere) cycles back to at least 2.6 million years ago. Site 1119 sediments contain evidence that the waxing and waning of the South Island ice cap over the past 600,000 years matches precisely the cyclic pattern of changing glacial–interglacial air temperatures over Antarctica, as determined from Russia’s Vostok ice core. The time resolution for this match is better than 1000 years, which shows that major long-term climate oscillations occur in phase over at least 45 degrees of latitude.

Treasure Troves

ODP 181, Site 1123, drilled in 3290 m water depth on the northern flank of the Chatham Rise, contains a unique and almost continuous record of global changes in the Earth’s magnetic field [see page 68] back to Early Miocene time (c. 20 Ma). The record also demonstrates the existence of a short geomagnetic reversal 15–14 million years ago that was hitherto unknown. For this reason and others, Site 1123 has become a global reference sedimentary section.

Because of their age continuity, the sediment cores obtained from deep-sea drilling have provided a rich resource for paleontologists studying the evolution of Zealandia’s marine microfossils. New species have been discovered, and the age ranges of many key species are now known much more precisely. There has been a giant leap in our ability to correlate sediment horizons between different core sites, both locally and globally. As a result, geoscientists can now determine much more accurately the ages of significant paleoclimatic events and changes recorded in the sedimentary rocks of Zealandia.

The full history of volcanic activity in Zealandia is difficult to unravel on land because volcanic deposits are often destroyed by subsequent eruptions or by erosion. Deep-sea cores from around Zealandia contain a record of up to 134 discrete tephra layers, deposited over the past c. 12 million years, and ranging in thickness from a few millimetres to almost a metre. Such volcanic ash is usually carried eastwards by prevailing westerly winds and accumulates in offshore sediments. Deep-sea cores have provided a new and detailed history of major explosive eruptions from central and northern North Island since mid-Miocene time (c. 12 Ma) [see *Far-flung Markers*]. The evidence indicates that very large eruptions were more frequent than previously thought.



▲ ODP 181, Sites 1123 and 1124 [for locations see page 44] provide a record of volcanic eruptions from the Taupo Volcanic Zone and the Coromandel Volcanic Zone over the past 12 million years. Spot ages on volcanic glass have been obtained using the fission-track dating (FT) method [see *Tracks in Time*].

▼ A glacier flows into the Ross Sea, Antarctica. The Earth’s present pattern of glaciation evolved during the chilling of Antarctica, c. 14 million years ago, and has waxed and waned in concert with cyclic global temperature fluctuations since that time.

Unlocking the Ice House

Peter Barrett
Tim Naish

Antarctica is remote and hostile, the driest, coldest and windiest place on Earth, but one that offers information essential to the understanding and prediction of global climate change.

Antarctica straddles the South Pole and is covered by a major ice sheet up to 4 km thick and more than 4000 km across. It contains 70 percent of Earth's fresh water and 90 percent of its ice. It has existed in roughly its present form, bisected by the Transantarctic Mountains, for c. 14 million years. The larger East Antarctic Ice Sheet contains c. 26 million cubic kilometres of ice — enough to raise global sea level by c. 53 m if it melted. In contrast, the smaller ~~adn~~ less-stable West Antarctic Ice Sheet contains just c. 3 million cubic kilometres of ice, which would contribute c. 4 m to global sea level rise if it all melted.

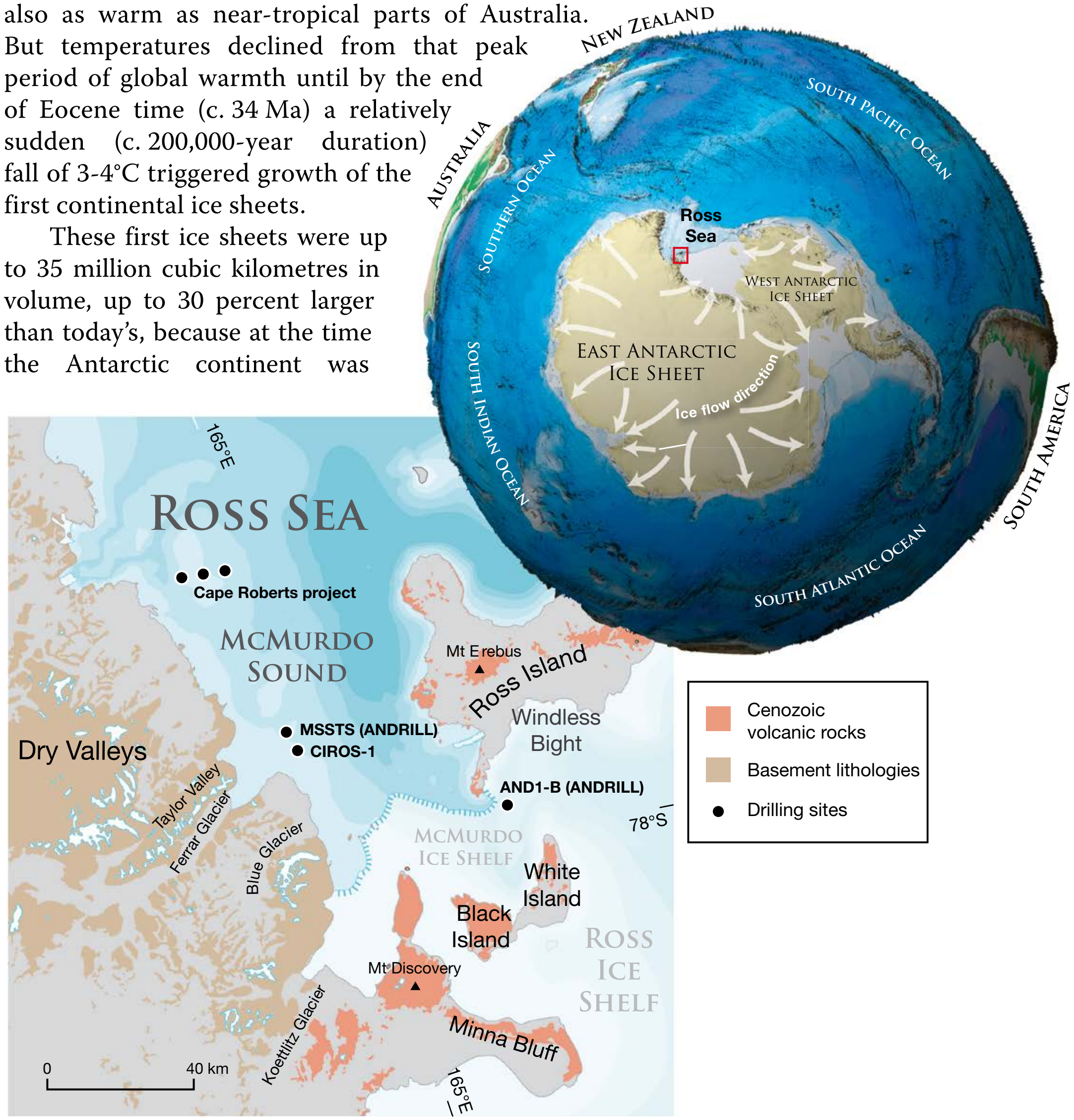
Within the ice sheets is a climate record from the past million years or so [see *Cold Comfort*]. Trapped bubbles in the ice hold atmospheric gases that contain evidence of past climates and of global pollution from industry, agriculture, and nuclear testing. The story of the continent's cooling from its subtropical coasts 50 million years ago to today's near-total ice cover is preserved in sediments beneath the surrounding seafloor, as well as at a few places on land.

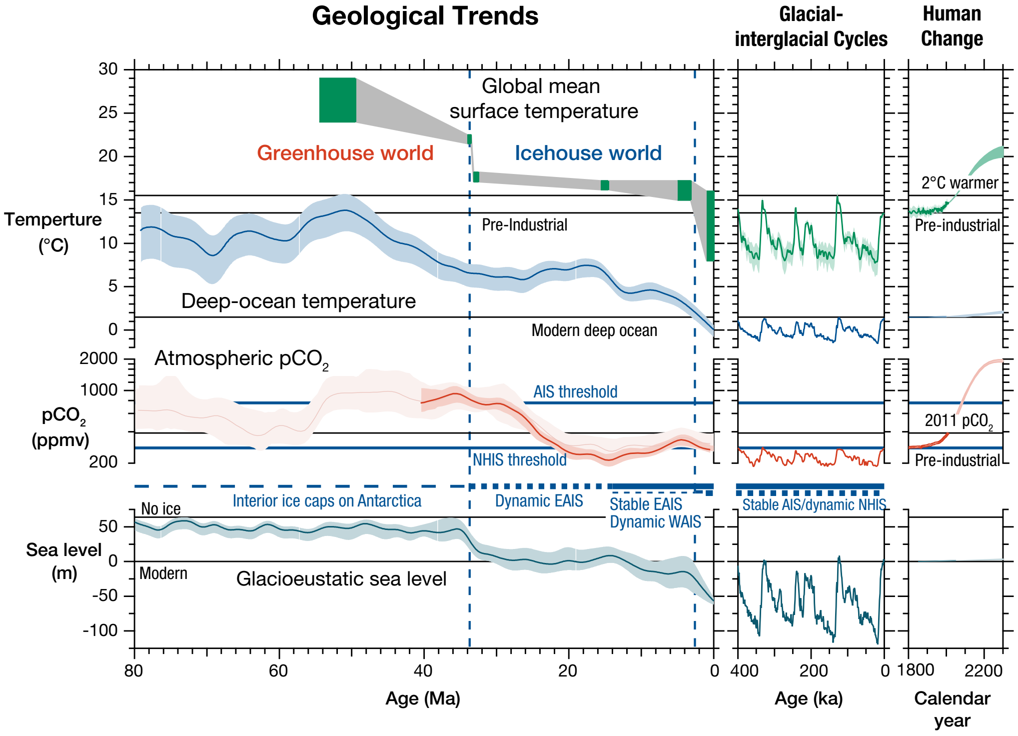
Climate scientists from New Zealand and many other nations contribute to periodic assessments of the Intergovernmental Panel on Climate Change (IPCC), whose aim is to understand Earth's climate system and assess the consequences of future climate under a range of projected greenhouse gas emissions scenarios. Knowledge of Antarctica's role in climate change is a key aspect being addressed by the panel. Its scientific findings are being used to develop international agreement under the United Nations Framework Convention on Climate Change (UNFCCC) on reducing future greenhouse gas emissions and dealing with the consequences.

From 'Greenhouse' to 'Icehouse'

Fifty million years ago the Earth's surface was on average 12°C warmer, polar temperatures were much higher, and global sea level was c. 65 m higher than today. Atmospheric carbon dioxide (CO_2), the main greenhouse gas, was three to four times the pre-industrial level. Antarctica had no ice sheet, and the coastal climate was temperate to near-tropical, although it may have had small inland ice caps and mountain glaciers. Coastal vegetation included palms, baobabs, ferns and rainforest, much like that of western South Island, or southwestern South America today, but also as warm as near-tropical parts of Australia. But temperatures declined from that peak period of global warmth until by the end of Eocene time (c. 34 Ma) a relatively sudden (c. 200,000-year duration) fall of 3-4°C triggered growth of the first continental ice sheets.

These first ice sheets were up to 35 million cubic kilometres in volume, up to 30 percent larger than today's, because at the time the Antarctic continent was



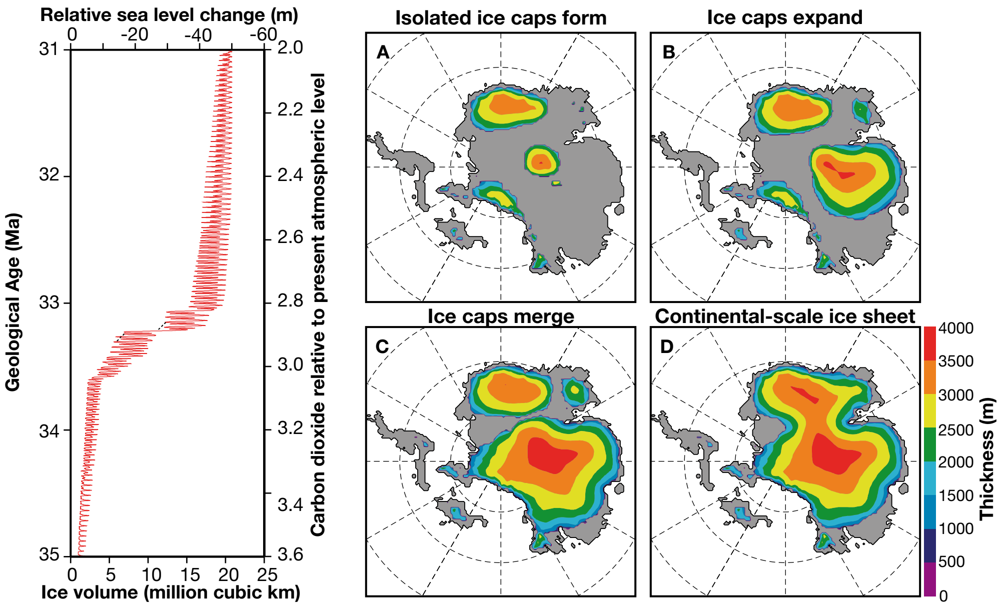


▲**Trends in four key climate-related variables—global ~~surface~~ temperature, deep-ocean temperature, atmospheric pCO_2 (partial pressure of CO_2), and global mean glacioeustatic sea level—are shown (left panel) over the past 80 million years, and with more accuracy (right panel) for the last four glacial-interglacial cycles and for 'human change' (as is observed from the years 1800 to 2011, and projected to 2300).**

that much bigger. The growth of the sheets resulted in a corresponding fall in global sea level of up to 80 m, as ocean water was incorporated into the continental ice sheets. We also know from drill cores at the Antarctic margin that these ice sheets were unstable, their growth and disappearance regulated by Milankovitch cycles [see pages 270 and 279]. The development of ice sheets on the Antarctic continent is one of the most significant changes to Earth's climate known in the geological record. It marked the abrupt end of over 200 million years of the 'greenhouse world', and the beginning of the 'icehouse world' in which we evolved along with the world around us.

For many years geoscientists believed that the freezing of Antarctica was related to movement in the Earth's major tectonic plates, because the timing of ice sheet growth coincided with seafloor spreading that dragged Antarctica away from Australia and South America [see *Leaving Gondwana Behind*]. The opening of these 'oceanic gateways' allowed the development in the Southern Ocean of the strong Antarctic Circumpolar Current that encircled Antarctica [see page 225]. The idea was that this current prevented warm subtropical ocean water from reaching the Antarctic continent, and hence allowed it to cool to a level where an ice sheet could rapidly grow.

In 2003, a new theory based on a computer-based 'Earth System Model' suggested that changes in atmospheric greenhouse gas concentrations, particularly a long-term decline in CO_2 from its peak 50 million years ago, were the major influence on the polar cooling that followed. Earth System Models incorporate changes in the orbital cycles, oceanic and atmospheric circulation, greenhouse gas levels, and the past geography of the continents and oceans to simulate the growth and decay of past (and future) Antarctic ice sheets. The values for Earth's past CO_2 levels in the Eocene were between 600 and 1200 parts per million (ppm)—two to four times pre-industrial levels—based on geochemical and fossil plant proxies. Global ~~average~~ temperature at that time was 12°C warmer than present [see *Life in a Greenhouse*]. By c. 24 million years ago, CO_2 levels had dropped below 500 ppm, with temperatures falling several degrees, and by 14 million years ago, CO_2 levels had dropped below 300 ppm, when the region cooled further



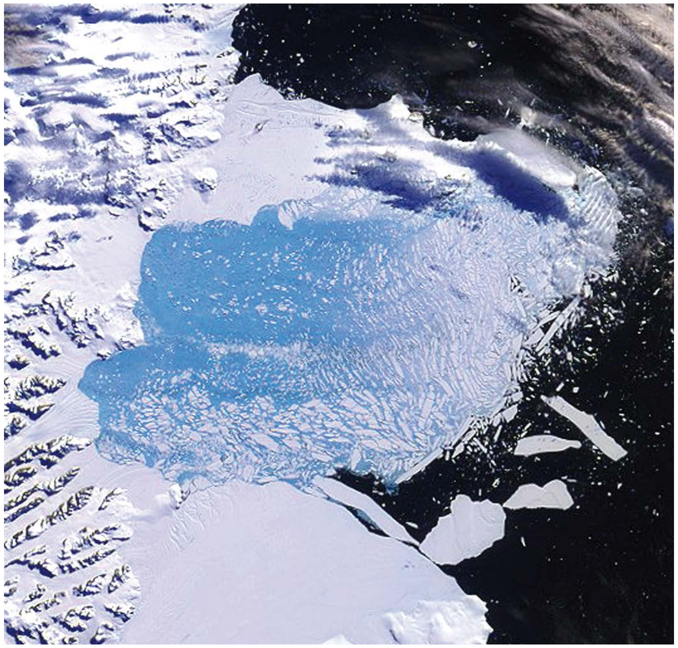
◀**Computer simulations A–D of ice sheet thickness show rapid development of the Antarctic ice sheets over a period of 1.3 million years, beginning in latest Eocene time (c. 34 Ma). The left-hand diagram shows modelled ice volume and equivalent sea level change through time.**

to temperatures close to the present, and the Antarctic ice sheet became more stable.

Ice Sheet Stability

Global sea level has risen and fallen many times during the past c. 34 million years, by between 25 and 130 m, with each cycle lasting c. 41,000 or c. 100,000 years [see page 270]. Much of the evidence for these cycles comes from the deep-sea oxygen isotope record, which suggests that from 34 to 14 million years ago Antarctica had extensive periods when its ice sheets were highly unstable, fluctuating in volume by up to 80 percent and causing global sea-level changes of many tens of metres. These ideas were first conclusively demonstrated in 1986 by a New Zealand-led multinational team when it drilled the oldest glacial strata on the Antarctic margin (at that time) in western Ross Sea, CIROS-1. Just over a decade later an expanded Cape Roberts Project, which included geoscientists from USA, Germany, Italy, UK, Australia, and The Netherlands, drilled three holes 70 km north of CIROS-1. They tapped into a remarkably complete, c. 1.5 km-deep sedimentary 'tape recorder' of ice-sheet behaviour spanning Eocene to early Miocene time (c. 34–17 Ma). This showed that the East Antarctic Ice Sheet had been highly dynamic, growing and shrinking in regular cycles that matched the duration of orbital cycles in the deep-sea isotope record in a past warmer world.

A second major cooling step in mid-Miocene time (c. 14 Ma) resulted in the Antarctic ice sheets expanding towards their present size. There has been much debate over their extent and stability, especially during the more recent warm Pliocene Epoch (5.3–2.6 Ma), when coastal deposits and offshore drill cores indicate warmer seas, and the latest computerised ice-sheet models indicate the loss of the West Antarctic Ice Sheet as well as marginal retreat in parts of East Antarctica. The modelled ice loss from Antarctica at this time represents an equivalent sea level rise of c. 15 m, which is similar to the rise indicated by coastal geological deposits of a similar age in other parts of the world, once an additional 7 m of sea-level rise from the Greenland Ice Sheet is taken into account. Interestingly, the models also show that the bulk of the East Antarctic Ice Sheet persisted through these warmer times.



◀ The collapse of the Larsen B Ice Shelf in March 2002 has been attributed to warming of the Antarctic Peninsula.

Recent Ice-shelf Collapse

The likely response of Antarctic ice sheets to projected greenhouse warming of up to 4°C by the end of the 21st century is not known. Further research into the extent of the ice sheets in past periods that are known to have been warmer than today will provide better ground truthing for model-based estimates. The marine-based West Antarctic Ice Sheet and its fringing ice shelves are likely to have collapsed during past 'super-interglacial' warm extremes, when global sea level was more than 5 m higher than today. Collapse of a dozen small ice shelves along the Antarctic Peninsula in the past two decades confirms the vulnerability of the marine-based sectors of all ice sheet margins to warming oceans. The Ross Ice Shelf represents the largest of these vulnerable components of the West Antarctic Ice Sheet—its future demise, now possible on time frames of decades to centuries, could be an important precursor to an inevitable collapse of the West Antarctic ice sheet.

Drilling for Answers

The Antarctic geological drilling programme, ANDRILL, successfully cored a 1285 m-long record (AND1-B) of climate history spanning the past 13 million years from sub-seafloor sediment beneath the McMurdo Ice Shelf. It used a New Zealand-designed drilling system developed especially for operating through a moving ice shelf. The cores are the most complete Antarctic record to date of ice sheet and climate fluctuations for this period of Earth's history. The more than 60 cycles of advance and retreat of the grounded ice margin preserved in the AND-1B core record the evolution of the

▼ ANDRILL Science Leader Tim Naish closely examines newly extracted core from the AND1-B drillhole, sited on the McMurdo Ice Shelf.

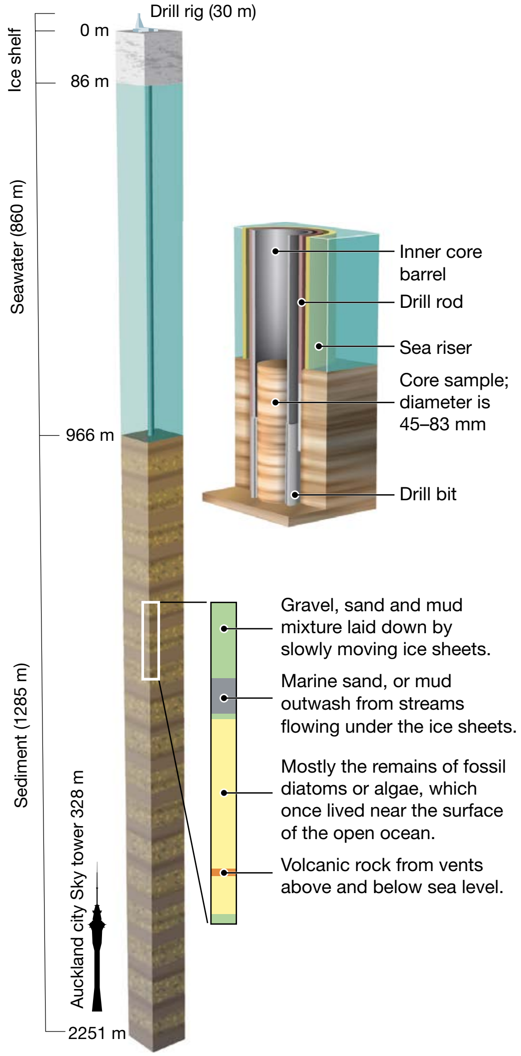
West Antarctic Ice Sheet since the profound global cooling step in deep-sea oxygen isotope records c. 14 million years ago. Recent and on-going research is focused on integrating the geological evidence for ice variability, and proxies for sea-surface and land temperatures, with ice sheet and global climate models, to understand the nature, and quantify the magnitude, of Antarctic ice volume changes during these past times of global warmth.

Will Global Warming Unlock the Icehouse?

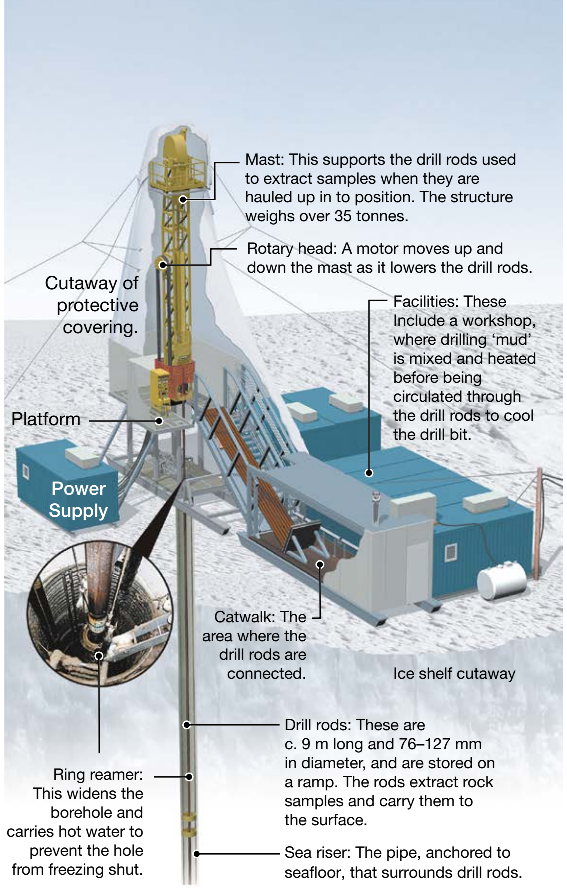
A critical question faces humanity: will human-induced global warming return us to a greenhouse world within the next few millennia? If so, what will be the consequences? The IPCC, in 2014, came to a number of conclusions about global climate: (i) since pre-industrial times c. AD 1750, global mean surface temperature increased by 0.85°C, and global ~~average~~ sea level rose by 19 cm; (ii) since 1960, atmospheric CO_2 has increased by c. 40 percent and methane has increased by c. 150 percent — these greenhouse gas concentrations are the highest they have been in the past 850,000 years, as inferred from ice-core evidence; (iii) current global warming is not part of the natural climate cycle, but is a result of human activities, primarily CO_2 emissions; and (iv) 30 percent of the CO_2 and 93 percent of the heat has gone into the ocean. For the next 100 years, the IPCC predicts that global ~~average~~ sea level will rise by up to one metre (but there are large uncertainties about the future contributions from Greenland and West Antarctic ice sheets), and global ~~average~~ ~~surface~~ temperature will increase by up to 4°C if present CO_2 emission rates continue. The IPCC acknowledges that if the marine-based sectors of the Antarctic ice sheets respond unpredictably to ocean warming then global sea-level rise by 2100 could be decimetres higher than one metre.

Most geoscientists thus believe that current and predicted increases in temperature and greenhouse gases will change Earth's climate within a couple of decades to atmospheric CO_2 levels similar to those of more than 20 million years ago, when the Antarctic ice sheets were highly dynamic. But, before we all set off in search of higher ground, it is important to understand that this will take centuries to unfold, even with continued unconstrained emissions. Still, recent modelling shows that if emissions are not reduced to zero by around AD 2070, then we are more likely than not to miss the UNFCCC 2°C target, and the loss of the West Antarctic ice sheet (as well as marine-based parts of East Antarctica) becomes inevitable.

The current focus of research in this field is in obtaining more records of past climate and ice-sheet history from key locations in and around the several ice-drainage basins of the Antarctic ice sheets. These records are needed to provide reality checks on the increasingly sophisticated and robust Earth System Models that are being used to reconstruct past ice-sheet histories for each basin. The models require well-dated information on past conditions. The same approach is then used to develop projections for the pattern and timing of rates of retreat for the same ice drainage systems over the next millennium. Society can then prepare with more confidence for adapting to the inevitable rise in sea level [see *Responding to Climate Change*], as we work to reduce our present trajectory toward this geologically instantaneous return to the Greenhouse world.



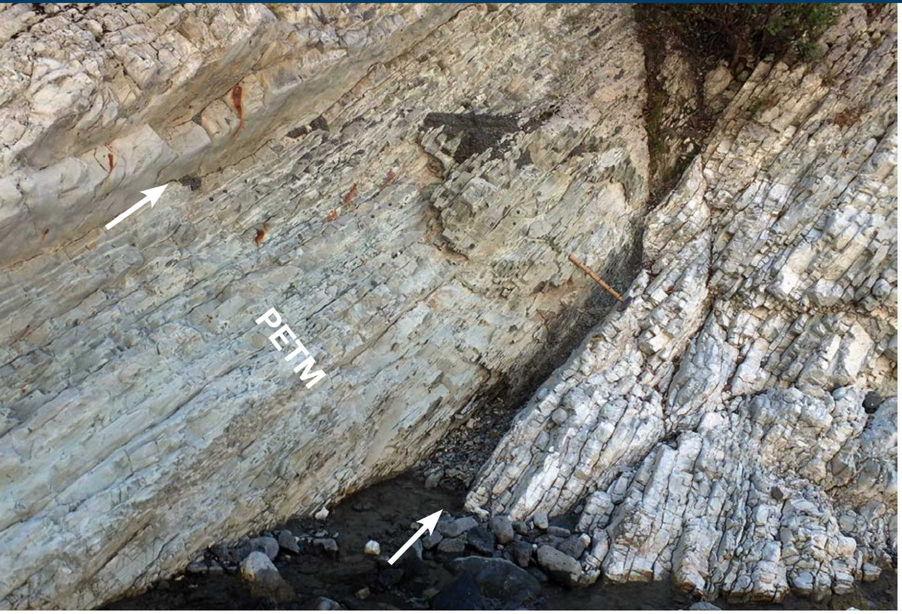
▼The drilling rig set-up for the ANDRILL McMurdo Ice Shelf Project was especially designed to allow drilling through 86 m of the McMurdo Ice shelf, 860 m of water, then 1285 m of seafloor sediment.



Life in a Greenhouse

A pulse of extreme and rapid warming c. 56 million years ago provides clues to conditions that might be experienced if the current rise in atmospheric greenhouse gases continues.

Chris Hollis
Erica Crouch
Liz Kennedy



▲ A muddy limestone unit marks the PETM at Mead Stream, in the upper Clarence River valley, eastern Marlborough.

The prediction that global temperatures will rise by 4°C within the next few hundred years, because of human-caused greenhouse gas emissions, has stimulated research into episodes of climatic warming in the geological past. One of these, the Paleocene–Eocene thermal maximum (PETM), occurred 56 million years ago when background carbon dioxide levels are inferred to have exceeded 2000 parts per million, well above the present level of 400 parts per million. We can learn how natural systems respond to global warming by studying the rocks and fossils of this age from New Zealand.

Too Darn Hot

The PETM was a climate event of about 200,000 years duration in which global temperatures increased by c. 5°C, with the deep ocean warming to c. 15°C. Evidence for this extreme climate event is found in the chemical compositions of foraminifera shells, which indicate that warming was linked to a release of 2000 billion tonnes of 'isotopically light' carbon, most likely methane from beneath the seafloor or polar permafrost. Seafloor-dwelling foraminifera appear to have been the main casualties of this event. Reduced oxygen levels and food supply are the most likely causes of the extinction of 30-50% of deep-water species. This extinction had long been recognised as a key biostratigraphic marker that defines the New Zealand Teurian–Waipawan stage boundary [see page 389].

During the PETM, the geographic ranges of cool-climate species contracted and the ranges of warm-climate species expanded. Local studies of foraminifera and other microscopic fossils show that many species of tropical plankton migrated southwards into Zealandian waters at this time for short periods during peak warming. Several warm-climate plants first appeared around this time, such as *Nypa* mangroves, which presently live only in southeastern Asia.

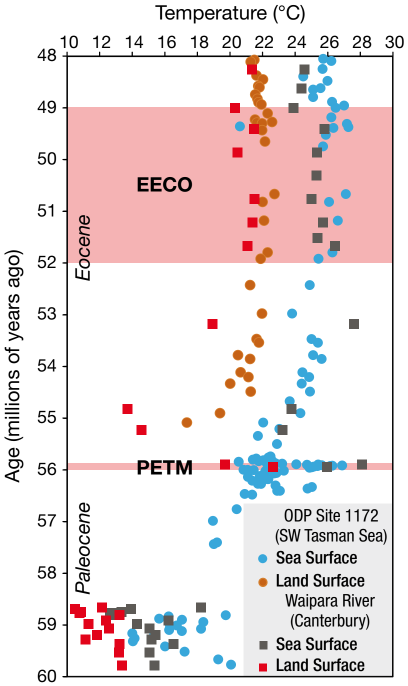
Algal Blooms

New Zealand geoscientists have played an important role in recognising the PETM and its significance for global warming. In 1991 expatriate New Zealander Jim Kennett and US colleague Lowell Stott first described the PETM in deep-sea sediment cores from the South Atlantic Ocean, and in 1996 the first on-land evidence was found along the banks of the Akitio River at Tawanui, southern Hawke's Bay. The marine mudstone exposed in the gully also provided the first evidence that a specific type of marine algae, belonging to the dinoflagellate genus *Apectodinium*, a type of *peridinoid* [see figure on page 277] during the event. Subsequently, peaks in the abundance of *Apectodinium* have been found in the PETM world-wide.

At Tawanui an influx of pollen and land-derived sediment suggests that the algal bloom may have been a response to increased delivery of nutrients into coastal waters. An increase in river discharge is consistent with climate models that predict warming on the scale of the PETM would greatly increase rainfall in the New Zealand region. Deep-sea limestones now uplifted and exposed on

Greenhouse Flora

The fossilised leaves of flowering plants show that New Zealand's Late Cretaceous climate was also unusually warm, even though the landmass was 15–20 degrees of latitude closer to the South Pole.

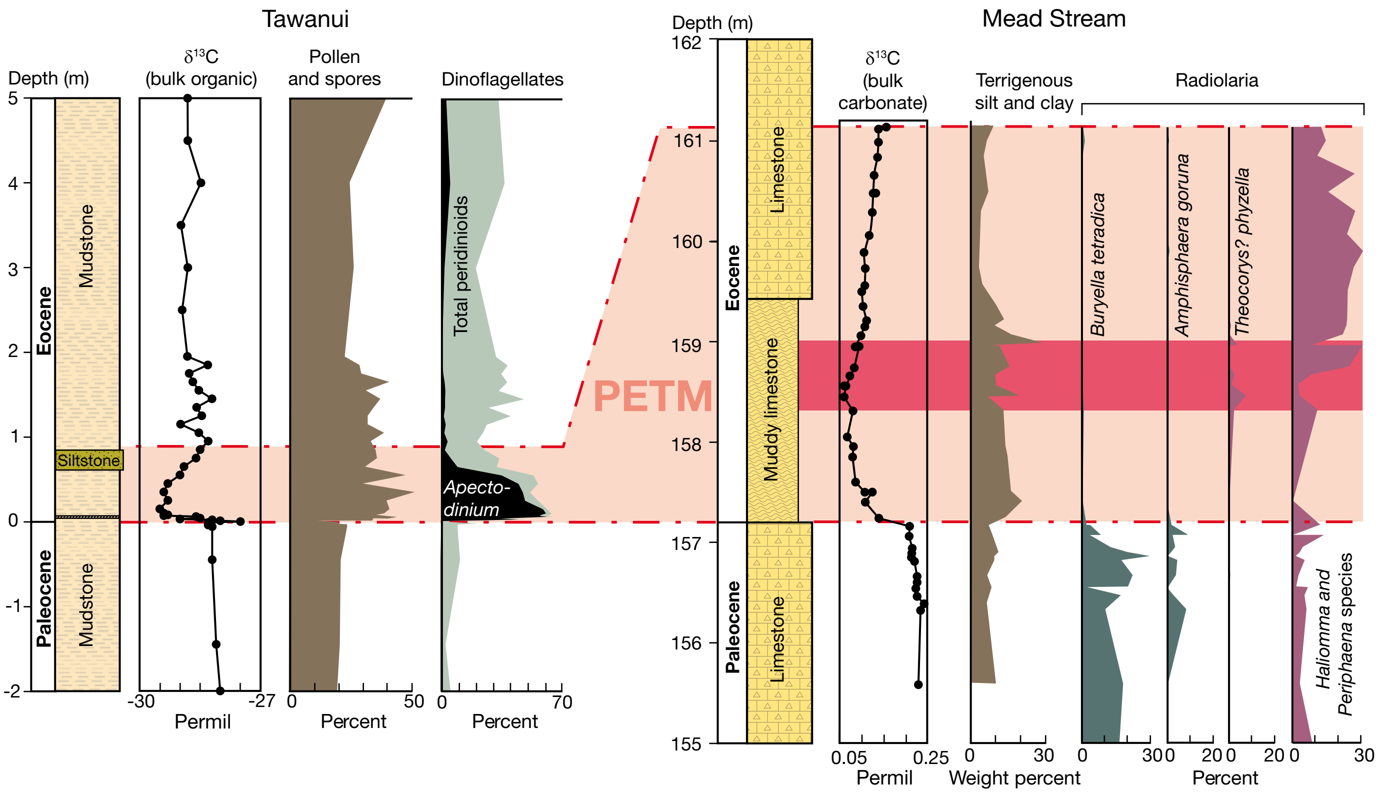


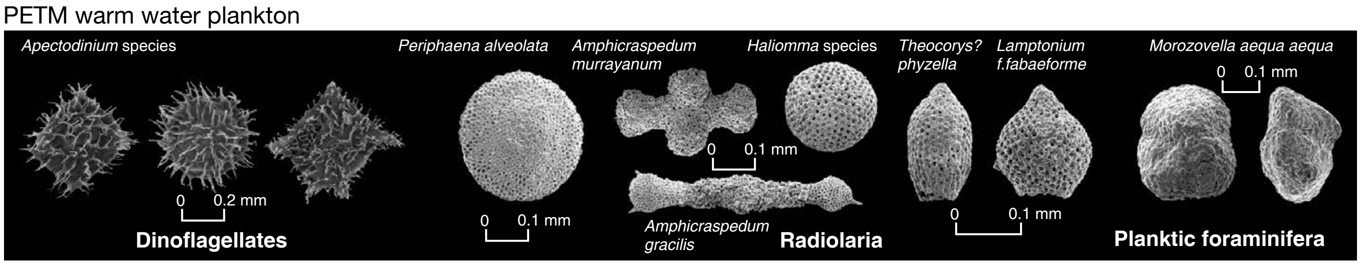
▲New geochemical methods for estimating past temperatures indicate that the Southwest Pacific experienced subtropical temperatures about 10°C warmer than the present day during episodes of global warming such as the PETM and Early Eocene Climatic Optimum (EECO). ~~Land~~ temperatures of c. 22°C were close to mean annual temperature, whereas sea temperatures of c. 27°C probably reflect summer conditions.

land in eastern Marlborough provide further evidence of climatic influences on sedimentation and biological changes during the PETM. A thin interval of muddy limestone at Mead Stream signals an abrupt influx of land-derived clay and ~~silt~~ silt, and also contains the microscopic remains of marine plankton species, which are otherwise only known from warm low-latitude waters.

In contrast to Tawanui, changes in fossil type and abundance at Mead Stream suggests that the PETM was a time of reduced marine productivity. Whereas high rainfall and delivery of terrigenous nutrients to coastal waters promoted phytoplankton blooms in coastal waters, changes in oceanic circulation appear to have led to decreased productivity in the open ocean. This change is exemplified by the abrupt drop in abundance of two common elements of the Paleocene radiolarian assemblage, *Buryella tetradica* and *Amphisphaera goruna*. Both species persist in small numbers through the PETM before finally becoming extinct later in the early Eocene.

Mead Stream indicates that a southward shift of nutrient-poor subtropical water masses, at the expense of nutrient-rich subantarctic water masses, may have been triggered by the PETM and then sustained by on-going early Eocene warming. The increased influence of subtropical waters through Eocene time may be partly explained by the progressive northward drift of Zealandia after its split from Gondwana.





▶Changes in microfossils, chemical composition and rock type are associated with the PETM at Tawanui and Mead Stream. Warm-water planktic microfossil species typify the PETM in and around Zealandia.

Fleming's Legacy

Bob Carter

The Whanganui Basin was first recognised as a globally important site for studying changes in ancient sea levels and climates in the 1940s by geologist Charles Fleming, who later became one of New Zealand's most eminent conservationists.

◀Well-sorted, shelly, inter-tidal beach sands — the Nukumaru Brown Sand — forms part of the Whanganui coastal succession. Sedimentary layering is defined by fossil bivalves and the shallow-water gastropod Zethalia.

Amongst the first fossils illustrated from New Zealand were beautifully preserved Quaternary age (c. 2.6–0 Ma) molluscs from the Whanganui coast (such as the turritellid gastropod reproduced here) from the Whanganui coast, described by Englishman Gideon Mantell (of dinosaur fame) in 1850. Thus it was established early in New Zealand's European history that the Whanganui region was an outstanding place for the collection of geologically young marine fossils and the study of their host rocks.

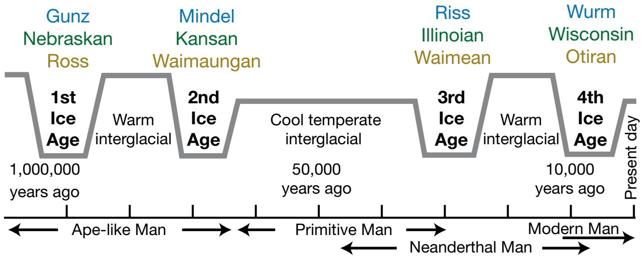
Globigerina and Oxygen Isotopes

In 1947, two scientific advances revolutionized the study of paleoclimates. First, the invention of the piston-corer made it possible to retrieve continuous, undisturbed cores up to 20 m in length of *Globigerina* biogenic ooze from beneath the seafloor [see page 42]. At about the same time, it was determined that the proportions of different isotopes of oxygen that were incorporated in the shells of marine organisms depended upon the temperature of the seawater from which the shell was deposited [see page 266].

Against this background of knowledge, and on opposite sides of the globe, two gifted young scientists began their studies of different aspects of Quaternary history. One was New Zealander Charles Fleming, who in 1945 began his field study of the fossil-rich sediments of the Whanganui Basin. The other was US scientist Cesare Emiliani, who determined ancient ocean chemistry using microfossils from cores collected beneath the seafloor of the Caribbean. Both discovered early that the fossils they were studying were important for interpreting paleoclimates, and that global climatic history did not consist of just four great glacial–interglacial cycles, as conventional wisdom dictated.

Application of the oxygen isotope technique to cores of *Globigerina* ooze from the Caribbean led Emiliani to conclude that an increase of ~~surface-water~~ temperature of up to 6°C had occurred since the peak of the most recent glaciation c. 20,000 years ago. The cores demonstrated also that seven earlier glacial–interglacial fluctuations had occurred back to c. 400,000 years ago at the base of the longest core. At the time, these results were greeted with disbelief and criticised on technical grounds, and their climatic implications largely ignored.

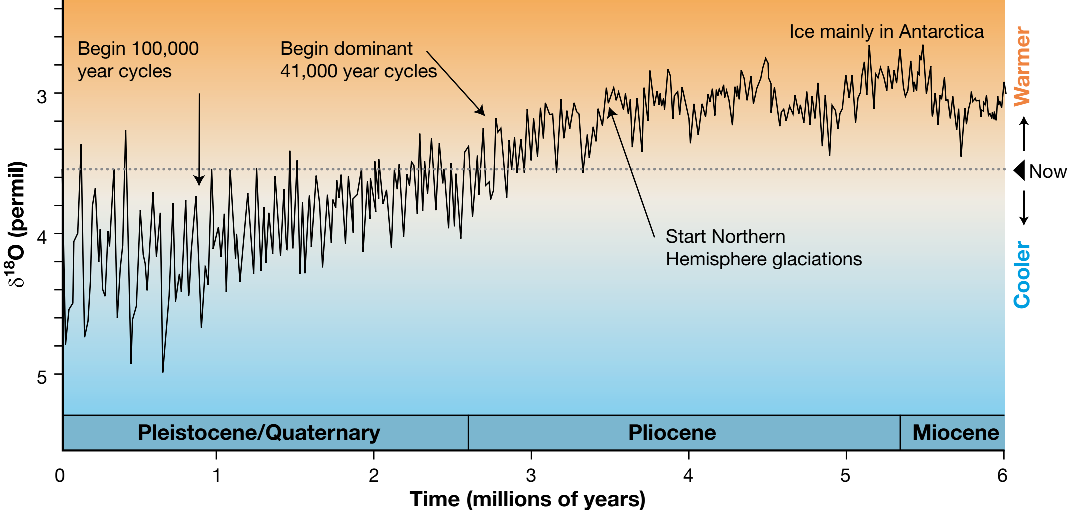
Vindication had to await the publication, in 1973, of research by Englishman Nick Shackleton and American Neil Opdyke, who showed that all of Emiliani's Caribbean climatic episodes occurred also in a sediment core from the western Pacific Ocean, and that the record of glacial–interglacial alternations reached back more than one million



◀In the 1950s it was believed (erroneously) that there had been only four major glacial–interglacial cycles over the past one million years. These were named after glacial deposits from the European Alps (in blue). Equivalent glacial episodes recognized in the USA are in green, and those in New Zealand are in brown.

Conservationist

Sir Charles Fleming (1916–1987) was one of New Zealand's greatest natural scientists. His 195 geological bulletin on the Whanganui Basin established it as a classic site for studying changes in past sea level and climates. During his long career with the New Zealand Geological Survey, Fleming was recognized as a fellow the Royal Society, ~~of~~ London, and became ~~P~~resident of the Royal Society of New Zealand.

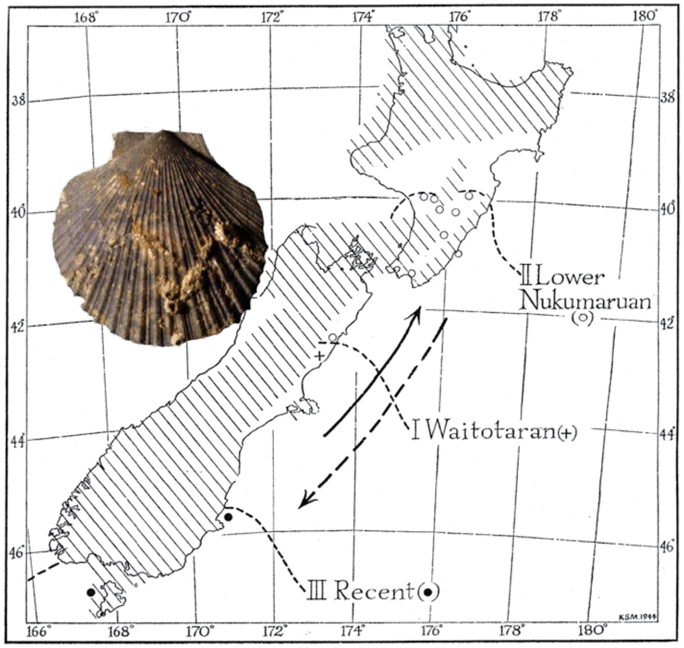


▲ Modern representation of Earth's changing temperature over the past 6 million years is based on oxygen isotope measurements of cores drilled through *Globigerina* ooze by the international Ocean Drilling Program [see *Core Beliefs*].

years. Since then it has been established that over the past 2.6 million years the Earth's climatic history has included 50 glacial–interglacial cycles, with a dominant periodicity of 41,000 years, thus putting to rest the classical geological theory of four alpine glaciations. The period of 41,000 years, and two other observed cycles of 21,000 and 100,000 years ('Milankovitch cycles'), are now known to be related to influences on Earth's orbital geometry within the Solar System [see page 270], and to have a controlling influence on Earth's long-term climate.

Sedimentary Cycles

Together with New Zealand Geological Survey colleagues, Fleming conducted field studies in the Whanganui Basin between 1944 and 1948, publishing the results in a Geological Survey bulletin, *Geology of the Whanganui Subdivision*. In 362 clearly written pages, illustrated by more than 200 photographs, hand-drawn sketches, cross-sections, maps and tables, Fleming 'wrote the book' on Whanganui Basin stratigraphy. He described and illustrated in detail the sediments and fossils which represent the past c. 5 million years of New Zealand's geological history. Because of his interest in paleontology, Fleming paid special attention to the accurate location and identification of the rich fossil molluscan faunas that occur in the Whanganui Basin. Like earlier observers, he recognized that most of the fossil species represented still live in modern New Zealand seas and therefore could be used to infer past ecological and climatic conditions. In a now-famous example, Fleming recognized that the first or repeated occurrence of the cold-water scallop *Zygochlamys delicatula* in a section represented the arrival of pulses of cold subantarctic water, and therefore climatic cooling. By integrating his observations of repetitive sand and mud sediment layers with his interpretations of the habitats and temperature preferences of the fossils preserved within them, Fleming arrived at powerful interpretations for the Whanganui Basin sediments, establishing new world-class standards for integrated stratigraphic studies.

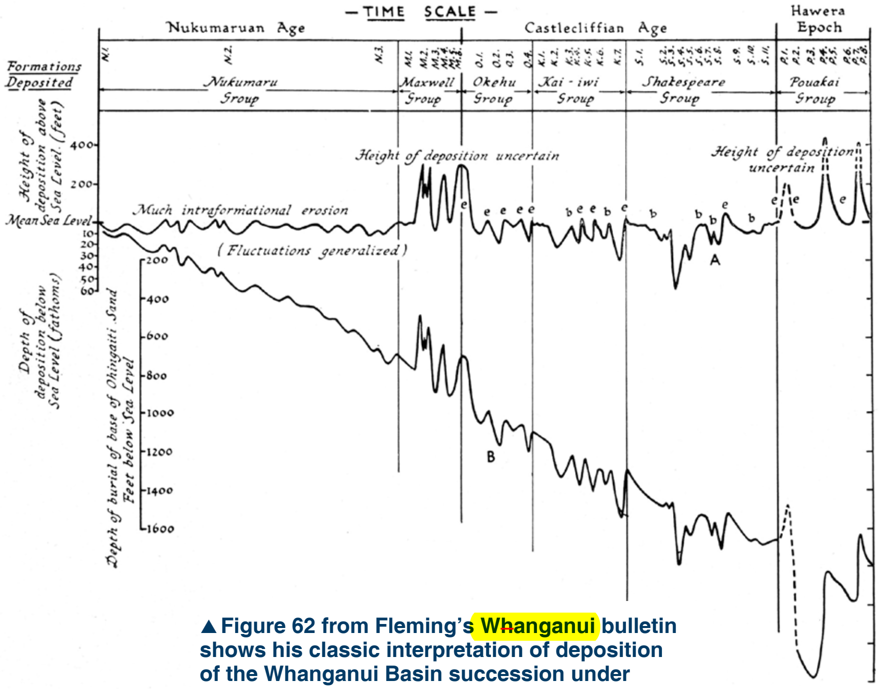


▶ This paleogeographic map published by Fleming in 1944 shows the northward movement of *Zygochlamys delicatula* during glacial coolings. The inset shows a specimen of *Zygochlamys delicatula* from the Greycliffs Formation at Mangaopari Stream, northern Wairarapa.

Fleming's key conclusion, and a finding of global significance, was the recognition of a repetitive vertical succession of sediment types, which he termed cyclothems, after similar sea-level controlled sedimentary cycles described previously from ancient glacial–interglacial sedimentary sequences in the USA and elsewhere.

In explanation of these repetitive beds — in what had seemed to earlier observers to be a random vertical succession of shallow marine sands, silts and shellbeds — Fleming wrote: "*… as the shore advanced and retreated in response to repeated … tilting, it rapidly deposited a sequence of cyclothems. The cyclothems are typically separated by unconformities representing periods when the sea advanced and carved wave-cut platforms after each phase of [uplift] and erosion of underlying beds. With renewed subsidence, shallow-water beaches were deposited followed by offshore sediments … which accumulated until renewed tilting of the sides of the basin terminated the cyclothem by elevating the sediments into the zone of erosion and wave-attack*".

Working within Fleming's cyclothem template, later researchers have discovered that it is the differing types of shellbed that provide the key to unlocking detailed environmental interpretation of the Whanganui succession.



▲ Figure 62 from Fleming's Whanganui bulletin shows his classic interpretation of deposition of the Whanganui Basin succession under oscillating sea level, combined with longer-term tectonic subsidence [see page 266].

For resting on a marine-cut erosion surface that marks the lower boundary of each cycle lies a shellbed of similar type to the Nukumaru Brown Sand, with inter-tidal fossil species, which reflects the passage over the site of a landward-moving shoreline driven by a rising sea-level. Above this, and representing the time when the shoreline has moved up to tens of kilometres further ~~shore~~ward in response to continuing sea-level rise, lies a mid-cycle shellbed rich in epifaunal shell-ground fossils (for example, the Tainui Shellbed) and which represents a sediment-starved mid-shelf (40-80 m deep) seabed that existed at the time of maximum marine transgression within the cycle. Sea-level fall follows, causing the deposition of copious seaward-advancing muddy sediment that first smothers the mid-cycle shellbed, and then, as sea-level fall continues, accumulates to form the 10-20 m thick siltstones (cliff-forming 'papas') that mark the upper part of each cyclothem (for example, the Lower Kai-iwi Siltstone). These siltstones also contain common fossils, but scattered throughout rather than concentrated in shellbeds, with species that either ~~deposit~~ feed directly on the muddy substrate or, if suspension feeders, are tolerant of muddy conditions.

In a classic diagram, Fleming summarised the evidence for the occurrence of about 14 such cyclothems through Nukumaruan and Castlecliffian time (Pleistocene: 2.4–0.34 Ma). Surprisingly — with the benefit of hindsight — and although he often mentions global sea-level change as a possible agent for causing the sedimentary cycles, Fleming surmised that the depositional cycles he observed were mostly controlled not by sea-level fluctuations but by "… *pulsating geosynclinal sinking and tilting …*". In this, he was undoubtedly influenced by the strong contemporary belief that Earth's most recent glaciations were but four or five in number.

A Stratigraphic Revolution

After Fleming and Emiliani had completed their research, during the 1960s and 1970s, the discipline of stratigraphy underwent a revolutionary change. The change was driven both by scientific insight and by technological developments, which included improved methods for obtaining images of underground strata by seismic reflection profiling [see page 266] and improved techniques for determining the age of deposits and rocks, such as radiometric dating of tephras.

The new scientific insight came from the corporate world. Led by Peter Vail and other researchers within the Exxon oil company, a new method, termed sequence stratigraphy, was launched in 1977. Sequence stratigraphy is based upon the analysis of seismic reflection profiles to identify sequences — units of strata bounded by unconformities, from whose geometric relationships a contemporary 'global' sea-level curve can be constructed. Its application resulted in the grouping of sedimentary strata into 'packets', each of which corresponds to a low-high (glacial–interglacial) sea-level cycle. This was precisely what Fleming had already observed and described — terming them cyclothems rather than sequences — from the Whanganui Basin succession.

In the last two decades of the 20th century, the sequence stratigraphic model was further developed and the dating of young sedimentary rocks was refined, greatly aided by the availability of long uninterrupted deep-sea drill-core

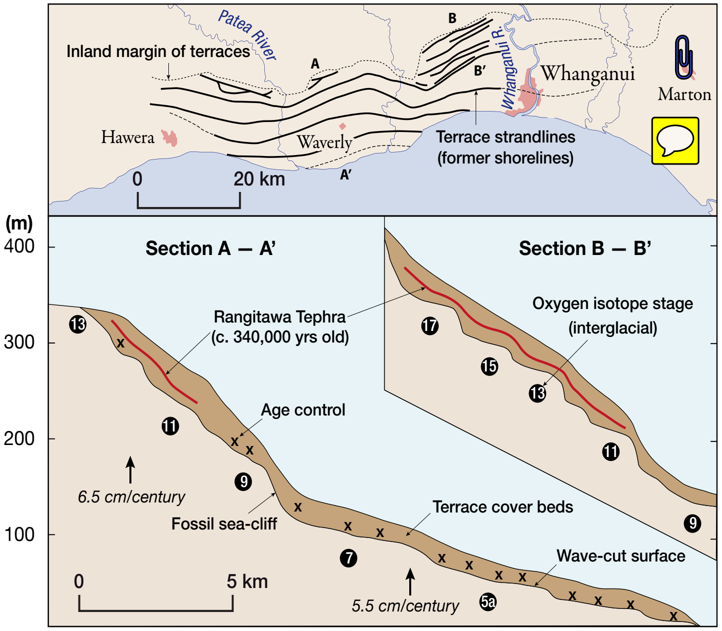
▶ Kai Iwi Beach, ~~near~~ Whanganui city, and the cliffs of Lower Kai-iwi Siltstone to the south (in shadow), are capped by terraces cut by the sea across the uplifting land during warm interglacial periods of high sea level. The houses in the centre are on the Rapanui Terrace, formed c. 125,000 years ago during the interglacial immediately before the present one. The widespread surfaces further inland mostly belong to the Ngarino Terrace, which formed c. 220,000 years ago during the previous interglacial. Coastal uplift rates of ~~50-60~~ centimetres per ~~thousand years~~ have been sustained over the past one milllion years, causing terraces to become successively older and higher in an inland direction.

◀ This selection of fossil molluscs from a locality near Whanganui city is an assemblage typical of those found in soft, muddy seafloor environments. This seafloor is now represented by the fossil-bearing siltstones ('papas') exposed in the Whanganui cliffs, which were deposited in water depths of 40-80 m, representing the deepest-ocean conditions within each individual sea-level cycle.

sequences back to earliest Pliocene time and beyond. It was realised that the alternating pattern of warm and cold climatic periods extended far back in geological time, and was controlled by the 41,000-year Milankovitch cycle. This allowed sedimentary records, and therefore geological events, to be 'astronomically tuned' to an accurate timescale. The chronology has been confirmed by various methods, including independent dating of fossil corals using uranium-series, paleomagnetic and tephrochronology methods.

It is no surprise that scientists from Gideon Mantell onwards have been able to study extremely young fossils and sediments from the Whanganui Basin. It is a reflection of New Zealand's location straddling the Pacific–Australian plate boundary. Because of uplift along this plate boundary, undeformed continental shelf sediments less than 300,000 years old are now exposed on land in southern North Island. Elsewhere in the world, such sediments are nearly always submerged beneath shallow continental shelf waters and can only be studied using expensive submarine drill cores.

▶ Two north-south oriented cross-sections, located west of Whanganui City (A-A near the coast and B-B further inland), display a series of marine-cut coastal terraces. These terraces reflect progressive tectonic uplift, and therefore become both higher and older inland. First mapped in detail by Brad Pillans in 1983, the inner edge of each terrace represents the temporary location of an ancient sea-level high stand that developed during a warm, interglacial period. The youngest (Rapanui Terrace) is c. 50 m high at the coast and c. 125,000 years old; the oldest (Mararou Terrace), mapped inland at a height c. 350 m is c. 520,000 years old. To establish the age sequence of terraces, Pillans used their physiographic height in combination with the known dates of tephra layers, such as the Rangitawa Tephra (c. 370,000 years old), which occur within their covering sediments, as well as amino acid racemisation and fission-track dating.



By the 1980s the Whanganui Basin had become established as an outstanding location for climate change research. The place was right — it was almost unique in the world in exhibiting such young marine sediments on land. The stratigraphic framework was right—with the completion of Fleming's Whanganui bulletin. The intellectual milieu was right — with the development of sequence stratigraphy, oxygen isotope stratigraphy, and accurate, astronomically-tuned geological timescales. And, as it turned out, the people were right — with the emergence of a new generation of talented young New Zealand stratigraphers whose interests lay in Quaternary geology and paleoclimate. The result was a burgeoning of research, the publication of numerous scientific papers, and the positioning of New Zealand geoscience at the forefront of global paleoclimate research.

After the completion of the Whanganui bulletin, New Zealand geologists were able to take samples from fossil-bearing strata of similar age elsewhere and say *"this is Castlecliffian in age"*, meaning older than Haweran, younger than Nukumaruan, and with an actual age of several hundred thousand to c. 1.5 million years old. Today, geologists can assign many units of Nukumaruan or Castlecliffian age from throughout Zealandia, whether fossil-bearing or not, to a single marine oxygen isotope stage [see pages 266 and 271], thereby estimating the formation age to within a few thousand years and indicating whether deposition occurred under glacial or interglacial conditions.

Charles Fleming left many scientific legacies, but none surpasses the Whanganui bulletin. The work serves as a model for the publication of a regional geological monograph — it is thorough, comprehensive and accurate, with a restrained beauty of illustration and scientific insight that mark the work of a great natural scientist. Fleming's work has also served as the foundation for further important scientific advances in Quaternary geology and paleoclimate reconstructions. The Whanganui bulletin remains a fundamental reference for all those who are interested in climate change, and who therefore come to study the superb stratigraphic record of the globally important Whanganui Basin.

Feeling the Cold

The most recent global glaciation, which peaked between about 30,000 and 18,000 years ago, played an important role in the development of the modern New Zealand landscape.

David Barrell
Rewi Newnham

▲The landscape of the Rakaia River valley in the central Southern Alps is ice-sculpted and has changed little since c. 18,000 years ago when the glacier rapidly melted away at the end of the most recent glaciation. The winter snowline in this view is at c. 1500 m elevation, roughly the same as the summer snowline during the coldest glacial conditions.

New Zealand's modern glaciers are confined to Mt Ruapehu in the central North Island, and along the axis of the Southern Alps from Arthur's Pass south to the northern part of Fiordland. By the 1840s, scientists working in the European Alps had recognised distinctive glacial landforms in positions far down-valley of any modern glacier. This led them to propose the occurrence of a past 'ice age', when the climate was much colder than today and glaciers grew to prodigious size. Aware of the developing theory of past ice ages (now called 'glaciations'), the Canterbury Provincial Geologist, Julius von Haast [see page 347] had, by the early 1860s, recognised similar landform imprints of huge ancient glaciers at the fringes of the Southern Alps. Since then, the locations and character of Southern Alps glacier deposits and landforms have been described and depicted on maps at various scales. A distinction is made between the sediment deposits laid down by a glacier (till) and the landform surface developed on those deposits (moraine). By the mid-20th century, it had become clear from the arrangements of moraines and the characteristics of tills in the Southern Alps that there had been at least several episodes of glaciation in New Zealand [see *Fleming's Legacy*].

The best record of the effects of glaciation comes from the most recent episode of glacial climate, known in New Zealand as the Otira Glaciation. This climate episode was of global extent and, based on oxygen isotopes preserved in deep-sea marine sediments, occurred from c. 71,000 to c. 18,000 years ago and spans marine oxygen isotope stage 4 through to stage 2 [see *Core Beliefs*]. This glaciation is known by various local names in different parts of the world, such as the Wisconsin Glaciation in mid-western USA, the Devensian Glacation in the UK, the Weichsel Glaciation in northern Europe, and the Würm Glaciation in the Swiss Alps.

Geological hallmarks of the Otira Glaciation include relatively well-preserved landforms such as moraines and glacial sediments, the latter including tills deposited directly from glacier ice as well as outwash gravels laid down by meltwater rivers that flowed from the glaciers. The Otira

▶ When first documented in drawings by Julius von Haast in 1862, the Classen Glacier fully occupied its valley, but it has since retreated c. 3.5 km, with a lake forming in its trough. This modern glacier system illustrates several typical glacial landforms. Lateral moraines along the sides and terminal moraines at the down-valley end are composed of rock debris deposited by the glacier. The three forested ~~knobs~~ in the foreground are remnants of an older moraine. The braided meltwater outwash plain on the periphery of the moraine complex include bare active river beds and yellow, grass-covered abandoned outwash deposits.

Glaciation has long been regarded as having two main parts. Sediments deposited during the early Otira Glaciation have yielded organic remains, such as pieces of wood, whose ages lie beyond the range of radiocarbon dating (c. 60,000 years ago). The late Otira Glaciation lies within the range of radiocarbon dating and its sediments and landforms are generally very well preserved. This is because the glaciers withdrew far into the mountains at the end of the glaciation, leaving behind a wealth of relict glacial landforms that have not been overrun by subsequent glacier advance. In areas beyond the reach of glaciers, the cold climate of glaciations reduced the vegetation cover, leading to enhanced erosion in the hill catchments that produced abundant sediment, which was carried downstream to accumulate on the river valley floors, flood plains and the now submerged continental shelves.

Frosty Fluctuations

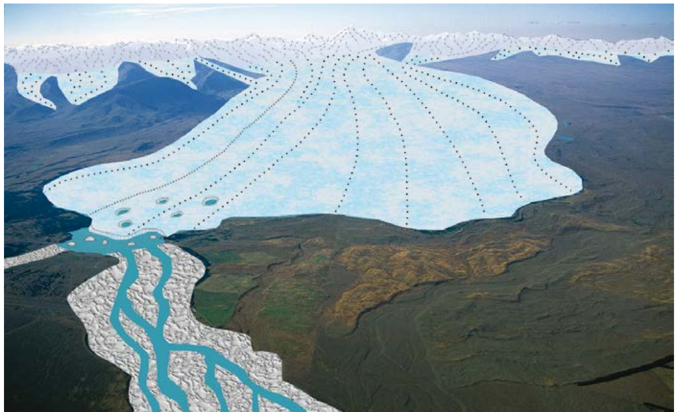
By the start of the 21st century, knowledge of the timing of advances and retreats of glaciers during the Otira Glaciation was based largely on a scattering of radiocarbon dates on organic matter, buried beneath, incorporated within, or laid on top of glacial deposits, and aided by global correlations using deep-sea sediment records. These data indicated a major glacier advance during the early Otira Glaciation, about 65,000 years ago, and a succession of three advance-retreat episodes during the late Otira Glaciation, between c. 30,000 and 18,000 years ago.

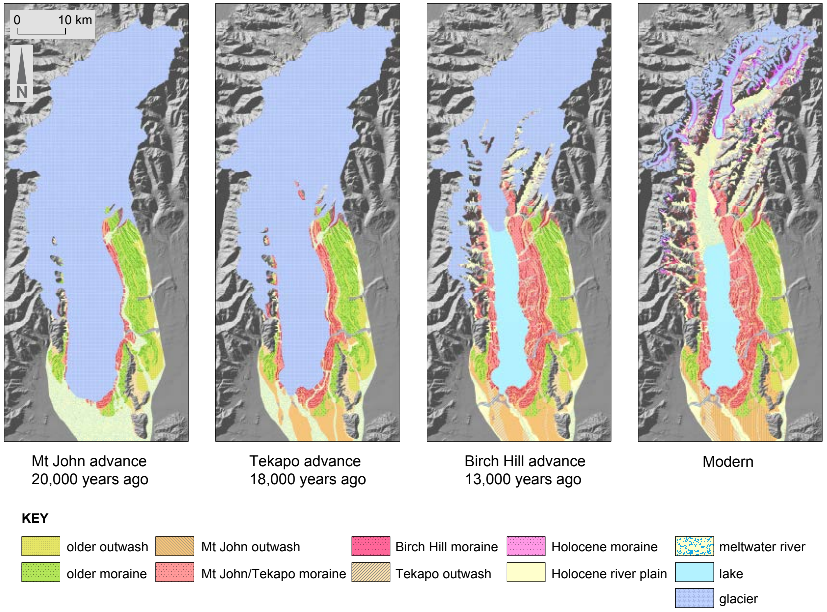
Since the mid-2000s, this picture of glacier fluctuations has been enhanced greatly by the emergence of new dating methods, such as luminescence [see *Illuminating the Past*] and, in particular, surface exposure dating using cosmogenic nuclides such as ^{10}Be [see *Cosmic Chronometers*]. Surface exposure dating targets large glacier-transported boulders projecting from the surfaces of moraines. The upper surfaces of these exposed boulders have been bombarded by cosmic radiation, causing measurable changes in their isotopic composition that relate to the length of time since the boulder was deposited by the glacier. By dating several boulders in a single belt of moraine, the age of the moraine can be established to a high degree of confidence. A particular strength of the moraine record is that the shape and position of a moraine belt can be mapped and used to produce reconstructed models of the size and shape of the glacier that formed it. From that, the climate conditions required to form a glacier of that size can be estimated.

In these ways, a detailed chronology of glacial climate variation has been constructed from the moraine record of the Southern Alps. Intensive surface exposure dating has been undertaken to the east of the highest part of

▶ Lake Pukaki lies in the trough of an Otiran glacier that drained southeast from the highest parts of the Southern Alps. Belts of hummocky moraine lie around the margin of the glacier trough and braided outwash channels issue from the moraine complex. The glacier retreated rapidly, beginning c. 18,000 years ago, and the lake formed in the depression left behind.

▼ The onset of retreat of Pukaki glacier began c. 18,000 years ago with a lake just beginning to form near the retreating ice front. Meltwater fed braided rivers transporting and depositing outwash sediments in the foreground.





Mt John advance 20,000 years ago | Tekapo advance 18,000 years ago | Birch Hill advance 13,000 years ago | Modern

▲ A schematic history of Lake Pukaki from c. 20,000 years ago shows a series of glacial advances, which generated hummocky moraines, represented by the coloured belts alongside the lake. These have been dated in detail using ^{10}Be, tracing the eventual retreat of Pukaki glacier to its surviving modern remnants, the Mueller, Hooker, Tasman and Murchison glaciers.

the Southern Alps, near Lake Ohau and Lake Pukaki. Exceptionally well-preserved moraines of the Otira Glaciation enclose the downstream ends of the glaciated troughs in which the lakes now lie. ^{10}Be dating has shown that there was a succession of ice advances of full glacial extent during the Otira Glaciation, and not just confined to the early and late phases. Glaciological modelling indicates that a climate between about 6°C and 6.5°C cooler, and as much as 25 percent drier, than today is sufficient to grow glaciers to their full extent. This cooling and drying equates to a permanent snowline as much as 1000 m lower than present. Independent evidence from fossil pollen also shows that mean annual temperatures during the Otira Glaciation were up to 6°C cooler than today .

Time and Tide

Sea level is linked to glaciation-interglaciation cycles. During glaciations, so much water became locked up in massive continental ice sheets that formed on parts of Europe and North America that the level of the sea dropped substantially. At the peak of the most recent glaciation, about 20,000 years ago, sea level was at least 120 m lower than it is now. As the vast ice sheets of the Northern Hemisphere melted, sea level rose, stabilising near its present level c. 7000 years ago. The last time the sea was as high as it is now was during the previous interglacial period, c. 125,000 years ago.

The sea-level changes had major effects on the New Zealand landscape. During glaciations, the ocean withdrew to the middle to outer parts of the continental shelf, extending New Zealand's land area by as much as 60 percent. At such times, parts of Cook Strait and Foveaux Strait were dry land, and the three main islands of modern New Zealand formed a continuous landmass [see *Rise and Shine*].

The extended coastline encouraged the accumulation of river sediments, because of the greater distances the rivers had to travel to reach the sea. The extended floodplains enhanced the production of wind-blown silt from dry river channels, some of which was deposited as loess across nearby terraces and gently undulating downland landscapes [see *Dusty Horizons*].

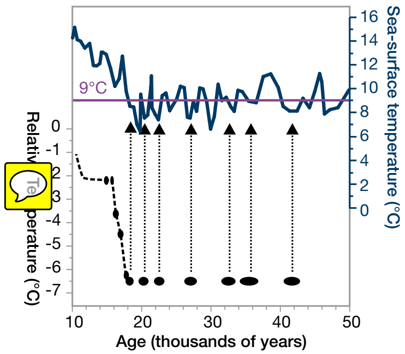
The Big Thaw

The Otira Glaciation was succeeded by a transition to interglacial climate. The glacier chronological record indicates that the temperature rise from glacial conditions occurred rapidly after c. 18,000 years ago, with the glaciers shrinking to about half their size by c. 17,000 years ago. The glacial record indicates a pause in recession by c. 15,000 years ago, locally with glacier advances that culminated c. 13,000 years ago, during a period of time commonly known as the Late Glacial Reversal, when the snowline was as much as 400 m lower than today, and temperatures were between 2-3°C cooler. Similar patterns are seen in fossil pollen, and other records, and in marine deposits in the wider New Zealand region. The Late Glacial Reversal coincides with a wider climate fluctuation event seen in paleoclimate records from Antarctica known as the Antarctic Cold Reversal. Following this brief cool climate episode temperatures then rose to full interglacial conditions, which were attained by the start of the Holocene Epoch, c. 11,700 years ago.

Plants and Animals Respond Too

Beyond those places overrun by glaciers, our picture of the landscape and climate of the Otira Glaciation is drawn from fossil remains and chemical signatures extracted from geological and paleoenvironmental deposits. A key indicator is pollen, which is found in sedimentary deposits both on land and offshore. Other important climatic indicators include fossil wood, leaves and seeds, beetles, and chironomids (non-biting midges), stable isotopes from cave stalagmites [see *Nature's Vaults*], and sedimentary deposits such as loess sheets [see *Dusty Horizons*]. Distinctive tephra layers with well-established ages are an invaluable asset

▼ ~~T~~emperature estimates (relative to today) based on reconstruction of Late Otiran glaciers in the valleys of Lake Ohau, Lake Pukaki, and the Rakaia River on the eastern side of the Southern Alps, are compared with sea-surface temperature indicators from marine sediments southeast of central South Island. The dark blue ellipses represent dated moraine belts, with the width of each ellipse denoting the age uncertainty. When the sea-surface temperature was cooler than c. 9°C (purple line), Southern Alps glaciers advanced to their maximum extent within their ice-age moraine belts. Because ~~atmospheric~~ temperatures decrease steadily with altitude (c. 0.6°C per 100 m), 9°C at sea level corresponds to 0°C at c. 1500 m altitude, which was the approximate snowline elevation during the Otira Glaciation in the eastern Southern Alps.



Leafy Thermometers

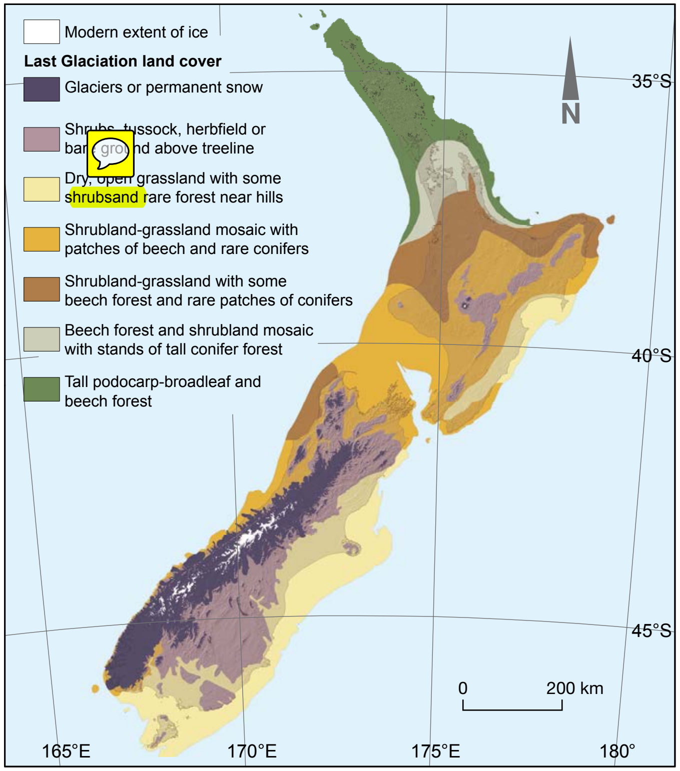
Three generations of palynologists, Neville Moar, Matt McGlone and Janet Wilmshurst, developed an innovative way of measuring past temperature change using fossil pollen. With colleagues, they compiled pollen records from sediments deposited in c. AD 1250 just before the arrival of Polynesian settlers and the ensuing vegetation disturbance, from various sites throughout New Zealand. At each 'pre-deforestation' (pre-human) pollen site, middle to late 20th century climatic measurements were used as an approximation of the pre-deforestation climate. In this way the problem of human impact on the vegetation distribution of today, which has blurred the climate influence, was overcome. Statistical techniques identified mean annual temperature as an important control on pollen distribution, and a 'transfer function' was developed using the relative abundances of different types of pollen to infer the mean annual temperature. This approach can now be applied to the fossil pollen record at any given site to determine how much the climate, notably temperature, has changed through time.

because they provide chronological tie-points that allow sedimentary records to be linked and compared across wide areas. Particularly important is the Kawakawa Tephra, which was erupted from the Taupo volcanic centre and dispersed across much of the New Zealand region c. 25,400 years ago [see *Slumbering Giants; Far-flung Markers*]. Fossils at the position of this tephra in sedimentary deposits give a snapshot of the ecological conditions prevailing across New Zealand at an 'instant' in time during the Otira Glaciation.

The early Otira Glaciation is identified in pollen records as an episode when forest cover was much reduced in western South Island, based on findings from sedimentary records near Okarito and Hokitika. In central North Island, at a location where there was full forest cover in more recent times, early Otiran vegetation comprised a mosaic of shrubland, grassland, and patches of beech forest. In other regions — near-coastal parts of Taranaki and Northland, Hawke's Bay, eastern Otago, and Southland — a lack of good records renders the picture incomplete, largely because wetlands and lakes that previously had been sites of pollen-bearing sediment accumulation were themselves filled in during the early Otira Glaciation by loess sheets or sand dunes, or simply dried out. Overall, the climate appears to have been cool to cold and probably much drier than present, especially to the east. Speleothem records [see *Nature's Vaults*] from western areas indicate cold and comparatively wet conditions at that time.

Sandwiched between the early and late Otira Glaciation was a period of milder climate (equivalent generally to marine oxygen isotope stage 3), characterised by more extensive forest, stronger soil development, and less loess accumulation. Pollen records from on land and offshore locations in northern and eastern North Island show an expansion of conifer-hardwood forest with kauri prominent north of Auckland. Rather than being uniformly moist and mild, there were intervals of several thousand years during which temperatures declined, montane forest gave way to shrubland, and loess accumulated in the east.

As with the glacial evidence, there are better records of vegetation and climate from the late Otira Glaciation. Often referred to globally as the Last Glacial Maximum or LGM, this period of markedly cold and dry climate was nevertheless interrupted by at least two short episodes of somewhat warmer climate. Overall, the LGM has left an indelible mark on much of the New Zealand landscape and helped to shape many of the dramatic landforms we see today. The effects were not just confined to the glaciated areas. For example, the alpine zone descended in altitude to between c. 900 m and 600 m from north to south in the North Island, reaching progressively to even lower levels farther south. Forest cover was limited to the northern third of the North Island and was dominated by beech and podocarp trees, rather than the kauri forests that grow there today. Even though these forests gave way southwards to sub-alpine scrub and grassland, some pockets of forest trees survived in 'refugia', where favourable topography and aspect provided local opportunities for plants to find shelter, warmth, moisture and nutrients. This concept of glacial forest refugia has a flipside in the form of our modern alpine herb communities, which are confined to an ever-shrinking alpine zone in the face of recent global warming. Will the ecological resilience of these now endangered communities, genetically hardened by the recurrent challenges of multiple interglacials, enable them to survive this new threat?



◀ About 20,000 years ago, when the sea was at its lowest level during the late Otira Glaciation, New Zealand's shoreline was at the outer edge of the continental shelf (the -120 m-depth contour).

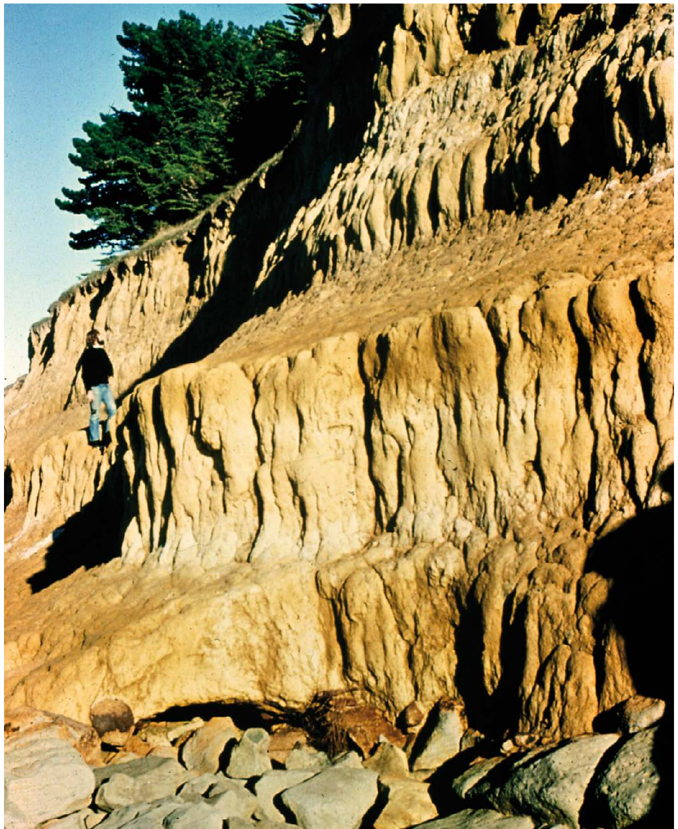
Dusty Horizons

Dust whipped up and deposited by wind forms sheets of loess, which drape over the land. These loess deposits and the soils formed within them yield insights into past climatic and environmental change.

David J Lowe
Philip Tonkin
Julie Palmer
Alan Palmer
~~Kerri Lanigan~~

Loess deposits are layers of wind-blown dust. They form the most widespread on-land cover deposits in Zealandia, and are especially common in eastern, western and southern South Island and southern North Island. Loess deposits greater than one metre thick blanket at least 10 percent of the land surface. The term loess (meaning 'loose') was first applied in the early 19th century in Germany to yellowish wind-blown sediment formed of silt-sized particles 0.002–0.06 mm in diameter. In China, loess is called *Hwang tu* ('yellow earth') and some deposits there are hundreds of metres thick. Thinner deposits occur in North America and southern South America.

Julius von Haast was the first to identify loess deposits in New Zealand, on Banks Peninsula in 1878. In 1889, John Hardcastle confirmed their wind-blown origin and recognised buried soils in the loess deposits of southern Canterbury. Hardcastle argued that the loess "… *accumulated not only slowly, but intermittently, with prolonged periods of pause; and that its growth was dependent upon a set of climatic conditions that no longer prevail in the neighbourhood*". He wrote that during cold glacial times "… *great ice fields and glaciers in the highlands … sent down floods of sludgy water, inundating the lowlands, and creating fields of dust, from which the winds picked up and deposited … a bed of loess*". He inferred that in warm interglacial times the supply of dust diminished and soils formed within the loess deposits. Hardcastle recognised several distinct buried soils within the loess, implying that climate had changed repeatedly in the past. Recent research, however, shows that soils form during, as well as after, episodes of loess deposition.

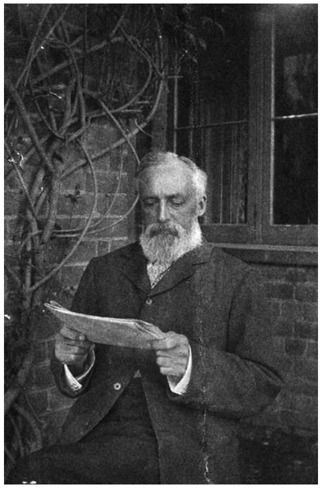


◀ **The Dashing Rocks sequence at Timaru, recognised by John Hardcastle more than 100 years ago, contains four loess sheets. Coastal erosion has formed a stepped cliff face, highlighting the soil features, especially the marked prismatic structures.**

Dust Engines

The major 'dust engines' creating loess deposits in New Zealand are riverbeds. Loess is thickest immediately downwind of rivers, and thins with distance from them. Loess deposition is usually linked to the climatically controlled infilling of valleys and the formation of plains by the build-up of sediment (aggradation). During glacial periods, over tens of thousands of years, large amounts of sediment are supplied to rivers by erosion. The rivers aggrade and widen. The sparsely vegetated flood plains and fans accumulate fine sediments along with coarse gravels. These fines are the source of loess.

Most of the fine material is derived by abrasion and breakdown of rocks as they are transported in rivers, especially during glaciations. Smaller amounts of fines are contributed by glacial grinding and by freeze-thaw processes. The dust engines that deposited the loess were driven by the belt of strong westerly winds that blew during the glacial



Reading the Signs

After time as a school teacher, John Hardcastle (1847–1927) worked at the *Timaru Herald* newspaper for nearly four decades. An amateur ~~geologist~~, his two brilliant papers on loess at Timaru, published in 18~~90~~ and 189~~1~~, were the first to make the connection between loess and glacial climate, many years before such interpretations were made in other countries.

▲ Dust blowing from the exposed bed of the Rakaia River creates a haze in inland Canterbury.

periods. Additional small amounts of dust were blown from Australia to New Zealand by these winds — aeolian dust deposits are ~~found~~ in drill cores from the Tasman Sea and southwestern Pacific Ocean. ~~On land, however, any~~ foreign dust was swamped by the much more voluminous locally derived fines.

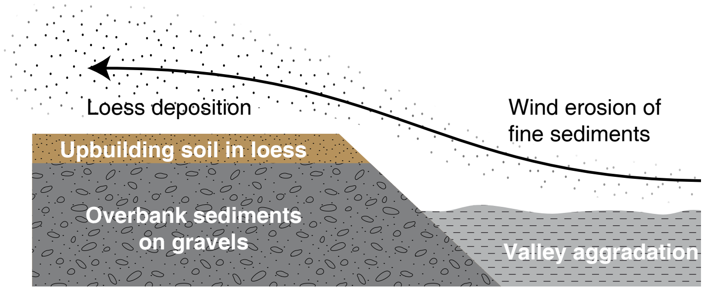
~~Air~~ temperatures during past glacials were c. 6°C colder on average than today, and the Southern Alps were covered by an extensive ice cap. Changed vegetation on land surfaces, especially hillsides and mountain slopes, made them prone to erosion. In places this susceptibility was further exacerbated by ongoing tectonic deformation and by changes in sea level. In central North Island, continuing volcanic activity generated large volumes of volcanic-derived sediment.

A Variety of Sources

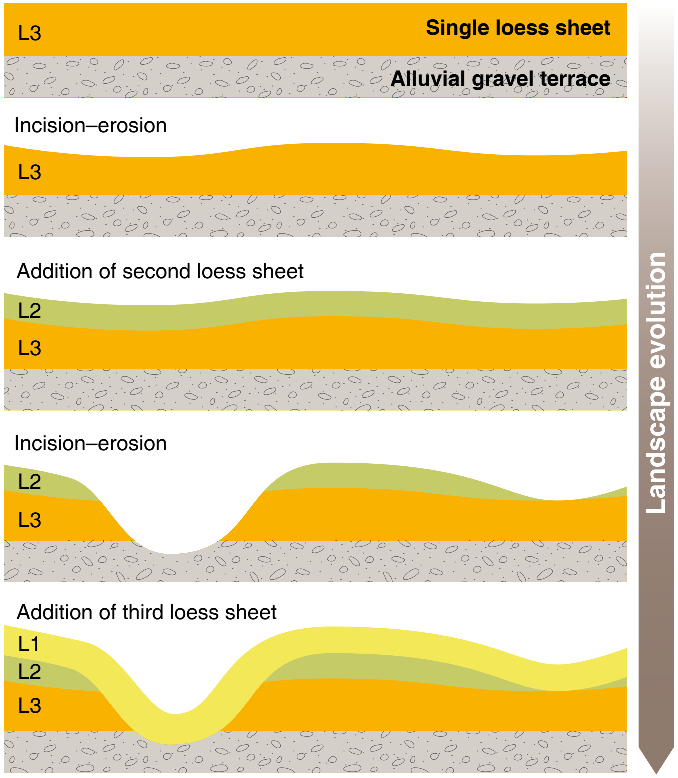
Most New Zealand loess consists of the minerals quartz, feldspar and mica derived from schist and siltstone, which are readily broken down to fine sediment. In central North Island, a major source of loess is the sediment eroded from the andesitic volcanoes of the Taupo Volcanic Zone and Taranaki, as well as andesitic and rhyolitic tephras, which give rise to tephric loess deposits [see *Far-flung Markers*].

In the South Island, loess is derived mainly from aggrading flood plains and fans within and beyond the main mountain ranges. During lowered sea level in glacial times, flood plains extended onto the exposed continental shelf to the east of the South Island and the west of the North Island, providing additional sources of dust. In eastern and southern South Island, where the mean annual rainfall is less than 1200 mm, the thickest loess deposits occur below c. 300 m altitude. For example, in southern Canterbury six loess sheets total 20 m in thickness, and in Southland five loess sheets total 6 m in thickness. In the West Coast region, where mean annual rainfall is greater than 2000 mm, five loess sheets total just 3 m in thickness, draping terraces and moraines. Nevertheless, new research has shown that the loess fluxes, although relatively slow, have effectively retarded the rate at which soils have evolved despite the super-humid environment.

In the Manawatu and Whanganui regions, a set of loess-draped terraces shows the relationship between periods of

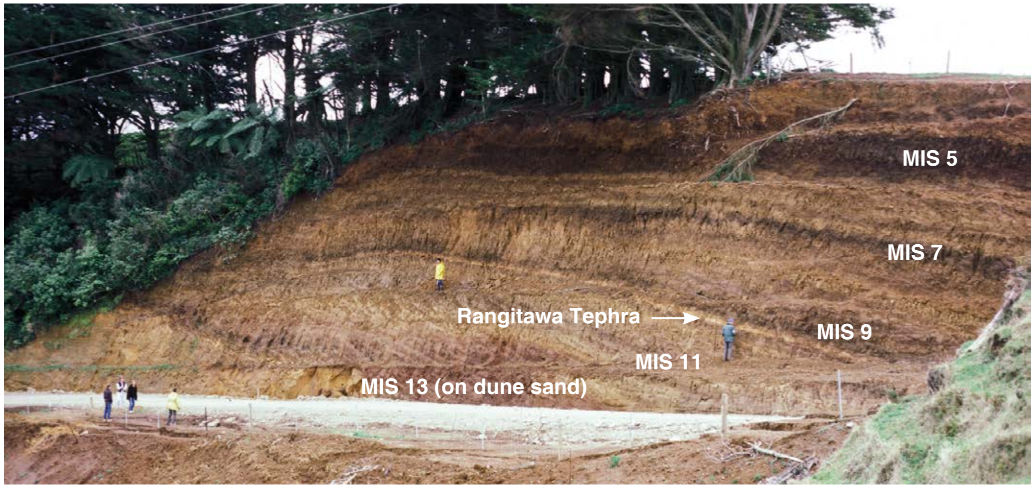


▶ A model for loess deposition shows rivers aggrading during glacial periods, and fine sediment being blown onto nearby terraces to accumulate as loess. The maximum rates of accumulation of loess coincide with major periods of river aggradation.



▲ Evolution of a loess landscape may involve several loess sheets (here labelled L1–L3 from youngest to oldest, in the order they would be encountered during drilling). With each additional loess sheet, ridges grow higher while the valley floors remain at about the same relative level or are lower. The result is a smooth, undulating 'downland' landscape, such as those seen in southern Canterbury, Manawatu and the Whanganui region.

river aggradation and increased loess production. Each loess sheet is named after the aggradational episode from which it was derived. The four youngest loess deposits and associated terraces are Ohakea (sparse cover), Rata (one sheet), Porewa (two sheets), and Marton (three sheets). At Rangitatau East, northwest of Whanganui city, there are 11 loess sheets with a total thickness of 17 m. To the southeast in the Ruamahanga River catchment in the Wairarapa region, where it was drier, there are three sheets with a total thickness of 20 m. In central North Island, c. 3 m of unstratified tephric loess deposits were derived from rhyolitic tephra-fall and ignimbrite deposits, which were eroded during glacial periods to form valley fill and fan deposits, supplemented by glassy dust blown from existing tephra deposits.



▲At Rangitatau East a sequence of 11 loess sheets is inter-layered with tephras, including Rangitawa Tephra. The dark bands represent buried soils formed during interglacial periods—marine oxygen isotope stages (MIS) 5, 7, 9 and 11 [see page 271]—when loess accumulation was minimal or zero.

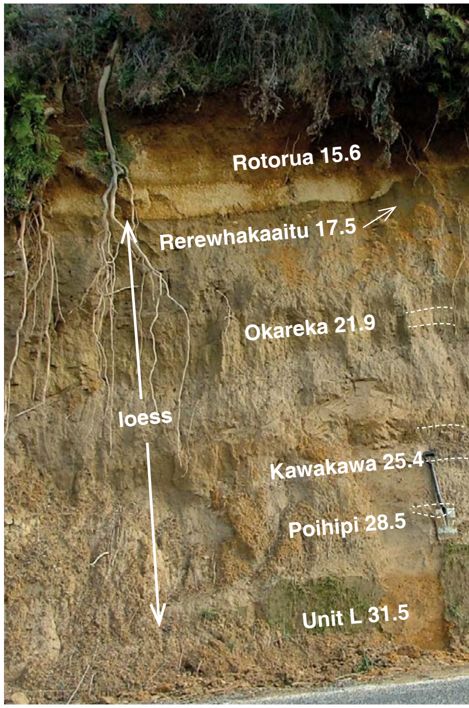
Dating Loess

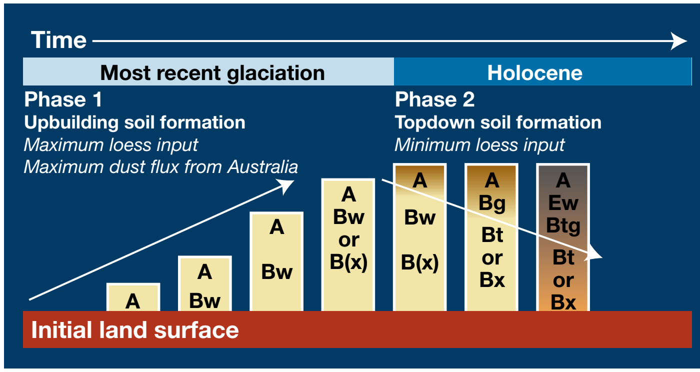
Determining directly the age of loess is not straightforward. Radiocarbon dating is limited in its application to the past c. 60,000 years [see *Cosmic Chronometers*], and dateable organic material is scarce in loess and often contaminated by younger carbon. Luminescence dating [see *Illuminating the Past*] produces inconsistent results for deposits older than c. 200,000 years, but has provided some credible dates for North Island loess deposits of younger age.

The oldest known loess deposits are of Middle Pleistocene age in the Waikato (c. 1.7–1.1 Ma) and Wairarapa regions (c. 1.0–0.9 Ma). The Rangitatau East section comprises the longest, continuous, loess sequence, ranging from c. 500,000 years ago to the present. At Bidwill Hill in the Wairarapa region, the oldest loess was deposited c. 70,000 years ago. In the Mohaka River catchment of central Hawke's Bay and the Waipaoa River catchments of the Gisborne region, the oldest loess was deposited c. 150,000 years ago, and at Tapapa near Tirau in the Waikato region, the basal loess is c. 200,000 years old.

In the North Island, many loess sequences have been correlated using well-dated tephras from the Taupo Volcanic Zone. Several of these tephras have been identified also in South Island loess deposits, including the c. 25,400 year-old Kawakawa Tephra. This tephra occurs as a thin layer in loess sequences to about half way down the eastern and western coasts of the South Island, and beyond that as glass shards incorporated in the loess (cryptotephra). The loess sheet containing Kawakawa Tephra, Ohakea Loess, began forming c. 30,000 years ago, and has been found widely throughout the Manawatu, Whanganui, Wairarapa, Hawke's Bay and Gisborne regions, and as far north as the Waikato and Bay of Plenty regions. Other widely distributed tephras used to correlate loess include Rangitawa Tephra (erupted c. 340,000 years ago), which has been identified as a cryptotephra in Marlborough, Rotoehu Ash (erupted c. 50,000 years ago), Omataroa Tephra (erupted c. 32,500 years ago) and Okareka Tephra (erupted c. 21,900 years ago). Rerewhakaaitu Tephra was erupted c. 17,600 years ago, close to the time when rivers began to cut into their sediments and dust-fall into the ocean east of the North Island decreased sharply. This tephra thus marks the slow-down or cessation of loess deposition over much, but not all of the North Island.

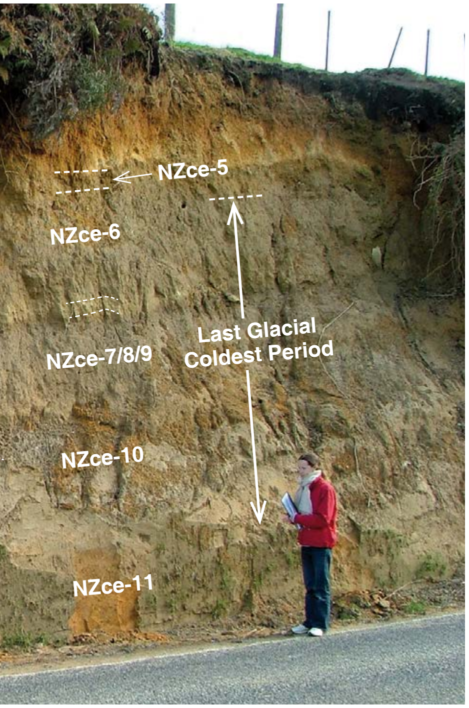
Contrary to general belief, loess deposits formed in New Zealand throughout the past 11,700 years (the Holocene), albeit at a much reduced scale. Deposition took place continuously along the margins of South Island braided rivers such as the Waitaki, Rangitata, Rakaia and Waimakariri in Canterbury, and the Awatere in Marlborough. The Holocene loess sheets are probably variable in age, with the age being dependent on proximity to the source of the loess. In the West Coast region, dust continues to rise today from rivers such as the Haast and Waiho, but generally it is not accumulating fast enough to form recognisable loess deposits. Minor amounts of loess were deposited throughout the Holocene in the North Island, mainly at inland or elevated sites close to sources, such as the Tukituki River in central Hawke's Bay, where dust is accumulating today. The influx of airborne quartz to western North Island dropped sharply to low or zero c. 15,000 years ago, as westerly winds weakened and the continental shelf was inundated by rising sea level.





A model of loess accumulation and soil development illustrates the gradation from upbuilding to topdown soil formation as environmental conditions changed from glacial to interglacial (Holocene) over c. 30,000 years. The letters represent various soil horizon types. Phase 1: Upbuilding soil formation during maximum but slow loess accretion under cold climatic conditions as the land surface gently rises. Phase 2: Topdown soil formation with minimal or no loess accretion during warm climatic conditions, with land elevation essentially constant. The maximum development of subsurface soil horizons occurs when soil formation has a greater impact, in phase 2.

▼This 4-m thick grey loess deposit on Oturoa Road near Ngongataha was deposited in the last glacial coldest period between c. 31,500 and c. 15,600 years ago. Named tephra layers provide ages (in thousands of years ago) for New Zealand climate events events (NZce) 10, 8, and 6, being the coldest periods or stadials.



Variable Rates

The rates at which loess has accumulated have differed from place to place and through time. In general, the fastest rates of accretion were during the cold glacial periods, and especially during marine oxygen isotope stage 2, when rivers aggraded very rapidly. Based on calculations from 18 sites throughout New Zealand, and assuming minimal loss through erosion or dissolution, net accretion rates of loess since the eruption of Kawakawa Tephra c. 25,400 years ago, and prior to the Holocene, have been mostly c. 3–10 mm per century. The fastest rates are 15–25 mm per century where deposition was enhanced by turbulence, and the slowest is less than one millimetre per century. Accretion rates for loess in southern West Coast, where weathering and dissolution probably affected preservation, are 2–7 mm per century, are similar to those for tephric loess in the Waikato, 3–8 mm per century. Holocene loess accumulation rates vary with proximity to rivers, and range from 60 mm per century within 5 m of the flood plain to 3 mm per century 2 km away from it. The average rates of loess accumulation in New Zealand are slow compared with those of China, where loess builds up at c. 20 mm per century, and Europe, where it ranges from 20 to 100 mm per century. The most extreme rates known are at Bignell Hill in Nebraska, USA, where more than 50 m of loess was deposited at up to 1200 mm per century (12 mm per year) between 22,000 and 18,000 years ago.

Soil Formation

As recognised by John Hardcastle, loess deposits commonly consist of multiple sheets, with distinct buried soils formed during phases of very slow or no loess deposition marking the boundaries between them. In some places, the loess–soil sequences represent cold and warm climates, respectively. For example, in the Manawatu and Whanganui regions, cold climatic conditions correspond to maximum loess accumulation and relatively slow soil formation, and warm conditions to relatively fast soil formation and no loess accumulation. Where little loess is accumulating, 'topdown' soil processes alter the underlying material in a downward-moving front, forming distinctive subsoil features. These same features identify buried soils in loess. They include fragipans, very dense, non-cemented, silt-rich (Bx) horizons that commonly form vertical prisms, the edges of which are typically highlighted by greyish zones depleted in iron and manganese. In other sequences, clay-enriched (Bt) horizons form.

During periods when loess is accumulating, topdown soil formation does not stop, but its effects are lessened because any one position in the loess deposit is not exposed to soil processes for long before it is buried too deeply for these processes to be effective. Nonetheless, this 'upbuilding' history leaves the loess deposit with a soil fabric of root traces and worm burrows throughout, inherited from when the loess was part of the ground surface (A) horizon. The burrows and traces are sometimes filled by secondary calcium carbonate. The fabric allows loess to be distinguished from other silty sediments such as siltstone. In an upbuilding phase, soil formation thus occurs simultaneously with slow loess accumulation, forming a 'soil-sediment'. This model of alternate developmental upbuilding and topdown soil forming phases applies widely to loess sequences in the South Island and to most of southern North Island where there has been limited tephra deposition.

Nature’s Vaults

Paul Williams

Caves are nature’s vaults, holding a treasury of information about past environments with much of it contained in stalagmites and stalactites that act like climate recording stations.

▲In the karst topography of the Craigmore Plateau in southern Canterbury, dolines pock the landscape, producing a polygonal pattern of adjoining depressions.

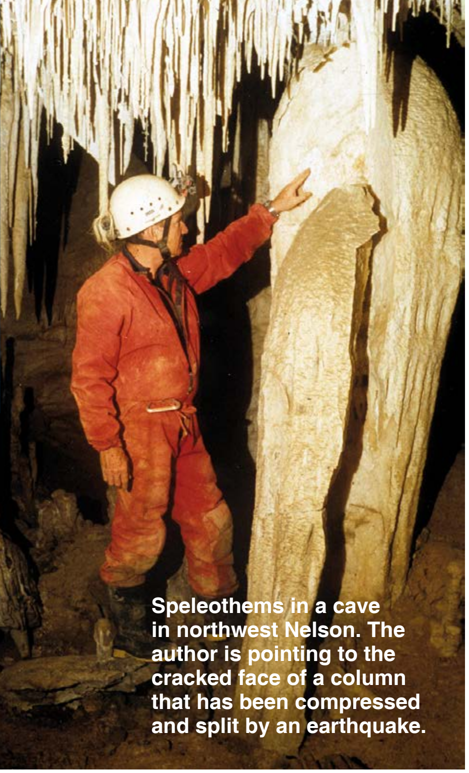
Most cave entrances are gaping black holes — perfect pit-fall traps for unwary animals that eventually get buried by falling debris. Farther into the cave, water drips through cracks in the roof, slowly depositing lime to produce stalactites (growing down) and stalagmites (growing up), which may join to produce columns. Collectively termed speleothems, these objects are composed of crystalline deposits of the mineral calcite ($CaCO_3$) derived from dissolution of overlying calcareous bedrock. New Zealand’s caves, which occur mainly within limestone or its metamorphosed cousin, marble, can be very long and deep, especially in the marble country of northwestern Nelson (for example, Bulmer Cave on Mt Owen, and the Nettlebed/Stormy Pot system on Mt Arthur). These caves were formed because water from rain and snow-melt dissolves the limestone or marble bedrock. On the surface the same process of dissolution gives rise to a curiously pocked and sculpted landscape akin to an over-sized egg box. Numerous sinkholes — dolines, also known locally as tomos — cover the surface, like large bomb craters tens to hundreds of metres across and tens of metres deep. Rock outcrops on ridges between dolines are covered by vertical solution flutes, imparting a sculpted appearance. Such landscapes are known as ‘karst’, after a region in Slovenia and Italy that was first described scientifically in the 19th century.

Fossil Aviaries

In New Zealand’s caves, the bones of extinct birds, such as the moa and Haast’s eagle, and the remains of lizards, snails and insects, can tell us much about the ecology of the region around the cave before the advent of humans. To date, there are fossil remains from cave sediments extending back to ~~the~~ beginning of the most recent glaciation 30,000-18,000 years ago [see *Feeling the Cold*]. Some species are found in cave deposits only up to a certain date, after which their absence suggests at least local extinction. Other species suddenly appear, indicating the date of their arrival in New Zealand — typically birds that have been carried by storms across the Tasman Sea from Australia.

New Zealand’s deepest and longest caves (selection)

Cave name	Location	Depth (m)	Length (m)
Nettlebed/Stormy Pot system	Mt Arthur	1174	38,252
Ellis Basin System	Mt Arthur	1026	33,400
Bulmer Cavern	Mt Owen	755	67,233
Bohemia Cave	Mt Owen	713	11,230
Incognito/Falcon System	Mt Arthur	540	4,278
Greenlink-Middle Earth	Takaka Hill	389	32,005



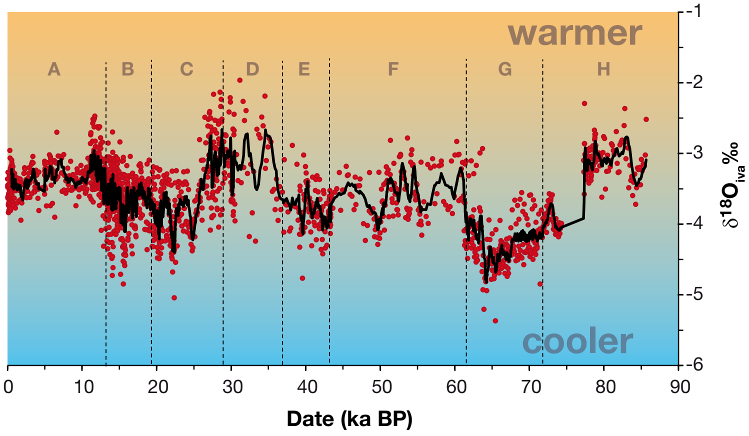
Speleothems in a cave in northwest Nelson. The author is pointing to the cracked face of a column that has been compressed and split by an earthquake.

Geological Thermometers

Caves are excellent sites from which to obtain information about past environments, because their deep interiors are sheltered and have extremely stable climates. Internal cave temperatures are close to the ~~average~~ annual external air temperature, but vary by only about 1°C or less through the year. The dampness of the cave interior does not vary much either, with relative humidity always close to 100 percent. However, when the external climate gradually changes (as it has since the Last Glacial Maximum), the average shift in external air temperature is gradually transmitted through the rock and the temperature of the cave interior adjusts in sympathy. Percolating water passing through the cave roof acquires the temperature of the bedrock, and as it drips from the cave ceiling and deposits another layer on speleothem surfaces, the newly deposited calcite carries a temperature signal in its crystal lattice — in effect, speleothems are recording thermometers.

The temperature signal is carried by oxygen within the water molecule (H_2O). Oxygen has two main isotopes, ^{16}O and ^{18}O, and H_2O is actually $H_2{}^{16}O$ and $H_2{}^{18}O$, with the former by far the more common. Surface water and groundwater contain variable amounts of carbonic acid (H_2CO_3), formed as a consequence of rain extracting carbon dioxide (CO_2) from the atmosphere and soil as it travels ($H_2O+CO_2=H_2CO_3$). When this weak acid encounters bedrock, it dissolves the limestone or marble ($CaCO_3$) by forming the much more soluble calcium bicarbonate $Ca(HCO_3)_2$, which becomes highly concentrated in the water that drips through the ceiling of the cave. Because the cave air has a much lower percentage of CO_2 than the soil air through which the water has passed, some of the CO_2 comes out of solution (like bubbles escaping when beer is uncapped) and this forces the deposition of crystals of calcite. The oxygen in the calcite is composed of both ^{16}O and ^{18}O, but the proportion of these isotopes depends on the temperature at which calcite deposition occurs [see also page 266]. Thus, if a stalagmite grows for thousands of years (as is commonly the case) and the temperature of the cave changes during that time, the ratio ^{16}O to ^{18}O (expressed as $\delta^{18}O$) within the calcite will also change.

◀A stalagmite from Waitomo Caves cut along its long axis to show its internal growth structure. The blue colour is caused by luminescence emitted by the speleothem when photographed under ultraviolet light; the darker bands contain humic substances deposited under relatively cool climatic conditions.



▲This five point running mean of $\delta^{18}O$ over the past 85,000 years for caves in the northwest coastal region of the South Island combines records from 11 stalagmites from caves below 300 m elevation. Sections A to H identify when major temperature changes occurred, often rapidly over short time intervals. C and G were times when there was a major expansion of glaciers in the Southern Alps, whereas A, D and F were relatively warm intervals.

The key issue of identifying the date when a change in temperature occurred is, fortunately, easily resolved. Traces of uranium transported in the percolating water and precipitated along with the calcite in speleothems can be dated by utilising short-lived stages in the uranium–lead decay scheme [see page 59, and *Hot Topics*]. Since a stalagmite grows upwards, dating it from the middle near the base will indicate when it first started to grow. Sub-samples taken at intervals will yield progressively younger dates towards the top. If oxygen isotopes are also measured on the same samples, a graph of temperature change with time can be constructed. Such a graph reveals a very important feature of the natural environment — the amplitude and rate of temperature change over the time period measured. Although this feature tells us when in the past it was warmer and when it was cooler, we still cannot be very precise about exactly how many degrees it was cooler or warmer. This uncertainty arises because $\delta^{18}O$ is also influenced by variations in the amount of rainfall — so $\delta^{18}O$ is not an exact thermometer. Calcite thus carries two environmental messages that can be difficult to unravel although, in New Zealand, the temperature signal is usually dominant. Speleothems, therefore, contain a high-quality and important record of climate change measurable over many thousands of years. These paleoclimate records help give perspective to the measured global warming experienced over the past century.

Cold Comfort

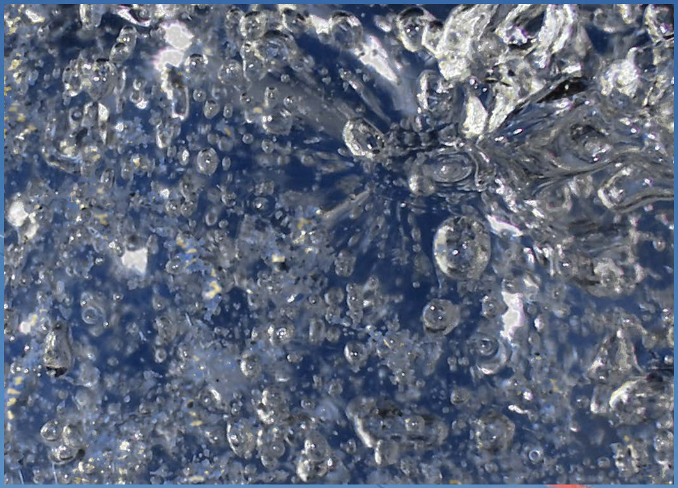
Nancy Bertler
Uwe Morgenstern

Recovered from ancient depths of the polar ice sheets, ice cores provide the most direct and highly resolved records of atmospheric signals over the past one million years.

As snowflakes gently precipitate from the atmosphere, they capture in their icy essence a wealth of information on climate's reign over the planet. As this snow accumulates over thousands of years in giant ice sheets, a spectacular record of the dynamic climate history on Earth is preserved. The testimony of these frozen witnesses has revolutionised our understanding of the temperament of the climate — the forces driving it, its switches and modes, and its strong propensity for change.

Bursting Bubbles

Advances in technology have enabled geoscientists to drill nearly 4 km to the base of the polar ice sheets, recovering ice cores with a climate memory back to Pleistocene time (c. 1 Ma). Annual layers within these cores are analysed and their history unthawed, revealing a story of changing temperature, humidity, precipitation, atmospheric circulation, storminess, and sea ice extent. The uniqueness of ice cores, however, lies within tiny air bubbles that are embedded amongst the ice crystals. These pockets of ancient atmospheres permit direct measurement of greenhouse gases such as carbon dioxide and methane.

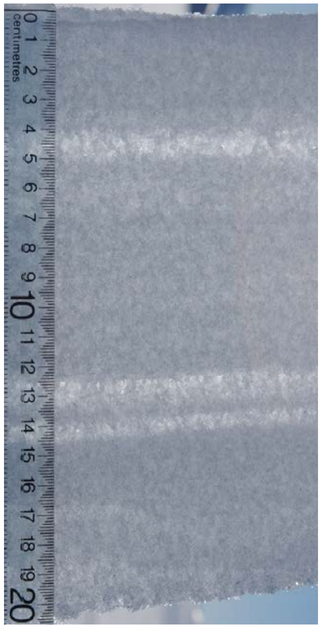


▲ Bubbles in ancient ice preserve samples of the atmosphere at the time the ice accumulated.

▼ Ice core drilling in Antarctica is carried out on the Ross Ice Shelf near Mt Erebus.

▲ **Analysis of tritium [see page 63] in ice cores extracted from the Tasman Glacier in the central Southern Alps has shown that the surface ice is only c. 100 years old, and that it moves down-valley at c. 200 m per year. The deeper ice inside the glacier is expected to be older, so climate records spanning several hundred years may be extracted.**

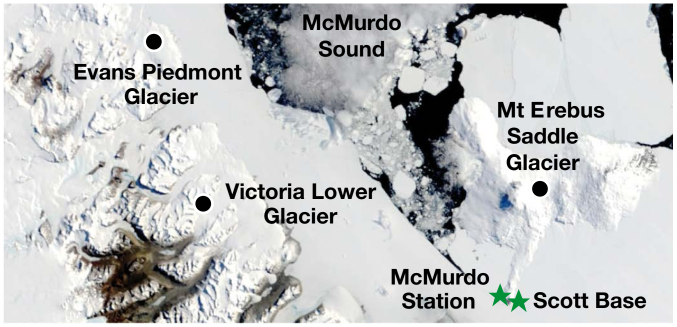
▼ **Seasonal layers in snow from Evans Piedmont Glacier, Antarctica, show darker winter layers, in strong contrast to paler summer layers.**



The ice core records reveal a close relationship between global air temperature and greenhouse gas concentrations over hundreds of thousands of years. They show that present atmospheric carbon dioxide levels are 40 percent higher now than in prehistoric times recorded in the ice, having increased by almost 120 parts per million since the industrial revolution. Changes in past greenhouse gas concentrations were accompanied by variations in global temperature, reflecting fundamental changes in environmental conditions. During glaciations, when colossal ice sheets covered most of North America, Europe and Asia, carbon dioxide concentrations were 80 parts per million lower, and global temperatures were at least 6°C cooler than today.

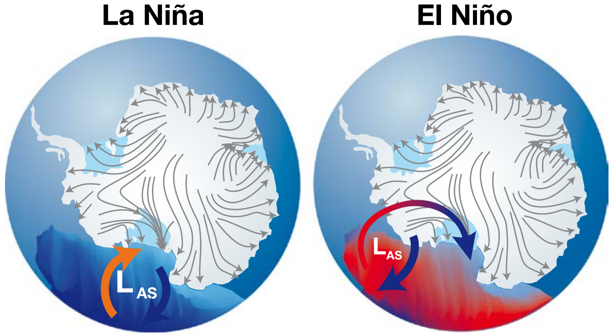
The Intergovernmental Panel on Climate Change in 2014 noted that atmospheric carbon dioxide concentrations will continue to rise due to the burning of fossil fuels (hydrocarbons) and predicted that, in response, global mean ~~surface~~ temperatures are likely to warm by 2.0-4.8°C by the end of the 21st century. However, it is not yet possible to predict smaller-scale, regional climate change with any accuracy, particularly for the Southern Hemisphere where available records are sparse.

A New Zealand-led ice coring programme is using ice cores from the Antarctic margin and from New Zealand to supplement the meagre record of long-term climate observations in the Southern Hemisphere. Such records help to improve our understanding of regional patterns of climate behaviour, leading to more realistic regional climate models, which are intended to assist New Zealand to adapt to a future warming world.



▲ **A satellite image of South Victoria Land shows the location of important ice core sampling sites.**

▼ **ENSO influences Antarctica and the Amundsen Sea Low (L_{AS}). Airflow directions are indicated by arrows, and relative ~~seawater~~ temperatures by red (warm) and blue (cold).**



How the Tropics Cool Antarctica

Since the early 1980s, New Zealand's Scott Base and the neighbouring US base at McMurdo Sound have experienced atmospheric cooling. Snow samples and ice cores from glaciers in the vicinity of these bases, such as Victoria Lower Glacier, Evans Piedmont Glacier and Mt Erebus Saddle Glacier, have unravelled the likely cause for this cooling — long-term change in the El Niño–La Niña cycle in the tropics of the Pacific Ocean.

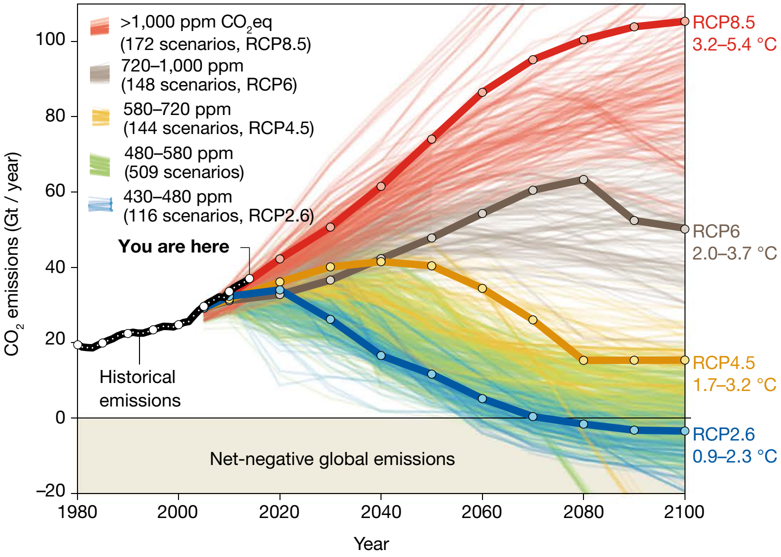
The El Niño–Southern Oscillation (ENSO) is a 3–4 year pattern of oscillating up-welling of warm El Niño and cold La Niña deep-ocean waters off the western coast of South America. This oscillation has profound effects on global climate and on New Zealand. In Antarctica the ENSO influence is via ocean currents and the 'jet stream', a strong westerly high-altitude wind. This wind influences the position of Antarctica's Amundsen Sea Low, a semi-permanent low-pressure system. During La Niña times, the low is centred south of New Zealand in the Ross Sea, Antarctica. Cooler ~~ocean~~ temperatures in the tropics propagate to the Ross Sea, cooling the waters there by about 0.5°C, while the Amundsen Sea Low transports relatively warm air from the Southern Ocean into the Ross Sea. During El Niño events the waters of the Ross Sea increase in temperature by c. 0.5°C, but the Amundsen Sea Low can shift to as much as 1400 km away from the Ross Sea. In its El Niño position, the Amundsen Sea Low promotes airflow from the cold interior of West Antarctica, which flows down to the Ross Ice Shelf and sweeps across Scott Base and McMurdo Station. This air is up to 15°C colder than the airflow of the Southern Ocean during La Niña events, and it masks the warmer ocean temperatures, thus bringing cold conditions to Scott Base during ENSO warm events. Since 1977, more and stronger El Niño events have occurred than previously, requiring Scott Base staff and scientists to wrap up warmly to battle the tropical cold spell in Antarctica.

Responding to Climate Change

The climate has been changing in part because of our greenhouse gas emissions, and the effects we have triggered will last thousands of years.

Brad Field
Martin Manning

Global warming will bring many environmental changes, including more-frequent extreme weather events, changes to local climate, sea-level rise, and oceanic warming and acidification. It is already causing species migration, changes in food and water resources, human conflict, and damage to infrastructure. Global warming is also triggering unprecedented research on climate and ocean systems, particularly on ways to mitigate change by reducing emissions, and adaptation to its effects.



◀ **Global CO_2 emissions and future representative combustion pathway (RCP) have been modelled through to the year 2100 by researchers contributing to the International Panel on Climate Change (IPPC) 5th Assessment Report (2014). Over 1000 scenarios have been modelled, which suggest emissions are on track for a likely 3.2-5.4°C increase above pre-industrial levels. Note that warming effects will last well beyond 2100.**

Reducing Emissions

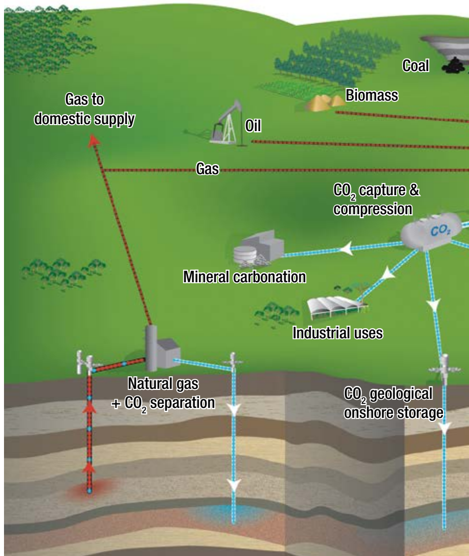
The predominant greenhouse gas, carbon dioxide (CO_2), enters the atmosphere through power generation, transportation, and industry, supplementing natural contributions from volcanoes, hydrothermal vents, and natural seeps. The concentration of CO_2 in the atmosphere is now higher than it has been at any time over the past several million years [see *Unlocking the Icehouse*]. This is also true for other greenhouse gases, for example, methane, produced by agriculture and industry. Governments have agreed in principle to reduce human-generated (anthropogenic) emissions to help keep global warming to 2°C or less. However, current trends would lead to a 3-5°C increase by 2100, with catastrophic effects on many ecosystems. It is unlikely that our systems for food and water management can adapt quickly enough to avoid major implications for humanity.

The fastest and simplest way to reduce emissions is by using less energy generated from fossil fuels. Fuel-switching, such as burning natural gas instead of coal, can also reduce emissions by up to 50 percent — the gradual change to burning gas at Huntly Power Station has helped New Zealand avoid emitting millions of tonnes of CO_2 annually. Transport emissions can be cut by using fuel-efficient and hybrid cars, and greater use of public transport. New Zealand could also reduce its agricultural emissions by using new enzymes and selective breeding of livestock and grasses. Cement, steel, and aluminium manufacture, however, have emissions that are harder to avoid — for these industries, and for hydrocarbon-based power stations, CO_2 can be captured and either used or stored.

Sea-level Rise

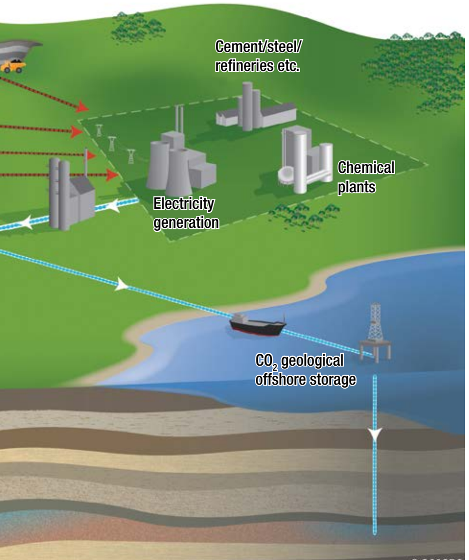
Relative changes in sea level result from a combination of thermal expansion of warming oceans, glacier and ice-sheet loss, regional tectonic uplift or subsidence, and local fault movements, and these vary around the New Zealand coastline [see page 144]. Over the next 100 years, for example, parts of the Wellington region can expect about 1 m of sea-level rise from global effects, plus up to 3 m of instantaneous sea-level rise if the Wellington Fault ruptures.

Global sea-level has risen by only about 0.2 m during the lifetime of our elderly population and this will have been barely noticeable to them. However, today's children will likely live to witness a rise of perhaps a metre, which will be much more noticeable. 'Nuisance flooding' is already becoming more common at high tides on low-lying land. When sea level rises, beaches starved of sand will tend to move inland — if they cannot because of sea walls, the sand migrate offshore. Some coastal recreation reserves could be adapted to allow beaches to migrate landward, thus enabling



Carbon Capture and Storage (CCS)

Carbon dioxide from burning fossil fuels and industry can be captured and pumped underground into rocks over 800 m deep at approved storage sites to prevent it from reaching the atmosphere. The CO_2 enters pore spaces in the rock that are usually occupied by salty water, oil, or gas — CCS is effectively the reverse of their extraction. Once underground, some of the CO_2 becomes permanently trapped, some dissolves in the salt water, and some forms new minerals. The largest storage project globally is at Gorgon in northwestern Australia, and the largest capture project from a coal-fired power station is at Boundary Dam in Canada. Capture processes (sequestration) can also remove noxious gases such as SO_2 and particulate pollutants. New Zealand captures CO_2 from Kapuni natural gas but currently has no underground CO_2 storage facilities or plans to do this.



▲The scale magnitude of a one metre rise in sea level, compared to the 0.2 m witnessed by this elderly person is illustrated at St Heliers Bay beach, Auckland.

our sandy beaches to be preserved in some localities [see *Living on the Edge*]. In places where there is increased supply of sand, for example by longshore drift, beaches could widen.

As sea level rises, the freshwater-saltwater interface in some unconfined coastal aquifers will likely move landward, making some coastal groundwaters brackish. In addition, a higher sea level can raise groundwater levels on low-lying coastal land and make flooding much more extensive during high rainfall. This increase in the water content of coastal sediments can also increase the risk of local damage caused by liquefaction during earthquakes. So far, few areas of New Zealand have been studied in enough detail to predict these effects and to define adaptation strategies.

Changes to Weather Patterns

Estimates of global temperature rise are annual averages and do not imply uniform change. Even for the New Zealand region, where temperature rises of 2-4°C over the next 100 years are likely, these average figures do not convey probable increased seasonal swings, and the effects will vary geographically too, with latitude and topography.

Climate models indicate that higher rainfall will occur, particularly on the western side of New Zealand, because warmer air holds more water vapour. ~~Also~~ drier conditions are expected on the eastern side and these would increase the frequency and duration of droughts, which can have significant implications for the dairy component of our economy and the capacity of dams in the South Island to produce hydroelectricity. However, parts of New Zealand might adapt quite well to changes in climate, and new forms of deep geothermal energy could offset any reduced production by other renewable methods.

Extreme Weather

Temperature changes in the atmosphere are altering wind strength and moisture content. Climate belts are moving towards the poles, with cyclones expected to both strengthen and track further south from the tropics. These will likely impact the northern North Island, with consequences for erosion, building codes, lowland flooding, and storm-surge events. New Zealand's soft, young rocks have been identified as highly vulnerable to landslides triggered by heavy rainfall.

Some communities have experienced storm surge, when seawater driven by wind surges inland along storm-battered coasts. Both the frequency and intensity of storms are increasing because of the increasing amount of latent energy in the atmosphere, and storm-surge magnitude is amplified many times when levels rise. Extreme wave heights in the New Zealand region are also increasing, some ten times faster than mean sea-level rise. We can therefore expect increases in the frequency and extent of flooding for coastal areas, as these become affected by raised groundwater levels and sea-level rise. Coastal communities should be evaluating these multiple effects of global warming on their properties and infrastructure so that they are prepared — the next few decades will provide valuable lead-in time.

Extreme weather events such as these are expected to be stronger and more frequent but, armed with this knowledge, we can choose to plan accordingly to reduce loss of life, property, and export earnings. Everyone should be aware of their community's plans to adapt to the effects of climate and environmental change, and plan accordingly.

▼Increased storm surge is having a marked effect on the southern Wellington coastline.