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TOWARDS A MODEL OF THE CENOZOIC TECTONIC DEVELOPMENT OF NEW ZEALAND

A thesis  
submitted in fulfilment  
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by

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## ABSTRACT

New Zealand has a regionally complex and diverse Cenozoic geological record. However, few attempts have been made so far to formulate a model of the Cenozoic tectonic development of New Zealand, which reconciles this regional complexity and diversity. The objective of this thesis is to work towards such a model. This has involved the identification and resolution of five critical and interrelated problems: (1) The age of inception of the New Zealand sector of the Australia-Pacific plate boundary. (2) The tectonic setting during the Paleogene. (3) The nature and location, north of the Alpine Fault proper, of the relative plate motion which is evident as dextral fault displacement on the Alpine Fault. (4) The total amount of Cenozoic horizontal displacement through New Zealand. (5) The Neogene and Quaternary extent and geometry of the subducted Pacific Plate beneath northern New Zealand. The proposed solutions to these problems are as follows: (1) The Australia-Pacific plate boundary formed during the early Miocene, about 23 My B.P. (2) A continental rift system developed through western New Zealand during the Paleogene. (3) Northeast of the Alpine Fault the relative plate motion was expressed as a combination of brittle and ductile shearing that formed a recurved arc. (4) There has been a total of 500 km of horizontal displacement through New Zealand. (5) The subducting slab of Pacific Ocean lithosphere progressively increased its extent to the southwest beneath northern New Zealand and concomitantly increased its dip.

Based on these solutions, it is proposed that the Cenozoic geological development of New Zealand may be modelled as a tectonic succession, involving the oblique dislocation and tectonic overprinting of a Paleogene north-south trending continental rift system through western New Zealand, by a Neogene-Quaternary transform

to obliquely convergent plate boundary. In this context most of the regional complexity and diversity arises for the following reasons:

- (1) The rift system developed as two independent segments, a North Island segment and a South Island segment, and each in different ways.
- (2) Rifting continued along some parts of the rift system after the transform plate boundary had started to dislocate the South Island rift segment in the early Miocene. Adjacent to the Alpine Fault in central Westland, rifting ceased immediately following inception of the plate boundary. However, the effects of the change in tectonic regime were recorded later and to a lesser degree in the rift system at localities further away from the Alpine Fault.
- (3) While the relative plate motion was accommodated on a continent-continent transform fault in the South Island, ocean-continent convergence progressively emplaced a slab of Pacific Ocean lithosphere beneath the North Island. The shallow dip of this slab beneath eastern North Island is responsible for a portion of the compression which dominates the Neogene and Quaternary record there. In northern and western North Island, the emplacement of the slab and changes in its geometry are responsible for the tectonic overprinting of the western rift system; the southwestward direction of slab emplacement accounts for the north to south overprinting of the North Island segment of the former rift system.
- (4) A major contributor to the regional complexity of the Cenozoic geological record is the nature of the basement. Differences in the competence of the Tuhua Orogen (late Precambrian-early Paleozoic) versus the Rangitata Orogen (late Paleozoic-Mesozoic) caused the relative plate motion to be expressed as Alpine Fault movement in the South Island but as the formation of a mega brittle-ductile shear zone in Marlborough and eastern North Island.

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## INTRODUCTION

New Zealand is geologically unusual, perhaps unique, in the extent and thickness of Cenozoic marine strata which are now exposed onland. This feature alone is indicative of profound and geologically recent vertical tectonic movements; this is emphasised by the evidence that much of this sediment accumulated at continental slope depths and formed successions 2-3 km, or more, thick. These vertical crustal movements are also spectacularly expressed in another way, as the Southern Alps, where basement commonly occurs over 3000 m above sea level. Biostratigraphic dating of the preserved Cenozoic marine cover rocks in the North and South Islands, and K-Ar dating of the Alpine Schists in the Southern Alps, indicate that the vertical movements responsible for much of the present landscape of New Zealand have occurred since the Oligocene, and largely since the Miocene.

The present outline of New Zealand and its geomorphology are due also to horizontal movements - in fact, it can be argued that these movements are of primary importance and that the later vertical movements are a consequence of the lateral displacements. Both the age and amount of horizontal movement is disputed; a popular view is that the movement is wholly of late Cenozoic age and involves 1000 km, of which 480 km is expressed as fault displacement on the Alpine Fault and the remainder as drag forming the S-shaped recurved arc in the basement structure (Wellman, 1975; Hunt, 1978). Alternatively, some consider this lateral displacement and bending to be chiefly a Cretaceous feature, although some late Cenozoic displacement is accepted (e.g. Suggate, 1963, 1978; Grindley, 1974).

That there has been tremendous tectonic activity within New Zealand during the Cenozoic was recognised from the early days of geological exploration, and earth movements associated with historic earthquakes reinforced this view. In Marlborough, Cotton (1916) inferred from such movements a "Kaikoura orogenic period". Since then they have been widely known as the Kaikoura Orogeny. Suggate (1978) redefined the Kaikoura Orogeny as those movements, whether continuing or completed, which have led, without significant known reversal, to the structural relations between Cenozoic and pre-Cenozoic rocks as found today. It is not my intention to critically examine the merits or otherwise of this definition; I am more interested in the nature, timing and origin of the deformation. However, it is noteworthy that in scientific articles where the concept of a Kaikoura Orogeny has been applied or discussed, the post-depositional, and thus post-Oligocene, deformation has been highlighted. Consequently, the importance or even occurrence of Paleogene tectonics has often been disregarded or diminished in importance, and the notion of tectonic quiescence emphasised, if only by implication. For example, in the two volumes of "The Geology of New Zealand" (Suggate et al., 1978), the nature and pattern of Neogene and Quaternary tectonics is discussed in Chapter 10 "The Kaikoura Orogeny," but there is no comparable discussion of Paleogene tectonics. In fact there were major vertical crustal movements during the Paleogene, and these movements permitted and facilitated the accumulation of cover rocks - the very materials subsequently uplifted and deformed during the "Kaikoura Orogeny".

To more fully understand the place of the Kaikoura Orogeny movements (as defined by Suggate, 1978) in the context of the Cenozoic tectonic development of New Zealand, it is essential to understand the tectonic setting that prevailed before the early Miocene imposition of the Australia-Pacific plate boundary through New Zealand - the probable cause of the Kaikoura Orogeny, as discussed further in this thesis. This understanding is necessary as the development of the obliquely convergent plate boundary reactivated pre-existing structures, and because the preceding tectonic setting persisted into the late Cenozoic in some regions long after the plate boundary had developed elsewhere. A wider view of the Cenozoic tectonic development of New Zealand will therefore incorporate the spatial and temporal patterns of sedimentation, volcanism and structure both preceding and accompanying the changes in tectonic setting. Moreover, this approach allows an internationalisation of the geology, by expanding it from the level of an understanding of the late Cenozoic geologic development of New Zealand, to a New Zealand example of, in this instance, the tectonic overprinting of a Paleogene continental rift system by an obliquely convergent plate boundary. While there have been major advances during the last decade in our understanding of the characteristics and kinematics of passive, active and transform margins, the next, or perhaps current, frontier, is in documenting, comparing and understanding the consequences of one type of margin tectonically overprinting another. Continents are an integration of the effects of successive tectonic regimes, and this is nowhere more obvious than in New Zealand, which has sustained at least three such tectonic cycles. A central objective of this thesis therefore, is to work towards an understanding of the last of these cycles, by

addressing critical problem areas in the interpretation of New Zealand's Cenozoic geology, and then, to develop a model of the Cenozoic tectonic development of New Zealand.

At this point it is pertinent to note that New Zealand has three major advantages over most other parts of the globe as a site for attempts to model a tectonic succession.

(1) The geological time scales (mainly biostratigraphic) are sufficiently refined to permit temporal resolution of spatial differences in the tectonic development or response to overprinting. On average, four biostratigraphic stages are identified for each of the six major epochs (excluding the Holocene) of the Cenozoic. Importantly, these are defined on the basis of microfossil zonation and thus permit subdivision of the often thick deep-water mud-dominated successions. The geological time scale that compares the New Zealand divisions with the international divisions (Stevens, 1980) is reproduced in Appendix I. Because of the understandable unfamiliarity of overseas geologists with our local New Zealand stages, every attempt is made in this thesis to use an equivalent epoch name in applying or discussing ages. It should, however, be appreciated that where otherwise not stated, the ages are based on biostratigraphy.

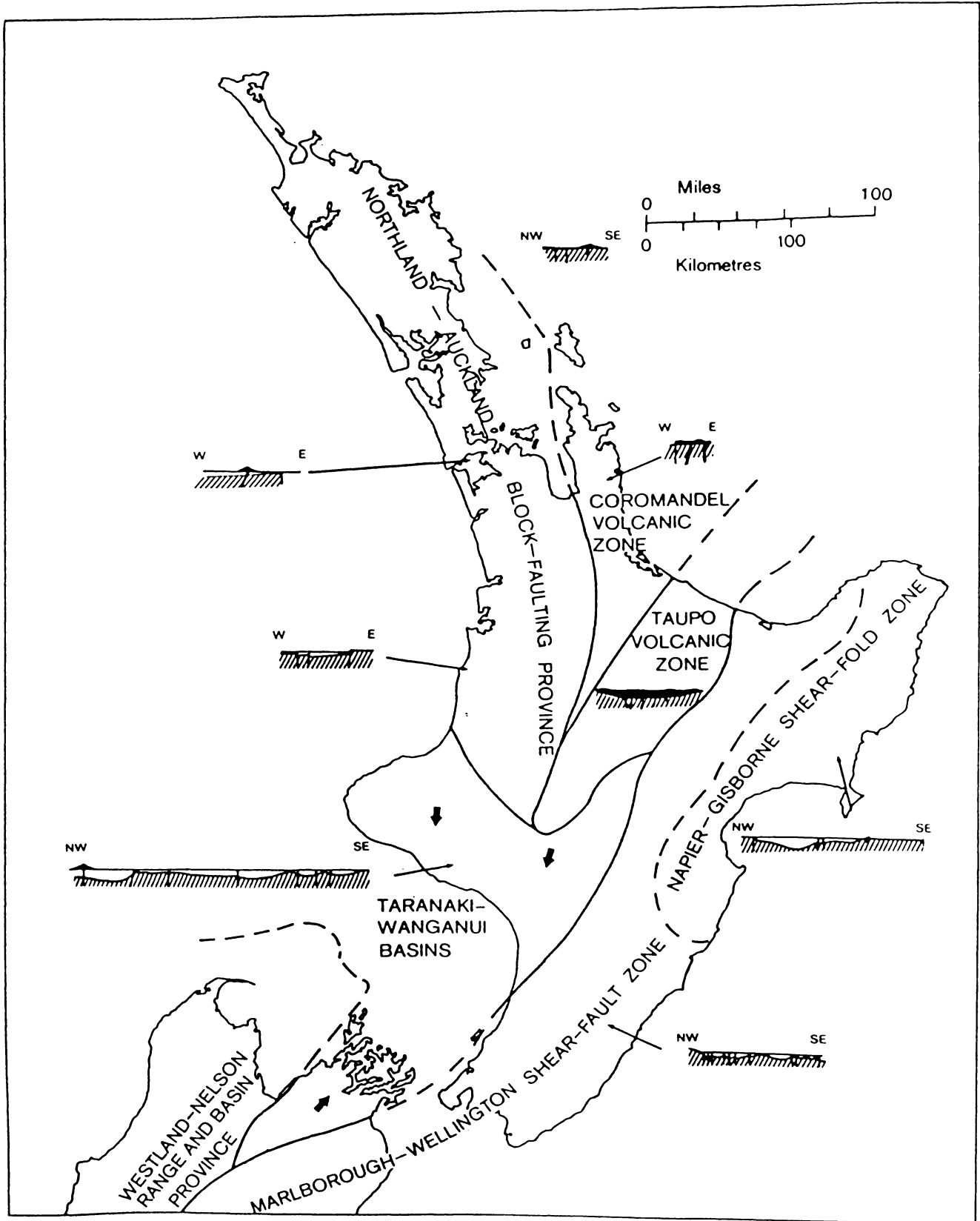
(2) The tectonic succession has been sufficiently recent and rapid that a useful balance exists between the amount of preservation of the sedimentary and volcanic record of events, and the amount of removal through erosion which has exposed these sequences and permitted their investigation.

(3) Because the age of the ocean crust surrounding the New Zealand subcontinent spans the ages of the last (Cenozoic) tectonic succession, it is possible to integrate the onshore and offshore geology. This is important as the age structure of the ocean crust constrains the ages, amounts, rates and directions of plate motion which caused the tectonic succession. California is another region where these three advantages also apply and have been exploited (e.g. Dickinson and Snyder, 1979; Howell et al., 1980).

Figure 1 illustrates a subdivision of New Zealand into the major zones of deformation during the late Cenozoic. The map is given chiefly to show the number and extent of different structural or tectonic domains that can be identified in New Zealand. Since these different domains developed concurrently, one may postulate that there is an underlying order to the complexity and that it may be simply explained. The application of the concept of plate tectonics has been found elsewhere (e.g. California) to be a powerful means of unifying and explaining geologic complexities, and I have applied this concept to New Zealand in this thesis.

#### Previous applications of Plate Tectonics to New Zealand

The concept of plate tectonics has previously been applied to New Zealand to explain several aspects of the regional Cenozoic geology. Hatherton (1969, 1970a, b) was the first to do so, and importantly, he identified the major elements of an active margin setting in northern New Zealand and southwestern South Island. The active volcanic arc in the North Island (White Island - Mt Egmont) was one of the circum-



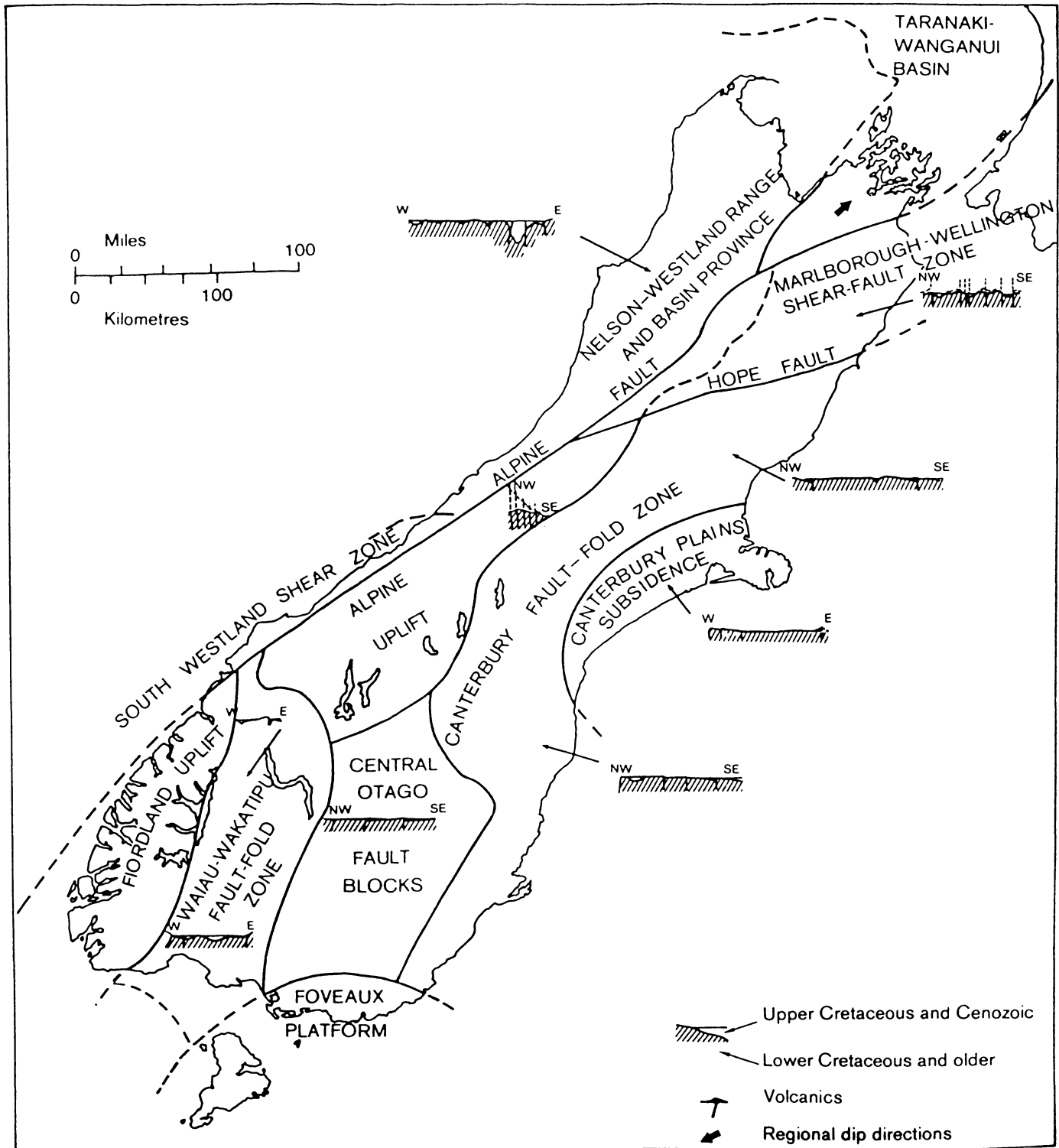


Figure 1: Major zones of late Cenozoic deformation. After Suggate (1978: Fig. 10.2).

Pacific calc-alkaline arcs from which Dickinson and Hatherton (1967) developed the well known andesite  $K_2O-h$  relationship. In 1971 Christoffel published a perceptive article showing how the 480 km of Alpine Fault displacement could be accounted for in the last 10 million years by the dextral rotation of the Pacific Plate relative to the Australia Plate about a finite pole to the south of New Zealand. This was the first recognition that the onshore and offshore geology could be reconciled. Subsequently papers, on a similar theme but mainly dealing with the development of the plate boundary to the south of the South Island, appeared by Christoffel and van der Lingen (1972), Hayes and Talwani (1972) and Griffiths and Varne, (1972). In 1973 Wellman initiated the idea of microplates in the New Zealand setting, a theme he has recently developed further (Wellman, 1983), and importantly, showed that the average rate of displacement predicted from the seafloor spreading data during the last 10 million years almost matched the rate of dextral fault displacement through New Zealand over the last 10 000 years. In 1974 Brothers attempted to show how the complex upper Cretaceous to lower Miocene geology of Northland originated in a subduction setting, but the ideas in this work were not constrained by the age structure of the surrounding oceanic crust.

From the middle 1970's onwards a new generation of articles on the subject of the plate tectonic context of the Cenozoic geology of different parts of New Zealand has been published. In Northland-Auckland much of this work was inspired by Ballance who proposed (1976) a series of Miocene to Recent volcanic arcs, which at the time of their eruption, were aligned with the Tonga-Kermadec Arc, a

position from which each was successively rotated anticlockwise by up to 70°. Subsequently, Hayward (1979) suggested that the different orientations of the younger arcs could alternatively be explained by successively different trench positions. An important contribution to the resolution of this problem was the determination of an Oligocene age of the South Fiji Basin, and the NE-SW orientation of the magnetic anomaly lineations (8-12) (Malahoff et al., 1982). These new data preclude the possibility of Miocene southwestward directed subduction at a trench parallel to eastern Northland as proposed by Hayward. These data also argue against the wholesale rotation of northern New Zealand as originally proposed by Ballance (1976). In a more recent paper (Ballance et al., 1982), the notion of 70° of anticlockwise rotation was reduced to 20°-30°, but subduction at a trench east of Northland was still an integral part of the model. Brothers and Delaloye (1982) and Brothers (1983) have taken a different view of the plate tectonic setting of Northland. They support the view of Malahoff et al. (1982) that the Vening Meinesz Fracture Zone (VMFZ), which parallels the east coast of Northland, is the structure which accommodated the NW-SE spreading in the South Fiji Basin relative to the continental crust of Northland. Moreover, they suggest that the rootless igneous massifs which cover over 1500 km<sup>2</sup> of Northland are ophiolite seamounts generated by shearing within the VMFZ during the Oligocene interval of South Fiji Basin back-arc spreading. It is not, however, clear why their obduction onto Northland was delayed by 5 million years after the transform motion ended.

During the last six years there have been significant advances in our understanding of the Cenozoic tectonic development of eastern North Island, especially Hawke's Bay. The early papers were published in a collected volume of papers edited by Ballance and Reading (1980) on sedimentation at oblique-slip mobile zones. Lewis (1980) showed that between the coastline and the Hikurangi Trench is a 150 km wide, imbricate-thrust controlled, accretionary borderland of seaward-faulted, anticlinal ridges and landward-tilted basins. He considered this borderland to have originated by subduction accretion. In a complementary paper, van der Lingen and Pettinga (1980) showed that the Miocene Makara Basin in Hawke's Bay was a fossil slope-basin now onshore, which had similar characteristics to those described offshore by Lewis (1980). This put much of the structurally complex geology of Hawke's Bay into context as the uplifted inboard margin of an accretionary wedge. Subsequently, Pettinga (1982) published a detailed structural interpretation of coastal southern Hawke's Bay and showed convincingly how the thrust deformation was controlled by subduction accretion.

The evidence for early Miocene subduction accretion in Hawke's Bay adjacent to a very young (late Quaternary) volcanic arc (White Island - Ruapehu) was viewed as a problem by Cole and Lewis (1981). They also noted the absence of an accretionary prism opposite the Miocene-Pliocene volcanic arcs of Northland-Coromandel. Accordingly, they proposed a geologically economical solution by suggesting that the eastern North Island accretionary prism originally lay in a forearc position adjacent to Northland, when the arcs there were active, and that this prism has subsequently been transferred along the VMFZ and a

northern extension of the Alpine Fault to its present position. Ballance et al. (1982) perceived the same problem and proposed a similar solution.

A series of papers by Walcott and Bibby have also contributed significantly to our understanding of New Zealand Cenozoic tectonics. They showed from geodetic data (Bibby, 1976, 1981; Walcott, 1978a, b) that horizontal fault displacements through New Zealand amounted to only  $\frac{1}{3}$  to  $\frac{1}{2}$  of the total displacement; the rest was accommodated aseismically by distributed ductile deformation. Walcott (1978a) proposed the concept of the Axial Tectonic Belt - a belt of rapid dextral shear some 70-100 km wide crossing New Zealand diagonally from the Hikurangi Margin in the northeast to the Fiordland margin in the southwest. He noted that an implication of the aseismic deformation would be bending of reference lines. More recently Walcott et al., (1981) and Walcott and Mumme (1982) have published paleomagnetic data interpreted as supporting 62° of post-Oligocene dextral rotation in eastern North Island and Marlborough.

In 1976, while Ballance was relating the onshore volcanic arcs to plate motions, Carter and Norris (1976) were comparing the Cenozoic history of the South Island with the plate tectonic predictions for New Zealand made a year earlier by Molnar et al. (1975) from a major synthesis of seafloor data to the south of New Zealand. The two major predictions were: (1) that between 38 and 21 My B.P. (latest Eocene - earliest Miocene) relative movement of the Australia and Pacific plates formed the dextral transform system of the Alpine Fault; and

(2) that between 10 My B.P. and the present, a major compressional component appeared along the Alpine Fault. Carter and Norris (1976) claimed an accord between these predictions and their geological observations. In particular, they considered that transcurrent movement on the Alpine Fault took place largely between the middle Oligocene and late Miocene, and that the post 10 My B.P. compression across the plate boundary was responsible for the mountain building that formed the Southern Alps. Their interpretations have changed slightly in subsequent papers (Norris et al., 1978; Norris and Carter, 1982). They now consider that the sedimentary history is consistent with latest Eocene inception of the Australia-Pacific plate boundary as a zone of slow oblique extension, followed by a through-going continental transform (early Miocene to late mid-Miocene), and then by a late Miocene-Recent compressive transform system.

Since the synthesis of Molnar et al. (1975) on the plate tectonic development of the southwest Pacific, other interpretations based on an expanded catalogue of seafloor data have been published by Weissel et al. (1977), Crook and Belbin (1978), Barron and Harrison (1979), and Stock and Molnar (1982). Two of these papers have addressed the question of the age of inception of the Australia-Pacific plate boundary (Alpine Fault) through New Zealand. Weissel et al. (1977) proposed an evolution of this boundary from the early Paleocene, while Stock and Molnar (1982) offered two possibilities, one a late Eocene age, and another a Late Cretaceous age. These differences are dependent upon assumptions about the late Cretaceous-Cenozoic integrity of Antarctica. The earlier ages (late Cretaceous-early Paleocene) are predicted if no significant displacement occurred within Antarctica; the late Eocene age is predicted if substantial late Cretaceous-Paleogene displacements occurred.

Finally, I wish to draw attention to the series of plate tectonic maps of the circum-Pacific region published for the Circum-Pacific Council for Energy and Mineral Resources by the American Association of Petroleum Geologists, Tulsa, U.S.A. At present, four maps, one for each quadrant of the Pacific region, have been published at a scale of 1:10 000 000, as well as a single map covering the whole of the region at a smaller scale. Each of these maps illustrates the location and character of the plate boundaries, the directions and rates of absolute and relative plate motions, major intraplate structures, earthquake epicentres and volcanic centres. In addition, and of importance to this thesis, the maps show the distribution and age of the seafloor magnetic anomaly lineations, and the distribution of seafloor fracture zones. The maps are a statement of the present plate tectonic setting, and thus the starting point in any consideration of the evolution of the southwest Pacific region.

#### Problem areas

From the preceding discussion five critical problem areas have been identified, which must be addressed to permit an improved understanding of the Cenozoic tectonic development of New Zealand in the context of plate tectonics:

(1) *The age of inception of the New Zealand sector of the Australia-Pacific plate boundary*

As reviewed earlier, widely different views of the age of this plate boundary, from considerations of both the onshore and offshore geology, have been published. The resolution of this problem is fundamental to the development and application of the concept of tectonic succession to New Zealand's Cenozoic record.

(2) The tectonic setting during the Paleogene

A Cretaceous versus Miocene age of plate boundary inception clearly has divergent implications for New Zealand's Paleogene tectonic setting. The geologic record of the Paleogene is therefore logically a critical area to investigate. In addition, if the plate boundary originated during the Neogene, an understanding of the tectonic setting which immediately preceded its development is also critical to the development of the concept of tectonic succession.

(3) The nature and location, north of the Alpine Fault proper, of the relative plate motion, which is evident as dextral fault displacement on the Alpine Fault

The New Zealand and wider southwest Pacific region tectonic interpretations reviewed earlier generally assumed that north of the Alpine Fault the relative plate motion occurred as fault displacements on a simple extension of the Alpine Fault through eastern North Island. While this might be an attractive solution to the apparent conundrum of discrepancies in the ages of the subduction prism and volcanic arcs, it nevertheless complicates lithologic and age trends in the basement rocks, when, in fact, it should simplify them as a result of removing the late Cenozoic deformation. Moreover, the notion of a single fault extension is not consistent with the late Cenozoic pattern of deformation in eastern North Island.

This problem is interrelated with the first problem of the age of the Alpine Fault. One of Suggate's (1963) arguments for a Cretaceous age of the bulk of Alpine Fault movement, was the absence of clear evidence in the Cenozoic structure and stratigraphy of the North Island for hundreds of kilometres of transcurrent displacement.

The solution to problem 3 has important implications for the pre-plate boundary shape of New Zealand, and this problem is interrelated with the next one (4).

(4) The total amount of Cenozoic horizontal displacement through New Zealand

Following Fleming (1970), Grindley (1974), Wellman (1975), and Hunt (1978), it is generally considered that there has been 1000 km of dextral displacement through New Zealand. This figure is measured from the ends of the recurved arc. This arc is commonly viewed as a gigantic fold which formed as a result of 500 km of bending immediately before the Alpine Fault formed, and the remaining strain was taken-up as 480 km of fault displacement. If, however, the recurved arc is a Mesozoic (Rangitata Orogeny) feature, and the Alpine Fault is a Cenozoic feature, the total amount of Cenozoic displacement through New Zealand will be approximately 500 km. This will also be the case if the bending was the expression in one part of the plate boundary zone of the relative plate motion that was concurrently expressed as fault displacement on the Alpine Fault. Recently published paleomagnetic data by Grindley and co-workers, and Walcott and co-workers, suggest that both of these possibilities exist - the recurved arc or orocline may have multiple ages and origins. If the

total amount of Cenozoic horizontal displacement is substantially reduced, the published models of the late Cretaceous-Cenozoic tectonic development of the southwest Pacific may need revision, as they have assumed 1000 km of displacement through New Zealand. The resolution of this problem also has implications for the pre-plate boundary shape of New Zealand.

(5) *The Neogene and Quaternary extent and geometry of the subducted Pacific Plate beneath northern New Zealand*

The preceding comments show that there is confusion over the orientation of the Neogene and Quaternary volcanic arcs, the position of the trench, and the attitude of the subducted slab from which the calc-alkaline volcanics were derived. The Cenozoic volcanic record is important as a potential monitor of the slab's extent and geometry. This is of wider importance because of the recognition in current literature that subduction geometry is a principal control upon the state of stress and thus the deformational style of the overriding plate.

Thesis objective

The objective of this thesis is to work towards a model of the Cenozoic tectonic development of New Zealand. This involves first resolving the interrelated problems that have been identified, and then, based on these solutions, to formulate a model of the Cenozoic tectonic development of New Zealand. This objective has been approached in a series of papers, which have been published or submit<sup>e</sup>ted for publication, in the following way:

Paper 1 is concerned principally with the Paleogene sedimentary geology of New Zealand. It is postulated that during the middle Eocene to early Miocene a 1200 km long continental rift system occurred through western New Zealand. The age and continuity of this rift system precludes any pre-Miocene transcurrent displacement on the Alpine Fault. An early Miocene age of fault inception is indicated by the age and pattern of disruption of the rift system. This paper addresses problems 1 and 2.

Papers 2 and 3 on the landforms and late Cenozoic structure and sedimentation patterns of Hawke's Bay and Wairarapa provide background material to subsequent papers (4 and 8) which more specifically address problems 3, 4, and 5. Papers 2 and 3 highlight the consequences of oblique convergence of the Australia-Pacific plates at a very shallowly dipping subduction zone.

Paper 4 addresses problems 3 and 4. It proposes that the relative plate motion north of the Alpine Fault was dissipated through Marlborough and eastern North Island as ductile shearing during the early and middle Miocene, and as brittle-ductile shearing during the late Miocene-Quaternary. The brittle-ductile deformation formed the recurved arc structures in Marlborough-eastern North Island, and since they developed concurrently with Alpine Fault displacement, only approximately 500 km of dextral displacement has occurred through New Zealand on the Australia-Pacific plate boundary.

Paper 5 considers the late Cretaceous-Cenozoic tectonic development of the wider southwest Pacific region, and in particular, integrates the continental geology of New Zealand with the age structure of the surrounding oceanic crust. This builds upon the conclusions of papers 1 and 4 which provide the following constraints not previously identified and hence not previously taken into account: (1) the occurrence of a rift system through western New Zealand, (2) the Australia-Pacific plate boundary did not transect the New Zealand sector until 23 million years ago, and (3), there has been only about 500 km of dextral displacement on the plate boundary through New Zealand.

Paper 6 addresses problem 5, and the controversial issue of the younging direction of the Neogene and Quaternary orogenic andesites. From the age-space distribution and composition of the North Island volcanics, the Neogene and Quaternary extent and geometry of the subducted Pacific Plate beneath the North Island is determined. This forms the basis of evaluation of the influences of subduction geometry on the general nature and pattern of the Neogene tectonics of the North Island.

Paper 7 builds upon the conclusions of papers 1 and 6, and proposes a seafloor spreading and subduction origin for the geophysical anomalies and igneous bodies off the west coast of the North Island. Although the origin of these features was not considered earlier to be a fundamental problem, their origin is controversial (contrast Hatherton et al., 1979 with Hayward, 1979), and should be considered in any model of the Cenozoic tectonic development of New Zealand.

Paper 8 also addresses problem 5, but more specifically the Quaternary structure, volcanism and tectonics of northern New Zealand. From consideration of the geophysical properties of mantle seismicity, upper mantle structure, gravity anomaly patterns and heat flow patterns it is postulated that the subducting Pacific Plate at present is actually buckled. This geometry, coupled with the persistent trenchward retreat of the slab, has controlled both the short term (100 y) and longer term (1 My) state of stress and deformational style of the overriding Australia Plate.

In the last chapter of the thesis a model of the Cenozoic tectonic development of New Zealand is outlined and discussed. The model is based upon the solutions to the problems identified and discussed in the papers in the thesis. It should not be viewed as an ultimate resolution, but rather as an advance towards one.

#### Organisation of the thesis

This thesis is organised and presented as a series of 8 papers. At the time of binding 5 of these were published, a further 2 had been submitted for publication, and one was still undergoing peer review. Because of the different requirements of the different scientific journals to which they have been submitted, each paper has a slightly different format. A degree of duplication, particularly of critical diagrams and some References, is one consequence of organising this thesis as a series of papers. The duplication arises because each paper is a discrete article.

Referencing within the papers is done in the normal way, with references cited in the text of a particular paper appearing in a reference list at the end of that paper. For the reader's convenience, I have also cross-referenced the thesis paper numbers with their appropriate references in a supplement following each reference list.

Three appendices are included at the end of the thesis. The first is a geological time scale. The second is a reprint of an article by the author concerned with problems in the Mesozoic basement geology, and the third is an abstract to a paper jointly authored with C.S. Nelson and R.M. Briggs on Eocene-Oligocene volcanic deposits on the Challenger Plateau. These last two papers are mentioned in the thesis, but as they are outside the scope of the topic, they are not to be considered part of the thesis. They are included merely for the reader to consult if desired.

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## PAPER 1

Extent, continuity and tectonic development of an early to mid-Cenozoic continental rift system through western New Zealand, and implications for the age of Alpine Fault inception

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EXTENT, CONTINUITY AND TECTONIC DEVELOPMENT OF AN EARLY TO MID-CENOZOIC CONTINENTAL RIFT SYSTEM THROUGH WESTERN NEW ZEALAND, AND IMPLICATIONS FOR THE AGE OF ALPINE FAULT INCEPTION.

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#### ABSTRACT

Analysis of the structure and sedimentary geology of western New Zealand has identified a middle Eocene to early Miocene continental rift system, 1200 km long and 100-200 km wide. Four phases of rift development occurred: (1) infra-rift subsidence, (2) active axial trough subsidence, (3) expanded rift subsidence involving collapse of the rift shoulders, and (4) incipient seafloor spreading. The spatial and temporal distribution of these phases identifies a northern and a southern rift segment, and shows that rifting propagated from both the north and the south. The northern segment shows a simple pattern of rifting comparable with Vink's model of rift propagation; the southern segment, with locked zones and rift nucleation segments, is comparable with Courtillot's model of rift propagation.

The seafloor spreading history of the southwest Pacific shows that the northern rift segment linked with a seafloor spreading centre in the Norfolk Basin, and the southern segment linked with the Southeast Indian Ridge. This is corroborated by the good correlation between the ages of seafloor magnetic anomaly lineations aligned with the rift and the biostratigraphic ages of rifting.

The probable continuity of the rift system in its early development precludes any pre-Miocene transcurrent displacement on the Alpine Fault; an early Miocene (23 My B.P.) age of Alpine Fault inception is indicated by the age and pattern of rift disruption attributed to compression originating at the Australia-Pacific plate boundary. Therefore the Australia and Pacific plates were not discrete entities until the early Miocene.

## INTRODUCTION

Fig. 1

The New Zealand subcontinent occupies an intra-oceanic position in the southwest Pacific Ocean (Fig. 1). A distinctive characteristic of this continental mass is the small proportion above sealevel. That any part is emergent is due mainly to the effects of the late Cenozoic convergence on the Australia-Pacific plate boundary, for the widespread occurrence onland of thick middle Cenozoic marine successions shows that the present landmass was formerly even less extensive.

The origin of this foundering has received little attention. It has been suggested that it may have followed the late Cretaceous separation of New Zealand from eastern Gondwanaland (Carter and others, 1974). Models of passive margin development show that subsidence is certainly to be expected about the margins of a rifted continent, but the problem with New Zealand is the extent of subsidence in the interior parts of the subcontinent. This may be partly overcome by post-rift subsidence about the finger-like re-entrants of the late Cretaceous New Caledonia Basin and Bounty Trough, which both protrude into the sub-continent. The objective of this paper is to document evidence for another rift system, of Eocene-Oligocene age, which trended north-south through western New Zealand from the Norfolk Basin to the Solander Trough (Fig. 1). This rift, by dissecting the subcontinent, induced subsidence of its most interior parts, and indicates that the foundering was associated with at least two periods of rifting, one in the late Cretaceous and another in the mid-Cenozoic.

The early to mid-Cenozoic rift system is now dextrally dislocated 480 km across the Alpine Fault suggesting that inception of the Alpine Fault, and thus propagation of the Australia-Pacific plate boundary through New Zealand, did not occur until the early Miocene. Therefore, in a strict sense, the Australia and Pacific plates were not discrete entities until

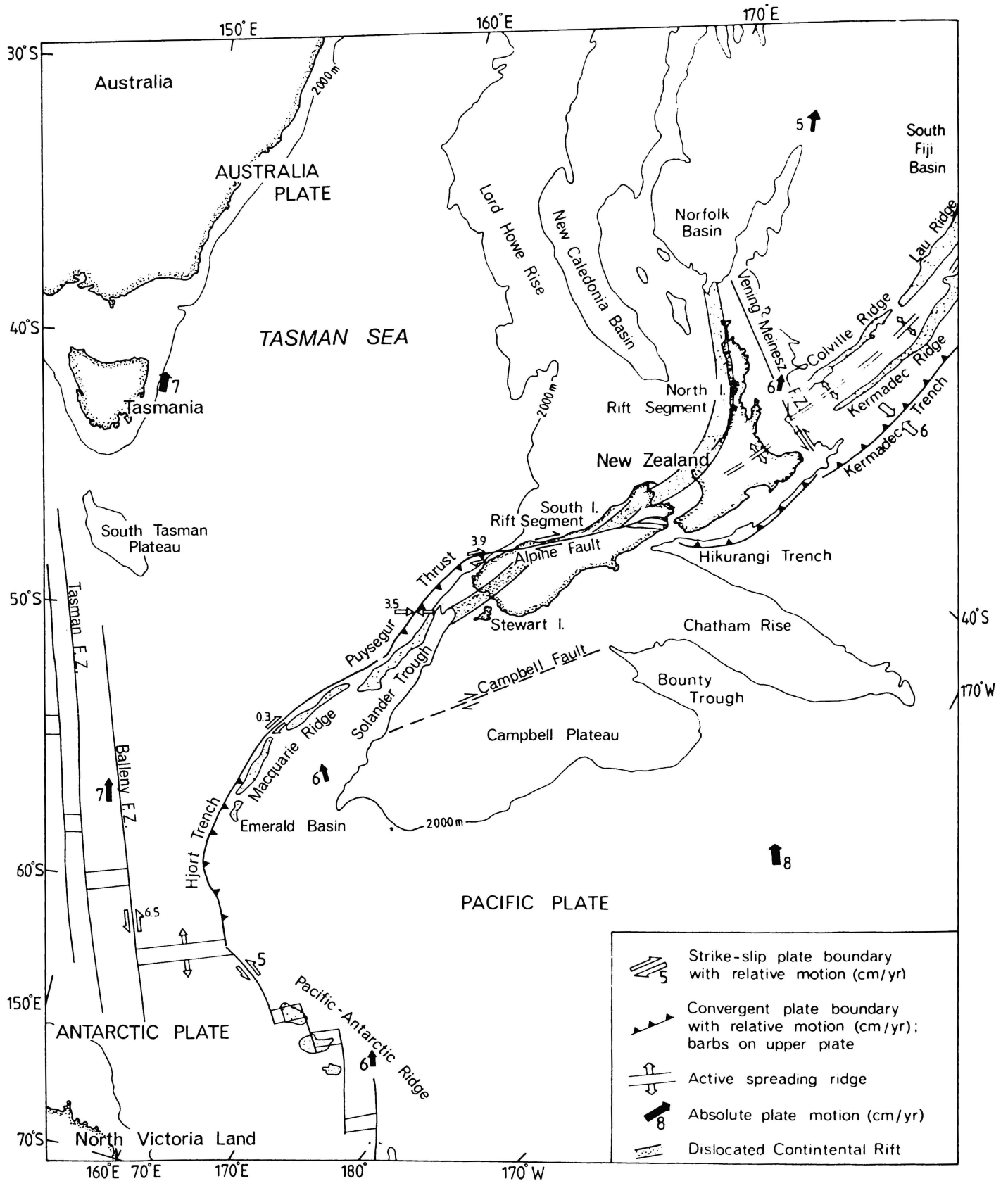


Fig. 1 Map of the Southwest Pacific showing the tectonic character of the Australia-Pacific plate boundary and Alpine Fault dislocation of the rift system through western New Zealand. Directions and rates of plate motion from the Plate Tectonic Map of the Circum-Pacific Region - southwest Quadrant (Copyright: The American Association of Petroleum Geologists, Tulsa, U.S.A.).

the early Miocene, compared with the present understanding that this was achieved by the late Eocene (Molnar and others, 1975; Weissel and others, 1977), or possibly as early as the late Cretaceous (Stock and Molnar, 1982).

The essential evidence for this rift system is the former occurrence through western New Zealand of a 100-200 km wide zone of interconnected normal fault bounded troughs and half grabens, which show many of the structural features characteristic of modern rifts and of continental margins in the early stages of passive margin development (Fig. 2). Paleogeographic considerations, and notably the spatial pattern of lateral differences in the degree of rift development, suggest that the rift system had a northern and a southern segment, and that rifting propagated towards central New Zealand from both the north and the south. At the late Oligocene peak of its development, the northern segment linked with the southern segment in NW Nelson, then a region of shallowly submerged plateaux with deeper basins to the north and south.

Fig. 2

Near the Oligocene-Miocene boundary, the tectonic style and sedimentation patterns changed in the southern segment of the rift system; it is inferred that movement began on the Alpine Fault, causing the rift system to become dislocated and overprinted by obliquely compressional tectonics. Crustal thinning which characterized the Paleogene setting changed to crustal re-thickening, and this was manifest in the South Island by reverse movement on the pre-existing normal faults, and thus rift basin eversion, uplift and erosion. Further from the Alpine Fault, and notably in the North Island segment, extension persisted until the late-middle Miocene, and the rift system may have developed into the early stages of a passive margin with incipient seafloor spreading.

Continental rift systems commonly connect with oceanic spreading centres. Because this is not evident when the Cenozoic rift system is

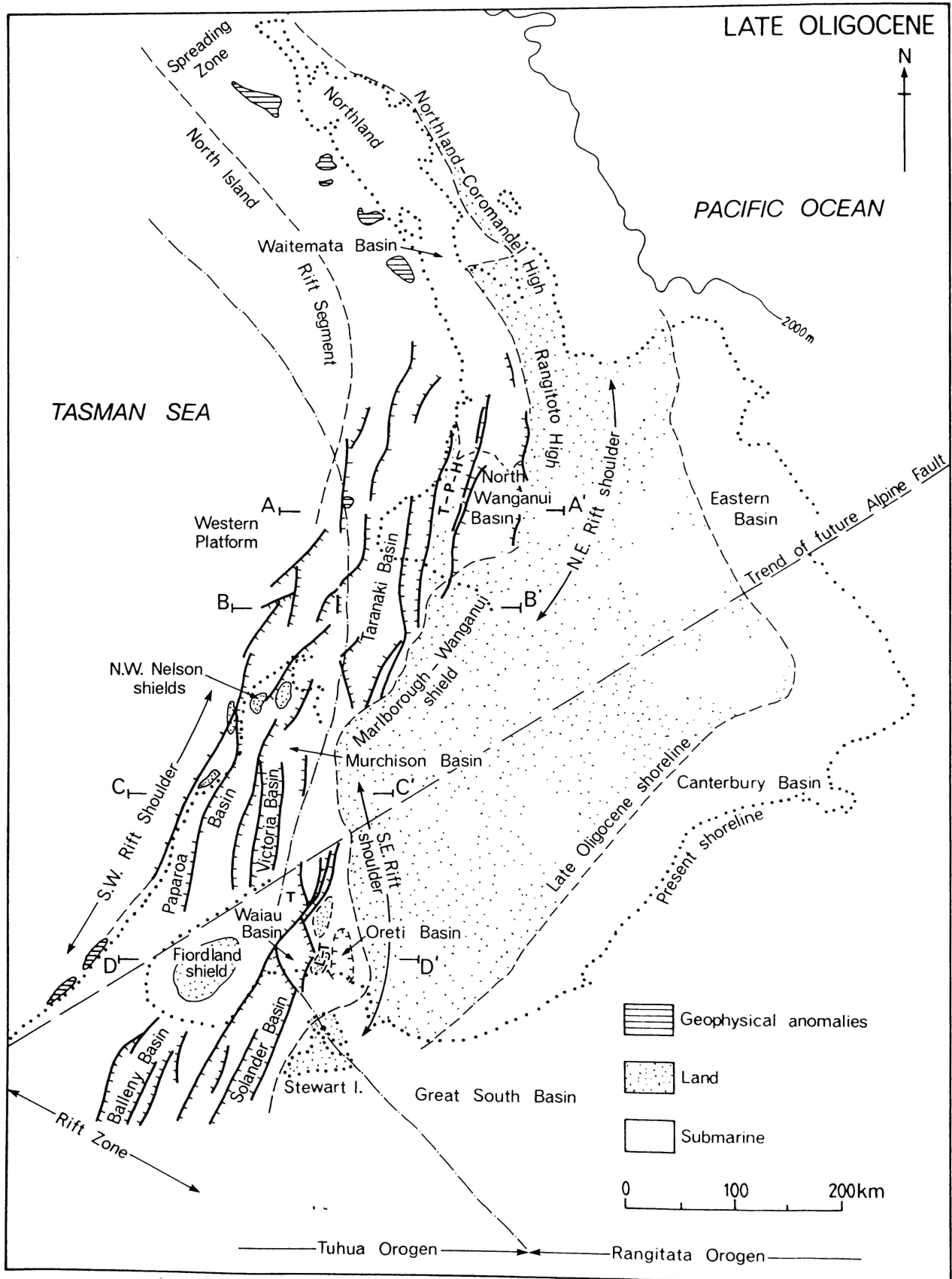


Fig. 2 Map of the late Oligocene distribution of basins and structural highs comprising the rift system in relation to the trend of the Alpine Fault. The outline of New Zealand is based on Fig. 3A. T represents Te Anau Basin; L-T, Longwood-Takitimu High; and T-P-H, Tongaporutu-Patea-Herangi High. The distribution of geophysical anomalies after Hatherton and others (1979).

compared with current plate tectonic syntheses of the SW Pacific (Molnar and others, 1975; Weisell and others, 1977), a new synthesis of the sea-floor spreading history has been developed, based on the constraints that (1), there has been only ~500 km of dextral displacement on the plate boundary through New Zealand, and (2), that the Alpine Fault was not initiated until the early Miocene. The result of such a reconstruction is that the northern segment of the rift system becomes aligned with an Oligocene Norfolk Basin spreading centre, and the southern segment with the Southeast Indian Ridge.

The interpretation of the origin of the Eocene-Oligocene depocentres in western New Zealand advanced here, differs from other current models. Whereas I attribute the origin of these depocentres to continental rifting, with subsequent dislocation of this structure by Alpine Fault movement, other workers have viewed these basins as originating in an obliquely extensional continental transform setting concurrent with, and indeed caused by, Alpine Fault movement (McQuillan, 1977; Norris and others 1978; Norris and Carter, 1980, 1982; Knox, 1982).

The challenge that the Eocene-Oligocene depocentres did not originate through transform displacement is based on the evidence that (1), the Alpine Fault clearly had a different trend from that of the western zone of depocentres, (2), the depocentres extended up to many hundreds of km northwest and southeast of the Alpine Fault, and (3), the depocentres originated by normal rifting rather than transtension. To show the extent and trend of the rift system in relation to the Alpine Fault at the time of the fault's inception, it is first necessary to establish the late Oligocene shape of New Zealand.

#### LATE OLIGOCENE SHAPE OF NEW ZEALAND

Large scale changes in the plan shape of New Zealand have accompanied

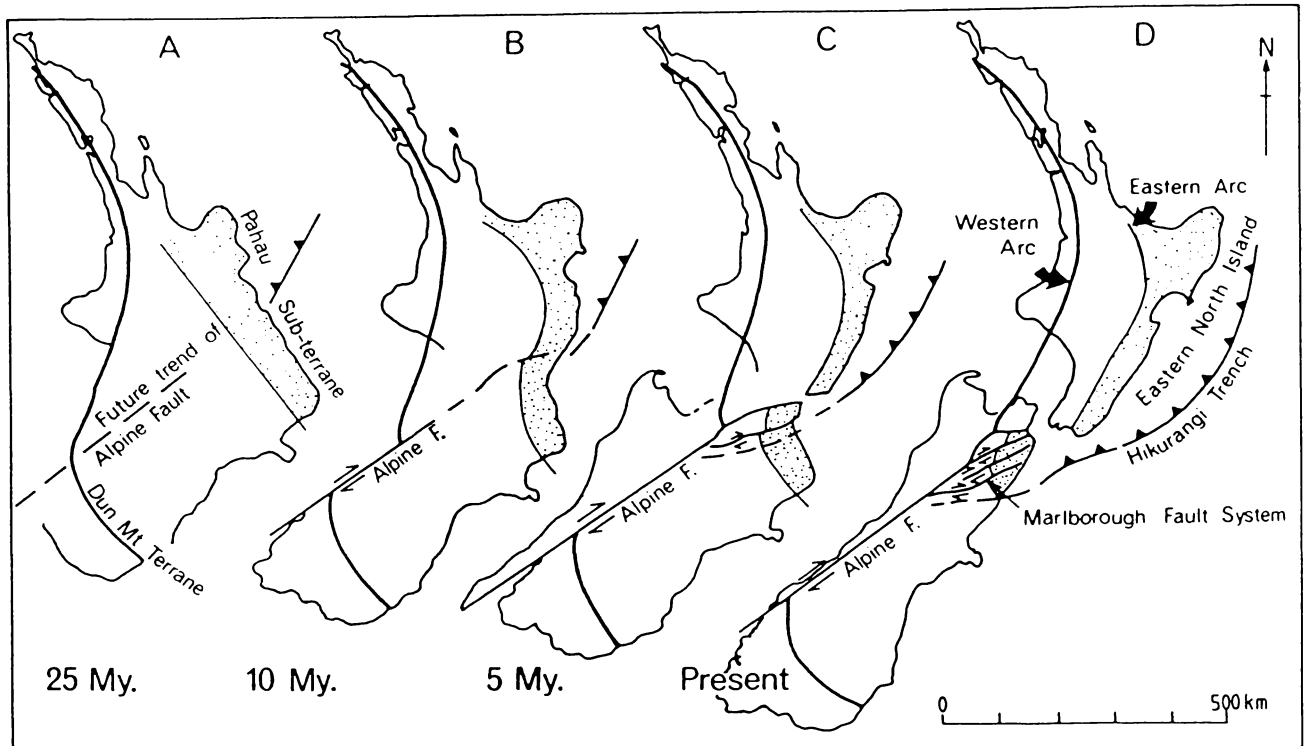


Fig. 3 A model showing the late Cenozoic development of the basement recurved arcs and the Alpine Fault in relation to the evolution of the plate boundary through New Zealand and the changing shape of the landmass. The distribution of basement terranes in 'A' after Bradshaw and others (1980). The relative displacements at 5 and 10 My BP are based on the respective amounts predicted to have taken place by Stock and Molnar (1982).

the evolution of the obliquely convergent Australia-Pacific plate boundary through the New Zealand sector. Because of the widely different views on the age of Alpine Fault inception, ranging from Cretaceous to middle Miocene, it is not surprising that widely different pre-Miocene configurations of New Zealand have thus far been published. Compare for example Carter and Norris (1976), Stevens and Suggate (1978), Cutten (1979), Cole and Lewis (1981), Ballance and others (1982), Cooper and others (1982), and Walcott and Mumme (1982). These differences arise not only from their different interpretations of the age of the Alpine Fault, but also from their conclusions of the total amount of dextral displacement across the plate boundary, and the nature and location of that displacement northeast of the Alpine Fault. The latter two issues are intimately related to the age and origin of the basement recurved arc (Macpherson, 1946) - itself a controversial topic of New Zealand geology, but one that is critical to the late Oligocene shape of New Zealand.

I have adopted the Walcott and Mumme (1982) configuration of New Zealand as a basis to plot the rift system in relation to the trend of the Alpine Fault. This can be justified in that it is the only shape which can be shown to evolve, with development of the plate boundary, into the present shape of New Zealand and satisfy the constraints of (1) the distribution of basement terranes (Bradshaw and others, 1980), (2) the occurrence in Marlborough and eastern North Island of a broad zone of distributed faulting and aseismic strain (Walcott 1978; Bibby, 1981), and (3) onland paleomagnetic data from both the Mesozoic basement and Tertiary cover rocks (Fig. 3). Further details of this model will be presented elsewhere, but the two main implications relating to the total amount of dextral displacement permitted through New Zealand, and the nature and location of that displacement northeast of the Alpine Fault are briefly outlined.

A characteristic of this model is the occurrence of two basement recurved arcs compared with the present concept of a single arc (Fleming, 1970; Hunt, 1979). The western arc is expressed by the outcrop and geophysical pattern of the Stokes Magnetic Anomaly System, of which the Dun Mountain Terrane is a part, and the second arc (Fig. 3) is defined by the outcrop pattern of the Pahau Sub-terrane/ The concept that the basement comprises two arcs is consistent with the two available sets of paleomagnetic data. One set suggests that the basement rocks in western South Island, including the Dun Mountain Terrane, were bent during the early Jurassic phase of the Rangitata Orogeny (Grindley and others, 1977; Grindley and Oliver, 1979 and 1980; Oliver and others, 1979). The other set of data from Tertiary cover rocks of eastern North Island and Marlborough, suggests that the recurved arc formed during the Neogene and Quaternary Kaikoura Orogeny (Walcott and others, 1981; Walcott and Mumme, 1982). In the context of a single recurved arc these data are contradictory, but are not so if the eastern arc developed during the Neogene-Quaternary while the western arc, already recurved in the Mesozoic, was linearly displaced on the Alpine Fault (Fig. 3).

The first implication of this model is that the Neogene and Quaternary relative movements across the plate boundary were expressed differently along different parts of the boundary. In the South Island they were expressed mainly as Alpine Fault displacements, but in eastern North Island and Marlborough, as the formation of a ruptured fold. The second implication is that only 500 km of dextral movement on the plate boundary is necessary to form the eastern arc and displace the Alpine Fault by the recorded 480 km; it has consistently been inferred that the basement recurved arc indicates a further 500 km of dextral movement additional to 480 km of Alpine Fault displacement (e.g. Hunt, 1978), and this assumption has been built into SW Pacific plate tectonic syntheses (Molnar and others,

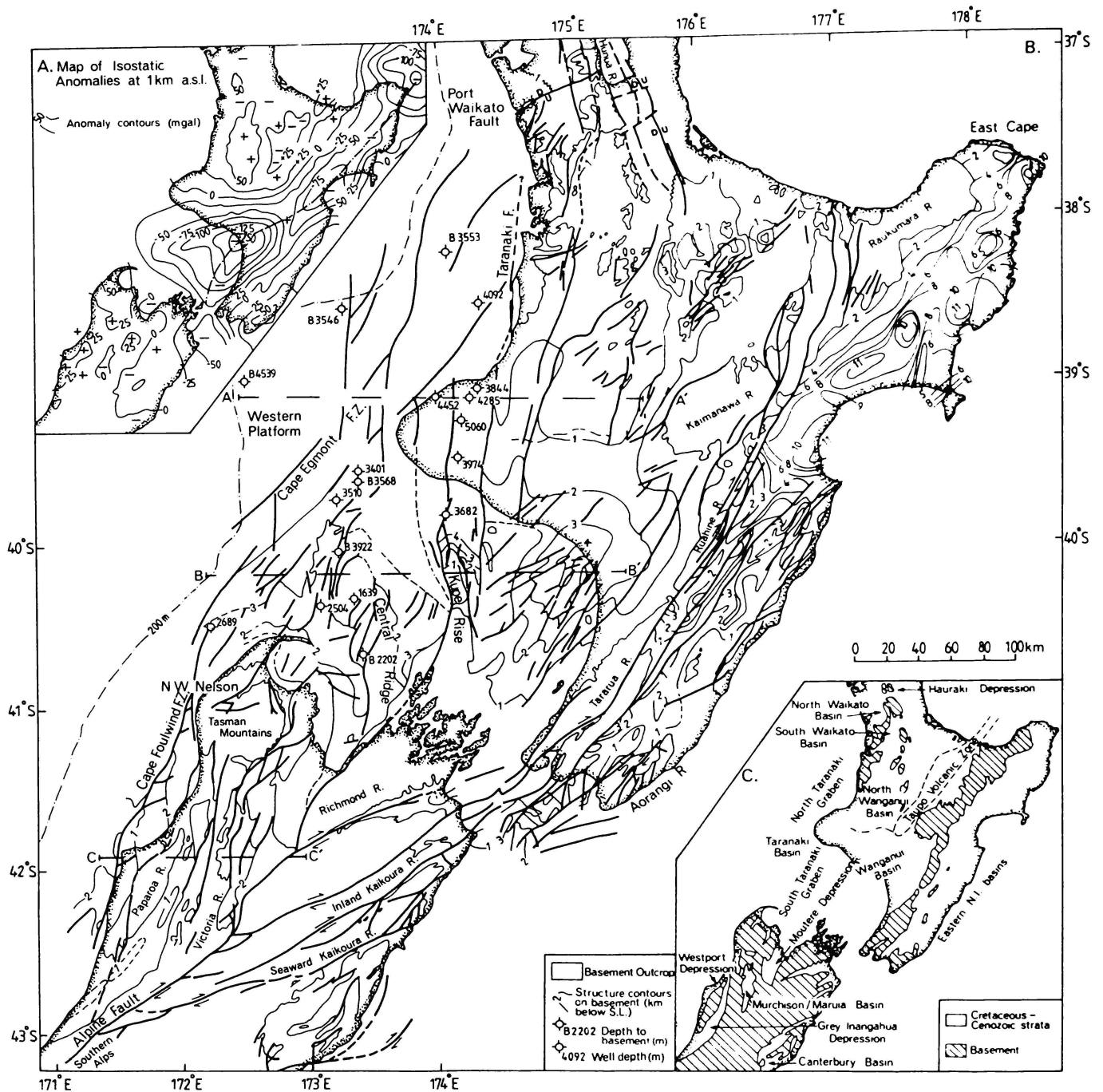


Fig. 4 A map of central New Zealand showing the depths to basement. Basement everywhere is older than middle Cretaceous. The depths onland are from gravity data, and offshore are from seismic reflection profiles. The map was compiled from many sources: Hunt (1969, 1980), Esso (1969), Pinchon (1982), Hicks and Woodward (1978), Anderton (1981), Rogan (1982), Hicks (1980). Inset map A is after Hatherton and Syms (1975) and Reilly and others (1977). Inset map B shows the location and names of the main Cenozoic basins.

1975; Weissel and others, 1977; Crook and Belbin, 1978).

#### EXTENT AND DIMENSIONS OF THE MID-CENOZOIC WESTERN BASINS

The extent and dimensions of the Cenozoic basins in western New Zealand are illustrated in two maps. The first is a structure contour map on basement covering the North Island and the part of the South Island north of the Alpine Fault (Fig. 4), and the second map covers SW South Island south of the Alpine Fault (Fig. 5).

Fig. 4

Fig. 5

Fig. 4 shows that a 100-200 km wide zone of north-south trending basins occurs in the onshore and near offshore parts of western New Zealand, and that this is separated from an eastern basin province by a thin strip of outcropping basement. Prior to the early Pliocene the zone of outcropping basement was much wider, and therefore the separation between the eastern and western basinal provinces was much greater; the subsidence in the Taupo Volcanic Zone is Quaternary in age (Grindley, 1960), and the Wanganui Basin originated in the early Pliocene (Fleming, 1953). From the distribution of isostatic anomalies (Fig. 4A) it seems that the Wanganui Basin subsidence has not yet been isostatically compensated at depth. The origin of this subsidence has recently been attributed to the changing extent and geometry of the subducted slab of Pacific Ocean crust beneath the North Island (Kamp, 1984). Critical to this paper is the evidence that the Wanganui Basin was not part of the mid-Cenozoic zone of basins, and prior to the Pliocene this basin was occupied by an extensive area of exposed basement.

A persistent reduction in depth to basement southward through the western basins to the Alpine Fault is another feature of Fig. 4. This feature is examined in the following subsections together with the evidence for the former continuity of mid-Cenozoic basins across the plate boundary zone.

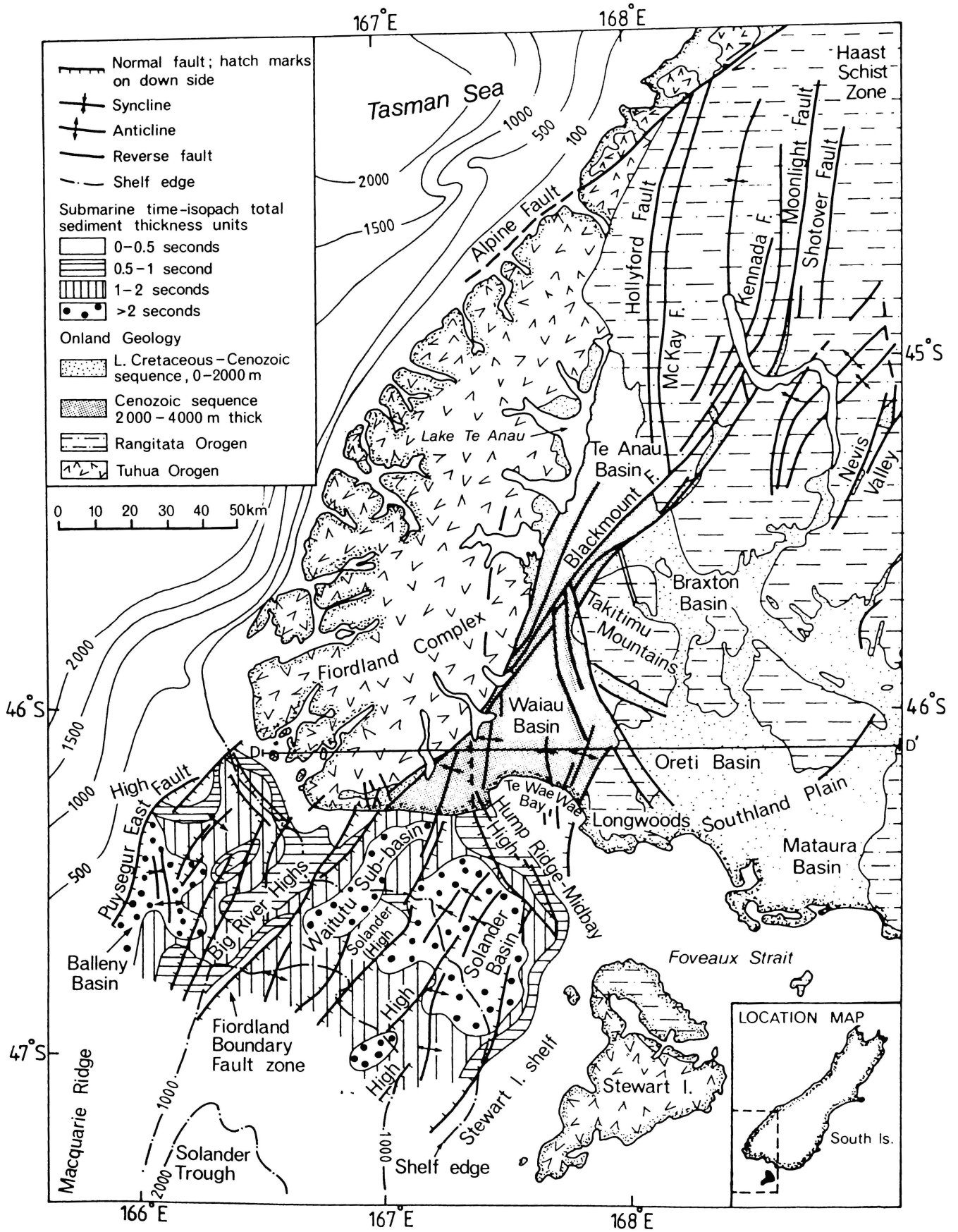


Fig. 5 Map of southwestern South Island showing the estimated depths to basement onland, and the seismic thicknesses offshore at the northern end of the Solander Trough. Seismic thicknesses after Norris and Carter (1980).

## Taranaki Basin

The mainly offshore Taranaki Basin extends from just east of the modern shelf edge to the Taranaki Fault (Fig. 4) and contains New Zealand's productive and most of its prospective hydrocarbon reserves. The basement has been down thrown at least 4000 m over most of the basin but progressively rises to sealevel in northern South Island. On stratigraphic and paleogeographic grounds a Western Platform has been identified as distinct from the Taranaki Graben Complex, and the latter has been classified into a northern and southern graben on structural grounds (Pilaar and Wakefield, 1978).

Insufficient data are available to contour the depth to basement in the northern part of the Taranaki Basin, however seismic profiles show that the basin has an asymmetric form (Pilaar and Wakefield, 1978). Basement is downthrown up to 7000 m on the steeply normal to slightly reverse Taranaki Fault, and rises to about 4000 m on the Western Platform; the Cape Egmont Fault Zone, which separates the platform from the graben complex, progressively displaces basement down to the east on steeply dipping faults. The Taranaki Basin contains a near complete Cenozoic sedimentary succession and was probably also the site of Albian sedimentation (Fig. 6). For much of this time the Taranaki Fault separated the basin from basement exposed to the east, but in the latest Oligocene to early Miocene the North Wanganui Basin developed between basement highs.

Fig. 6

The depth to basement north of the Taranaki Basin is not controlled by well data, but onshore and limited offshore geophysical data indicate that a trough of similar dimensions continues northward parallel to the coastline. Basement crops out at or near the coastline up to the Port Waikato Fault, but further north it is only exposed in a strip along the eastern coastline of Northland Peninsula. Most of central and western Northland is underlain by pervasively deformed Cretaceous-lower Tertiary

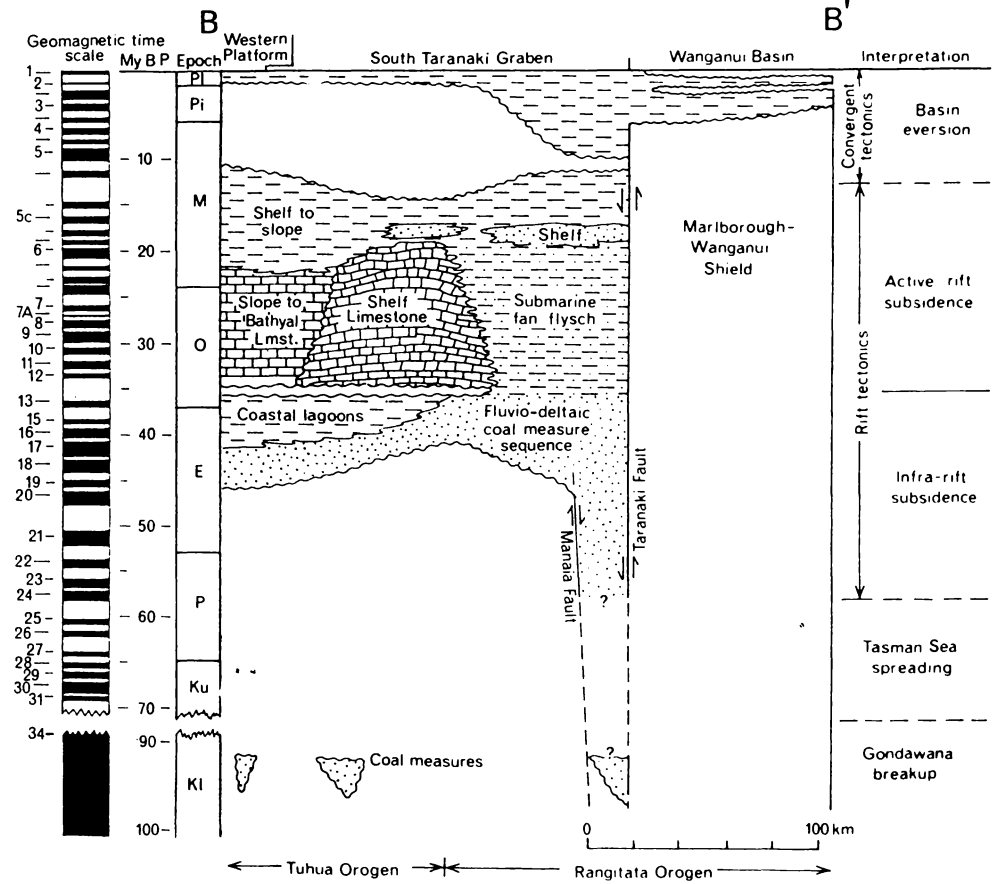
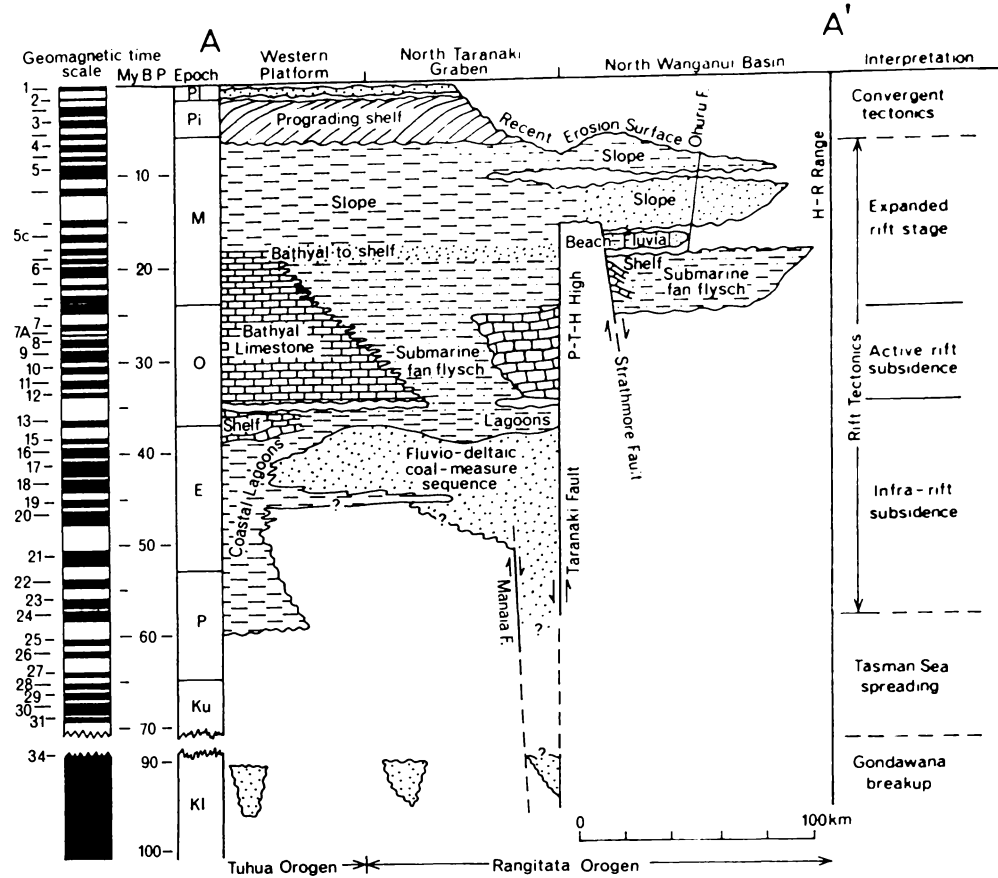


Fig. 6 Time-stratigraphic sections showing the development of the southern part of the North Island segment of the rift system. See Fig. 4 for the location of each section. The stratigraphic data after Pilaar and Wakefield (1978), Hay (1978) and Knox (1982). The geomagnetic polarity time scale simplified from the Plate Tectonic Maps of the Circum-Pacific Region (Copyright: The American Association of Petroleum Geologists, Tulsa, U.S.A.).

strata, considered by some workers to comprise an allochthon (Ballance and Spörli, 1979; Spörli, 1982), and thus it is difficult to infer anything of the subsurface geology. However, several lines of evidence indicate that the basement beneath western Northland and the western continental shelf is regionally depressed as much as the Taranaki Basin. (1) The onshore gravity maps (Woodward, 1971; Woodward and Reilly, 1972) show values of -6 mgals along parts of the west coast of Northland, but these values rise sharply to +35 mgals where basement crops out along the east coast or at Port Waikato. (2) Onshore drilling at Waimamaku on the west coast of Northland intersected basement at a depth of 3.0 km (Hornibrook and others, 1976). (3) Detailed gravity surveys across the Port Waikato Fault suggests that basement is downthrown 2.7 km at the coast on the north side of the Fault (Hockstein and Nuuns, 1976). (4) A series of east-west seismic sections across the continental shelf of western Northland show basement at depths of 6 km (Hatherton and others, 1979). On these bases it is inferred that the Taranaki Basin continues northward parallel to the west coast of northern North Island.

A critical issue is whether or not the Taranaki Basin in the mid-Cenozoic closed to the south as it does today (Fig. 4). The present shallowing occurs by way of two ridges, named here Central Ridge and Kupe Rise, and intervening troughs. These ridges however have different Paleogene histories. The thickness and age distribution of strata upon Central Ridge show that it was a basement high until the late Eocene, and only accumulated a thin Eocene-Oligocene sequence (Pinchon, 1972) (Fig.1). In contrast, Kupe Rise was initially a narrow trough and accumulated a thicker Paleocene-Eocene sequence than elsewhere in the south (Knox, 1982) (Fig. 6). Despite these initial differences both ridges accumulated comparable thicknesses of early and middle Miocene strata to other parts of the South Taranaki Graben, and both have been

uplifted since the late Miocene by reverse movement on previously normal faults. Knox (1982) measured from seismic sections 1000 m of reverse throw at the north end of Central Ridge, and at least 2000 m near the southern end. As there has been considerable late Neogene-Quaternary uplift, the South Taranaki Graben might previously have been more extensive to the south. However, Paleogene and early Neogene strata onland in NW Nelson are thin, suggesting limited subsidence. The strata that are present accumulated in non-marine to nearshore and shallow shelf environments (Bishop, 1971; Johnston, 1979; Grindley, 1980; Lewis, 1980). This strongly suggests that the Taranaki Basin did close into NW Nelson in the Paleogene and that this closure was accentuated by the late Neogene-Quaternary compression.

#### Westland-Nelson

Onland in Westland, between NW Nelson and the Alpine Fault, the stratigraphy and outcrop pattern of the Cenozoic cover rocks suggest the occurrence of a series of Eocene-Oligocene basins formerly of comparable depth to the Taranaki Basin. A well documented feature of Westland's geology is the occurrence of thicker Eocene and Oligocene strata upon the basement-cored Paparoa, Brunner and Victoria ranges, than in the adjacent Grey-Inangahua or Westport depressions (Wellman, 1946; Gage, 1951; Suggate, 1952) (Fig. 7). Accordingly, the concept was developed that since the early Miocene the Eocene-Oligocene basins have been everted and the former basement ridges have become the present depressions. Thus the present pattern of basement relief in Westland (Fig. 4) is of Neogene and Quaternary age and does not demonstrate the former continuity of Paleogene basins south to the Alpine Fault.

As the Eocene-Oligocene successions have been widely eroded as a result of their elevation (Fig. 8), the dimensions and configurations

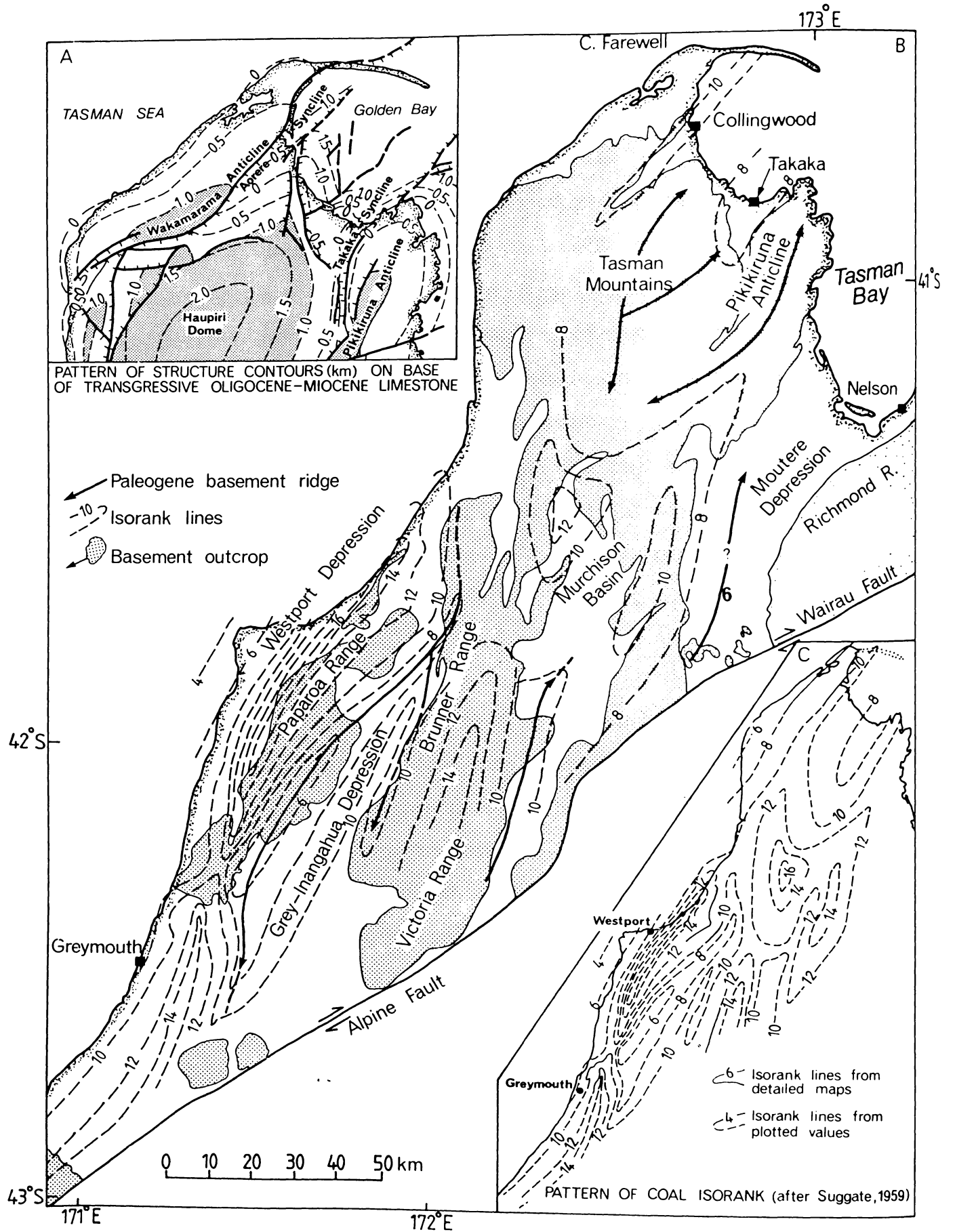


Fig. 7 Map showing the generalised late Oligocene distribution of coal isorank values in relation to the present basement outcrop and the Paleogene basement ridges. The isorank values in the Murchison Basin have been decreased by four numbers (equivalent to 4000 feet) from the values of Suggate (Inset map C) to remove the diagenetic effect of subsequent loading by Miocene sediments. Inset map A shows the pattern of structure contours on the base of the transgressive Takaka Limestone (after Grindley, 1974).

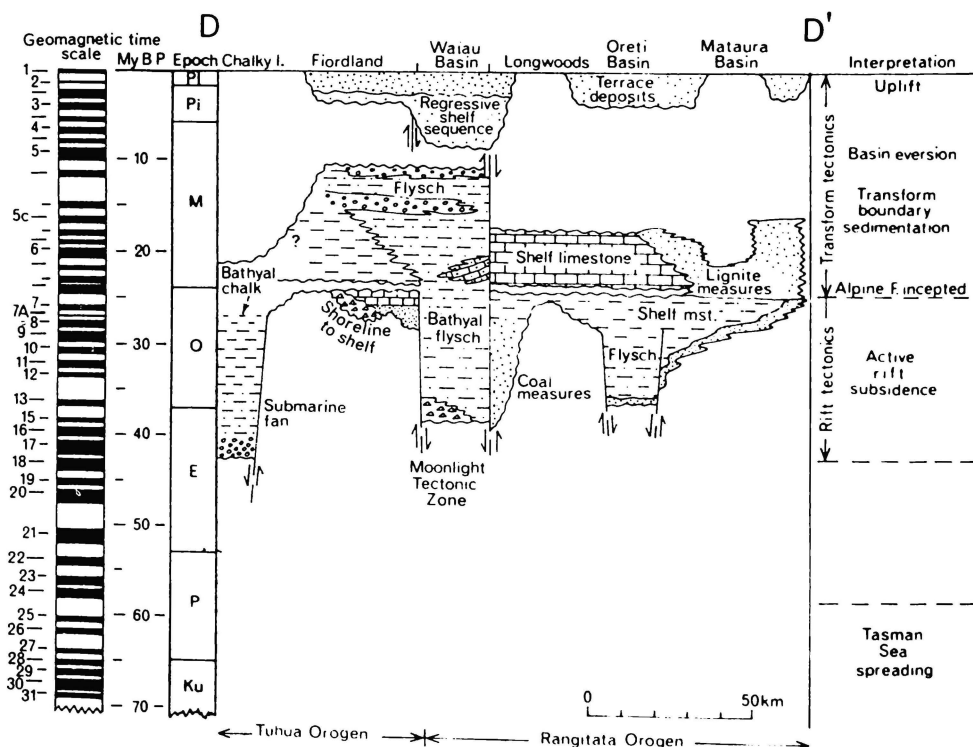
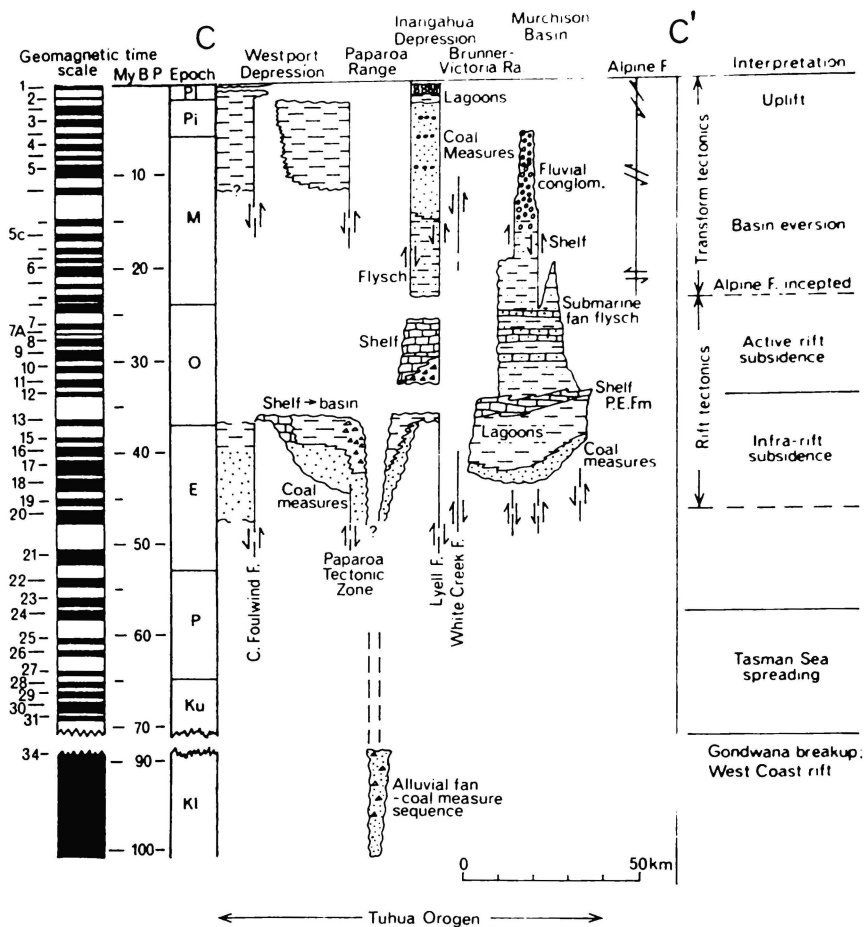


Fig. 8 Time-stratigraphic sections showing the development of the South Island segment of the rift system and the tectonic overprinting due to compression originating at the plate boundary. See Figs 4 and 5 for the location of each section. PEF stands for Port Elizabeth Formation. Stratigraphic data after: Suggate (1950), Nathan (1975, 1978b), Crooks and Carter (1976), Carter and Lindquist (1977), Norris and others (1978), Norris and Carter (1980), Hyden (1980), Carter and others (1982). The geomagnetic polarity time scale simplified from the Plate Tectonic maps of the Circum-Pacific Region (Copyright: the American Association of Petroleum Geologists, Tulsa, U.S.A.).

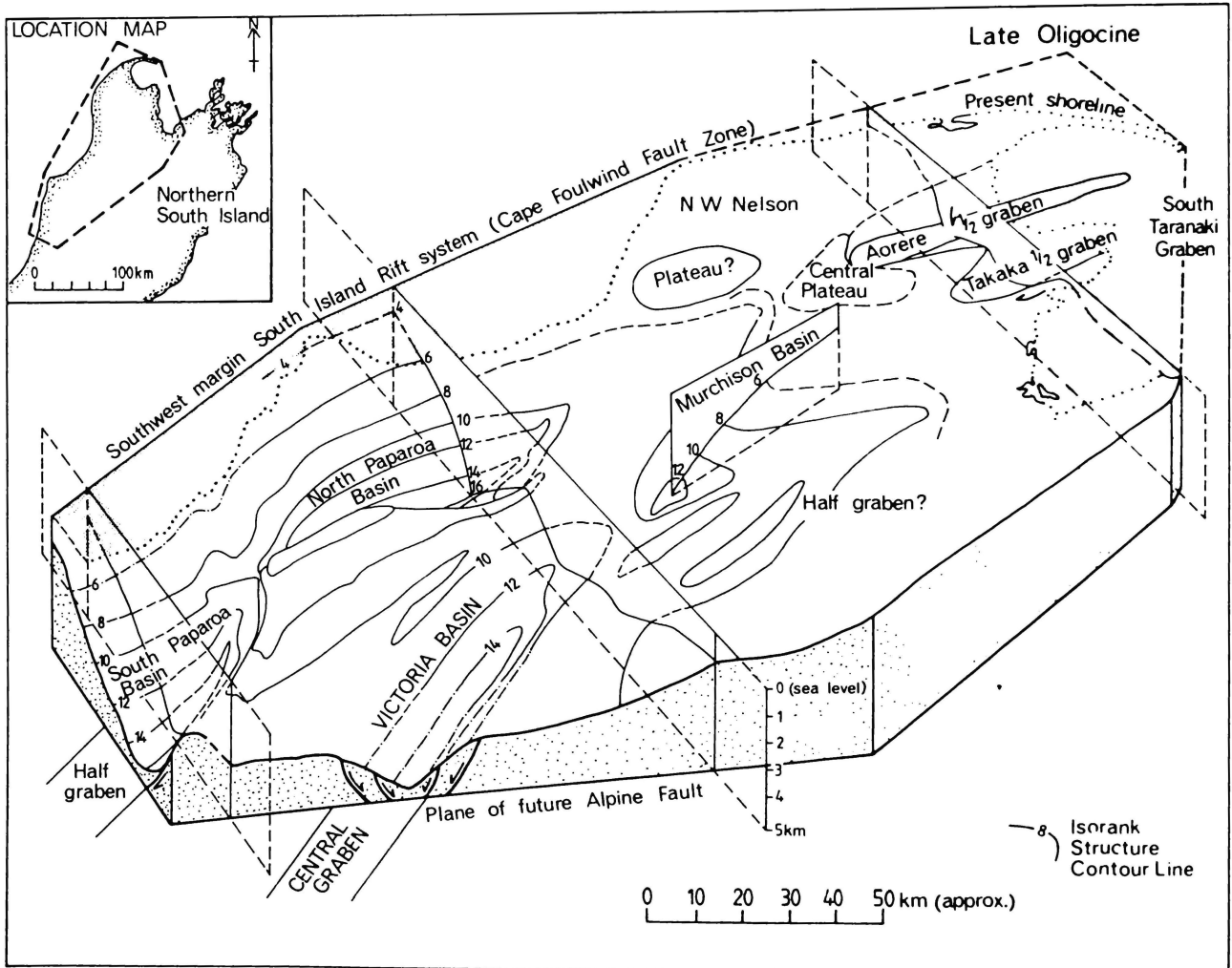


Fig. 9 Block diagram showing the late Oligocene depth to basement in Westland and NW Nelson based on coal isorank values (Fig. 7B) and the implied depths of burial (Suggate, 1959).

of the former basins cannot be reconstructed from the thickness distribution of the remaining sequences. Coal rank is, however, an approximate surrogate for succession thickness as coal measures invariably accumulated near the base of the transgressive basin sequences (Gage, 1952; Suggate, 1950), and because coal rank is a measure of depth of burial (Wellman, 1951, 1952; Suggate, 1959). The interpretation of an isorank map as a late Oligocene basement relief map is limited by at least two factors. Firstly, the rank values have been adjusted (Suggate, 1959) to the uppermost coal seam beneath the early Tertiary marine beds and therefore does not include any underlying non-marine beds; this gives a minimum estimate of depth to basement. Secondly, in the case of the Murchison Basin, which continued to subside after the Oligocene, coal rank will give an over-estimate of the depth to basement in the late Oligocene if it is not adjusted; Suggate's isorank map (Fig. 7c) has been modified to account for Miocene sedimentation in that basin (Fig. 7b). Undoubtedly the validity of applying coal rank in this way is limited by regional variations in coal ages and by differences in coal type, however the depths implied by the rank values are in accord with succession thicknesses for localities where this data is available (Nathan, 1974).

fig. 9 To illustrate the regional variations in depth to basement implied by the coal rank values, the isorank map has been transformed into a 3-dimensional perspective drawing (Fig. 9). This sketch shows that four discrete north-south trending basins with depths to basement of 3 to 4 km existed in Westland immediately north of the future Alpine Fault. This province of basins closed into NW Nelson where there was evidently a shield region probably with basement exposed in places. Confirmation that in NW Nelson there was minimal basement subsidence, and in particular that the present pattern of basement relief reflects that in the latest Oligocene, is offered by the structure contour pattern on the base of the

transgressive late Oligocene-early Miocene Takaka Limestone (Fig. 7a). From Figure 9 it is evident that in the late Oligocene the South Taranaki Graben did close into Nelson, but that south of this shield region deep basins were again established.

#### Southland to Solander Trough

The Oligocene extent and dimensions of basins in Southland are difficult to reconstruct as this region has also sustained much late Neogene-Quaternary compression and crustal shortening. The precise depth to basement at present within the Te Anau and Waiiau basins has not been determined because of the lack of well control, and because gravity modelling is frustrated by the very high densities of pre-Pliocene sediments. However, the profoundly folded and reverse faulted character of the basin sequences (Carter and Norris, 1977) means that the present depth to basement will not reliably indicate Oligocene basin depths. This can only be established by sedimentologic and paleoecologic studies; such studies indicate Oligocene basin depths of 2-6 km (Turnbull and others, 1975; Norris and others, 1978).

East of the Takatimu Mountains and Longwoods Range, but parallel to the Waiiau-Te Anau basins, are several shallower and largely undeformed Oligocene-Miocene basins (Fig. 5 and 8). Most of the subsurface geology is obscured, but gravity modelling suggests a sediment thickness in the Oreti Basin of 1.8-3 km (Hatherton, 1966), which is consistent with the limited exploration drilling in this basin (Wood, 1966; McLeron, 1972). The gravity anomaly values over the Matura Basin (Reilly and Doone, 1972) suggest that it is shallower than the Oreti Basin. Later, it is proposed that the Oreti Basin has the same relationship to the Waiiau Basin as the North Wanganui Basin has to the Taranaki Basin.

Offshore from southern South Island, seismic profiles show a pattern

of fault-bounded basins (Norris and Carter, 1980) similar to the South Taranaki Graben, and of a similar basement depth (2-6 km) to that envisaged for the Waiiau and Te Anau basins before their eversion (Fig. 5).

#### NORTH-SOUTH CONTINUITY OF EOCENE-OLIGOCENE BASINS

The north-south continuity of the Eocene-Oligocene basins through western New Zealand becomes evident when their positions are plotted on a map of the late Oligocene shape of New Zealand (Fig. 2). The eastern margin of the zone was continuously flanked by an exposed basement land surface, although there were at least two prominent enclaves : the North Wanganui Basin, and the Oreti Basin. The western margin was apparently not so prominently flanked by exposed basement; it was however exposed in central parts until the middle Eocene (Fig. 6), and there is good sedimentologic evidence that, at least in places, granitic basement was emergent along the southwest margin until the early Oligocene (Laird and Hope, 1968; Germane, 1976).

Within this zone of basins, shallowly submerged and exposed plateaux occurred in NW Nelson and Fiordland. Fiordland was flanked by deep basins on all sides, whereas NW Nelson had deep basins only on its northern and southern sides. The persistence there of a structural high across the zone of basins serves to distinguish a northern segment from a southern one.

#### A RIFT ORIGIN FOR THE MID-CENOZOIC WESTERN BASINS

The interpretation of a rift origin for the western basins is based on a comparison of their structural development with models of continental rifting and passive margin development (e.g. Boillot, 1978; Curray, 1980; Bally, 1981). Because the New Zealand rift system failed just before the introduction of oceanic crust, the important comparative elements of these models are those that characterize the transition from the subareal rift valley stage to the start of seafloor spreading. Some of these elements

are briefly outlined.

After the initial formation of a rift system, which may or may not be preceded by crustal doming, lithospheric thinning may persist for another 20 My before any oceanic crust can be introduced. During this interval there may be as much as 130% expansion in the width of the original rift (Cochran, 1983). This is accomplished by a mechanical decoupling of the brittle upper part of the crust from the ductile lower part of the crust which thins by visco-elastic creep. This degree of lithospheric stretching substantially modifies the original rift setting. The rift shoulders collapse isostatically such that a more extensive zone of half grabens and tilt blocks develop outward from the rift axis. The shoulders collapse because of the loss of lateral support formerly provided by the crust now depressed in the rift trough. Within this extended rift terrane individual blocks may be several to 20-30 km long, 10-20 km wide, and may have sustained up to 30° of rotation on listric faults (Montadert and others, 1979).

#### Taranaki Basin : a rift trough

Exploration data from the mainly offshore Taranaki Basin permit an infra-rift and an active rift phase of subsidence to be distinguished (Fig. 6). The infra-rift phase, of Paleocene and Eocene age, was characterised by the accumulation of fluvio-deltaic coal-bearing sequences in fault-angle depressions isolated by tilt blocks (Pilaar and Wakefield, 1978; Hill and Collen, 1978). The eastern margin was defined by the Taranaki Fault, and by the late Eocene a 1000 m sequence of non-marine beds had accumulated in a narrow trough between this fault and the Manaia Fault (Fig. 6). The western margin of the basin at this time was poorly defined as the half grabens extended across to the Western Platform. The marked displacement on the Taranaki Fault indicates that

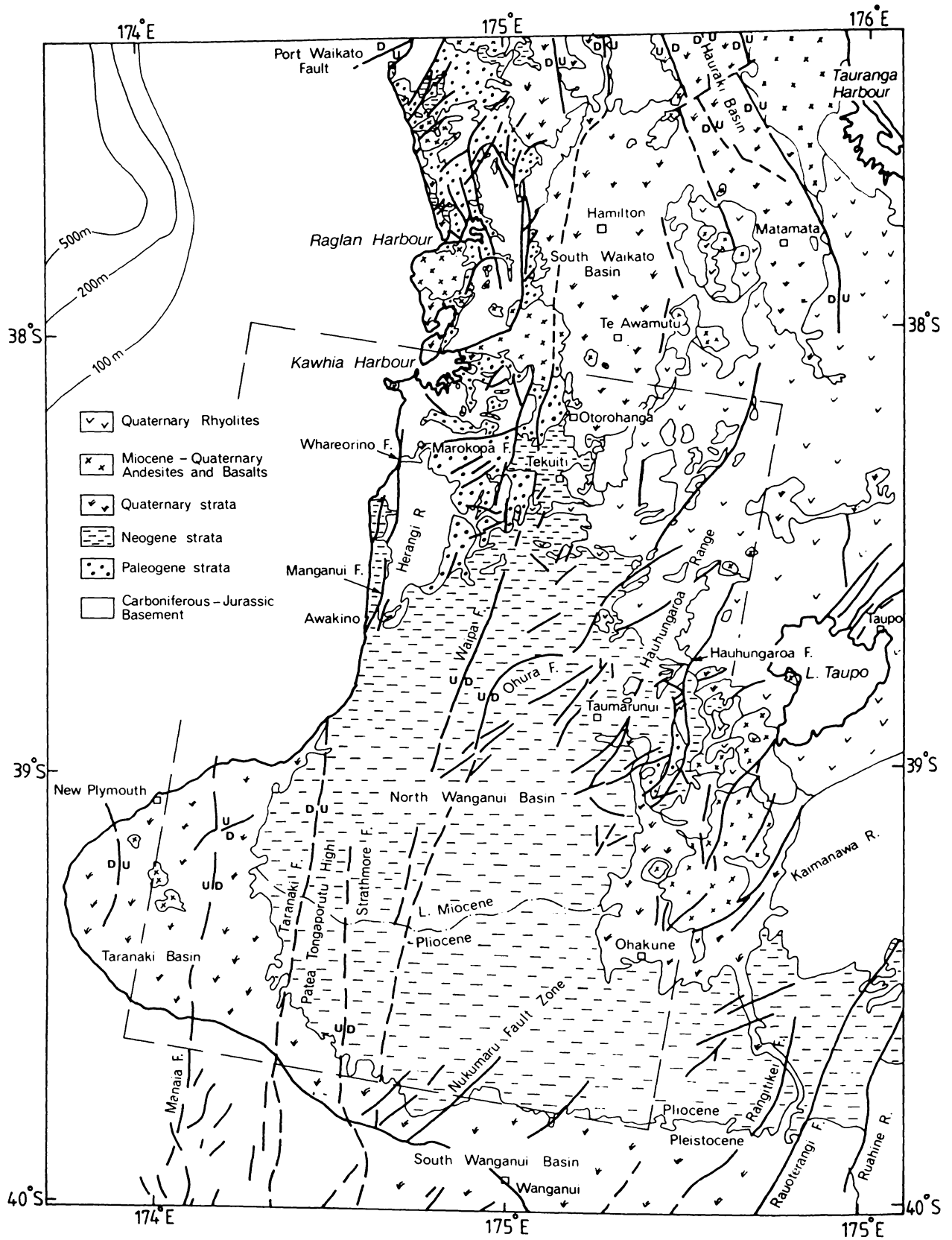


Fig. 10 Simplified geologic map of central-western North Island, New Zealand (after Suggate and Grindley, 1972).

the present asymmetry of the basin had its origins during this phase of subsidence. Towards the end of the infra-rift phase the differential subsidence culminated in the orderly transgression of nearshore and shallow marine facies across the whole of the basin from the north and west. An interval of slow deposition in the earliest Oligocene is indicated by the widespread occurrence of glauconitic sandstones and limestones.

An active rift phase of subsidence was initiated in the middle Oligocene. It started with the development of the Cape Egmont Fault Zone, where differential faulting distinguished the Western Platform from the down-faulted Taranaki Basin. In the context of rift tectonics, the formation of this fault zone may be viewed as compensatory movements for the continued extension which until then had been mainly accommodated on the Taranaki Fault. The rate of subsidence increased markedly through the late Oligocene and into the Miocene, and consequently terrigenous flysch deposits accumulated in the basin, while calcareous oozes accumulated on the stable Western Platform (Fig. 6). During this phase there is no evidence of the tilting of basement blocks and the deposition in fault-angle depressions that characterized Eocene sedimentation. Rather, basin subsidence appears to have been controlled by faulting at the basin margins; the trend for fewer faults and the marginal faults to control the later phases of rifting has also been noted by Anderson and others (1983) in the Basin and Range Province. The age of initial subsidence, the amount of subsidence, and the axial location, suggest that the Taranaki Basin represents the central trough of the rift system.

North Wanganui Basin : collapse of the rift shoulder

ig. 10            Pre-Miocene cover rocks south of Awakino are scarce (Fig. 10), indicating that basement was exposed east of the Taranaki Fault during the early stages of rifting. At the Oligocene-Miocene boundary the

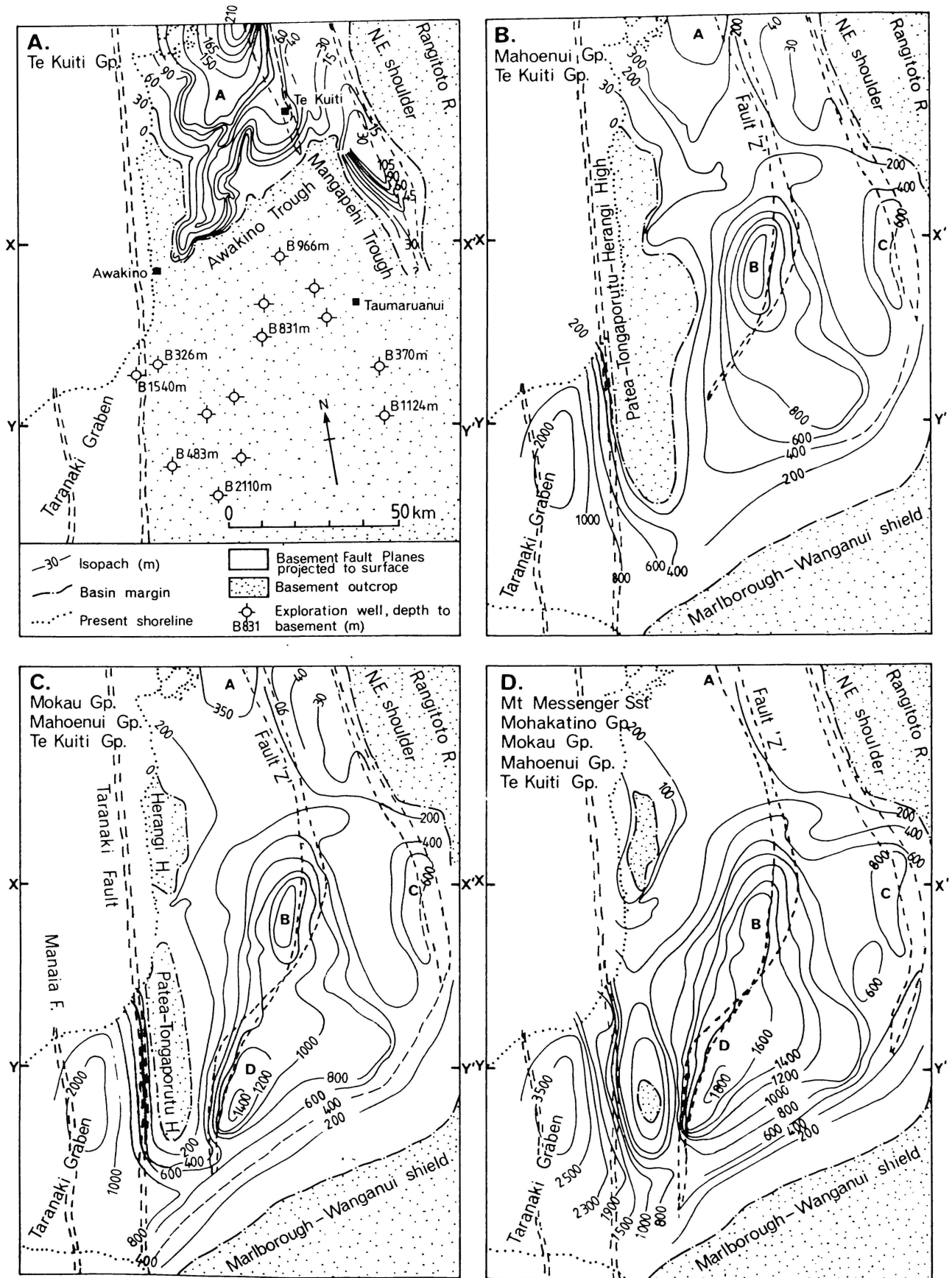


Fig. 11 A sequence of progressively cumulated isopach maps of the successive Oligocene and Miocene formations and groups in the North Wanganui Basin, North Island. The extent of the maps is shown in Fig. 10. Map A after Nelson (1978). Data for maps B, C and D from McQuillan (1977).

North Wanganui Basin (abbreviated NWB) suddenly developed between two structural highs of Mesozoic basement : the Hauhaungaroa-Rangitoto High to the east, and the Herangi-Patea-Tongaporutu High to the west (Fig. 10). Because the NWB lies immediately east of the Taranaki Basin, and its rapid subsidence followed the initiation of the active rift phase, the possibility is explored that its origin results from the collapse of the eastern rift shoulder, in the fashion predicted by the models of continental rifting at the expanded rift stage. The origin of the NWB has previously been attributed to transform tectonics (McQuillan, 1978). Details of the stratigraphy and structure of the NWB are reported by Nelson and Hume (1977) and Hay (1978).

Unfortunately the data available to reconstruct the present depth to basement in the NWB are limited. There are no deep seismic-reflection profiles, the low sampling density of a regional gravity survey does not permit gravity modelling to identify in detail the present shape of the basement surface (Hunt, 1980), and surface outcrops only expose the upper few hundred metres of a 2 km thick sequence. I have attempted to reconstruct the depth to basement and the sequential evolution of the NWB, from formational isopach data measured from outcrops in the north (Nelson, 1978), and from well logs in the central and southern parts of the basin (McQuillan, 1978). The individual formation and group isopach maps of McQuillan (1978) were progressively accumulated to produce isopach maps for each of four "times" between the late Oligocene and middle-late Miocene (Fig. 11). Because some formation and group contacts are mildly diachronous, for example the Te Kuiti Group-Mahoenui Group contact, each map is not strictly a stage in evolution. The 2-dimensional maps have been transformed into 3-dimensional diagrams to help conceptualize the pattern of basement subsidence and to illustrate thicknesses in cross-section (Fig. 12).

ig. 11

ig. 12

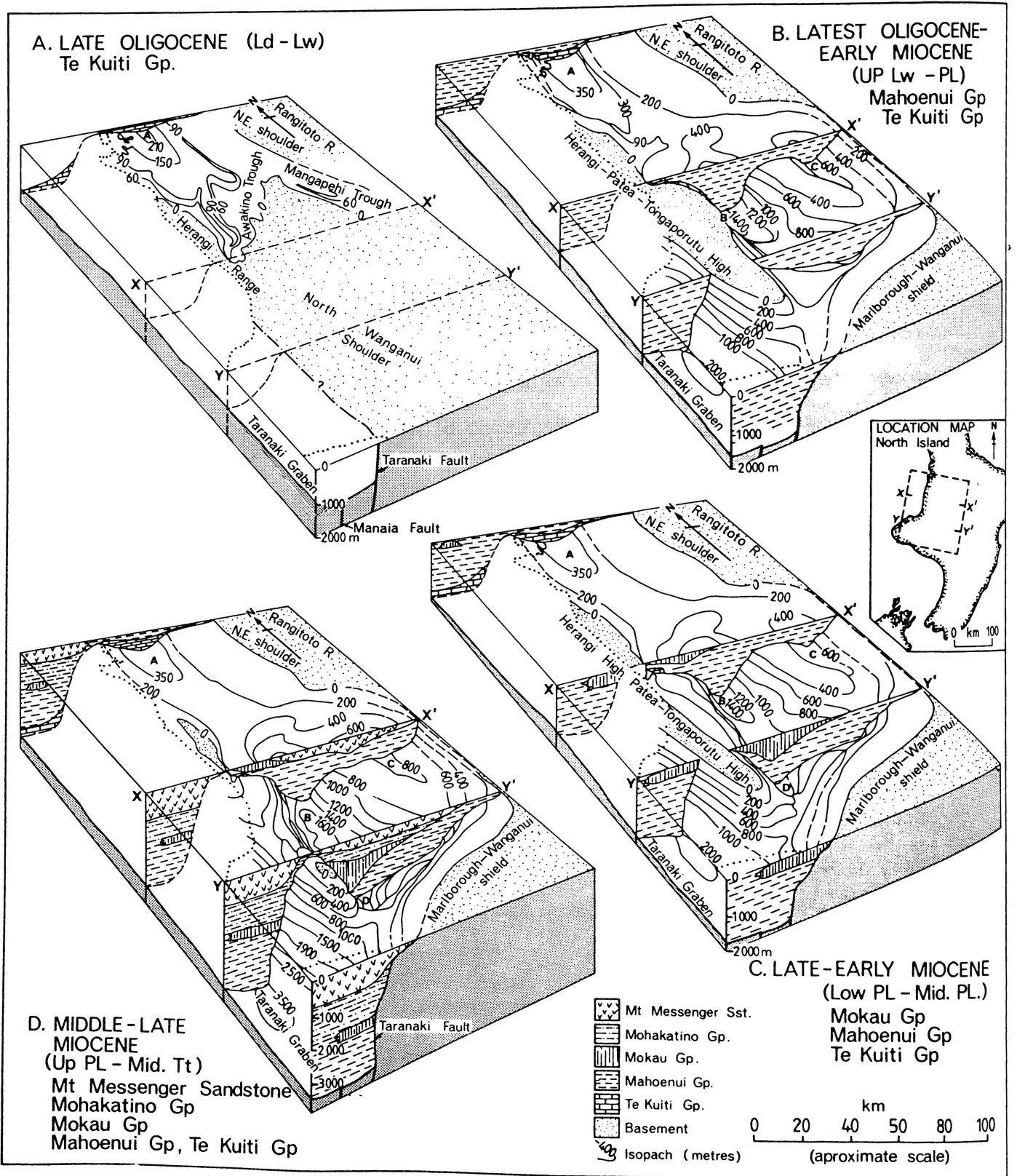


Fig. 12 A series of block diagrams conceptualizing the evolution of the North Wanganui Basin and showing the thickness distribution in sections of the strata upon which the depths to basement are based. Each block diagram is a 3-dimensional transformation of the corresponding isopach map in Fig. 11. Ld, Lw, Po, PL, Tt are abbreviations for New Zealand biostratigraphic Stages (Stevens, 1980).

These diagrams trace the sequential evolution of the North Wanganui Basin and its structural highs. They show that at different times the basin comprised four depocentres or sub-basins of the dimensions typically developed at rifted continental margins (Montadert and others, 1979). A striking feature is the rate at which the exposed basement was differentiated into the structural highs and depocentres B and C (Fig. 11A and B). This happened within 4 million years. Subsequently another depocentre (D) developed, and by the middle-late Miocene it had merged with depocentre B to become the north to north-northeast trending trough which Hunt (1980) identified from gravity modelling. Throughout this time the Patea-Tongaporutu-Herangi structural high persisted but its subareal exposure consistently decreased due to regional subsidence across the whole rift system. A second north-south trending high is inferred to have lain between depocentres B and C.

Despite the evidence of the rapid evolution of depocentres B, C and D, there are few clues at the surface to reconstruct the manner in which the subsidence was accommodated within the basement. Presumably faulting was involved. The near absence of north-south trending faults at the surface coinciding with the margins of these depocentres is strongly suggestive of low-angle growth-faults in the basement, which were concealed by contemporaneous sedimentation. I have inferred the subsurface locations and attitudes of such faults from the shape and gradients of the isopach structure contours; their surface projections are shown as shadow zones in Fig. 11 B, C, D. The least number of faults required to explain the first-order shapes of the depocentres have been shown.

The inference that subsidence of the depocentres was facilitated by growth-fault displacements in the basement enables one to formulate a structural concept which unifies evolution of the sub-basins and structural highs (Figs 13 and 14). Depocentre B is conceived of as a

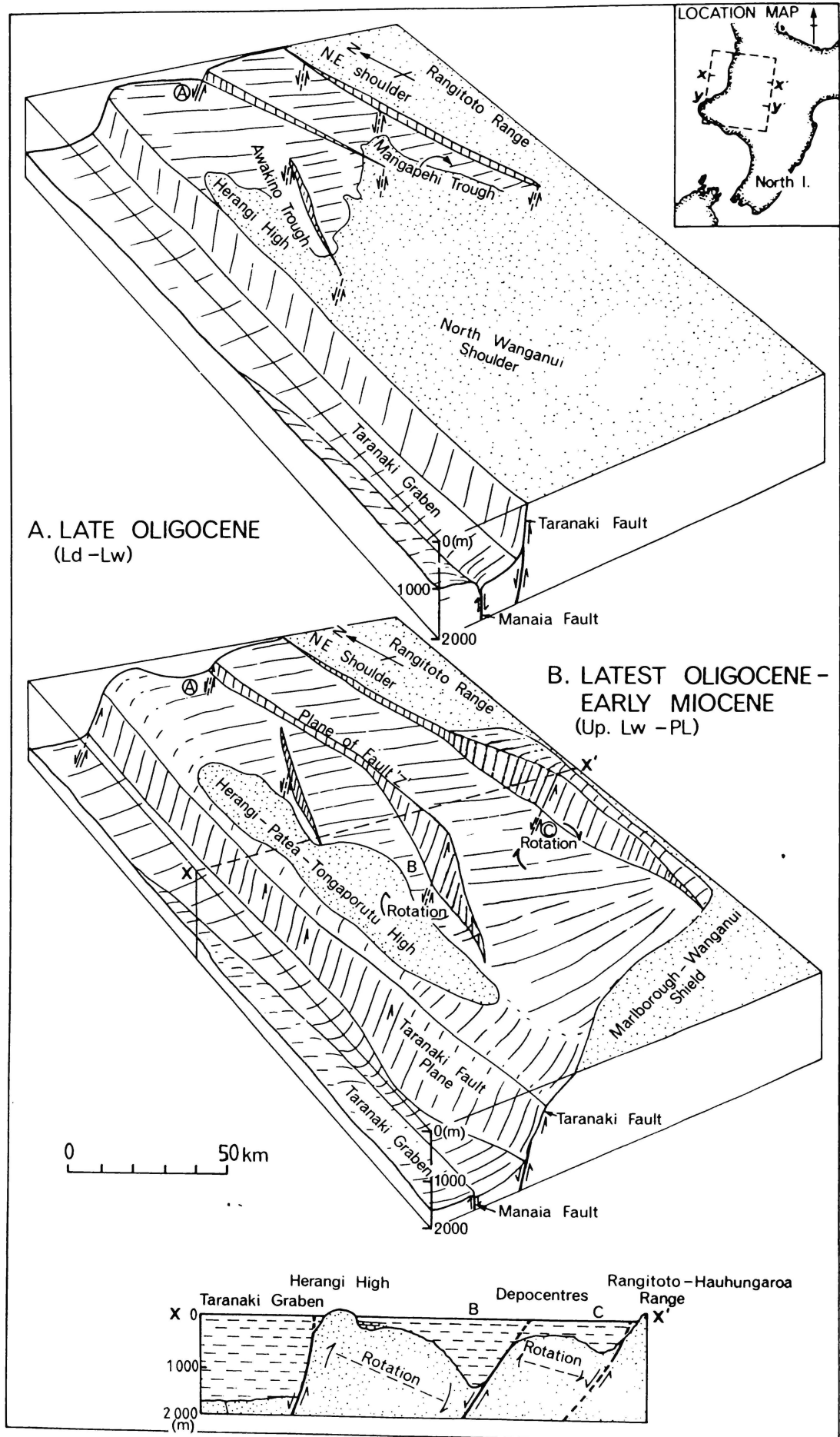


Fig. 13 Block diagrams conceptualizing the late Oligocene-early Miocene collapse of the basement shoulder marginal to the central rift trough of the Taranaki Basin thereby forming the North Wanganui Basin. They show the location and attitude of basement growth faults, inferred from the shape of the depocentres (Figs 11 and 12), in which the subsidence of depocentres B and C are linked to the differential uplift of tilt blocks. Ld, Lw and Po are abbreviations for New Zealand biostratigraphic Stages (Stevens, 1980).

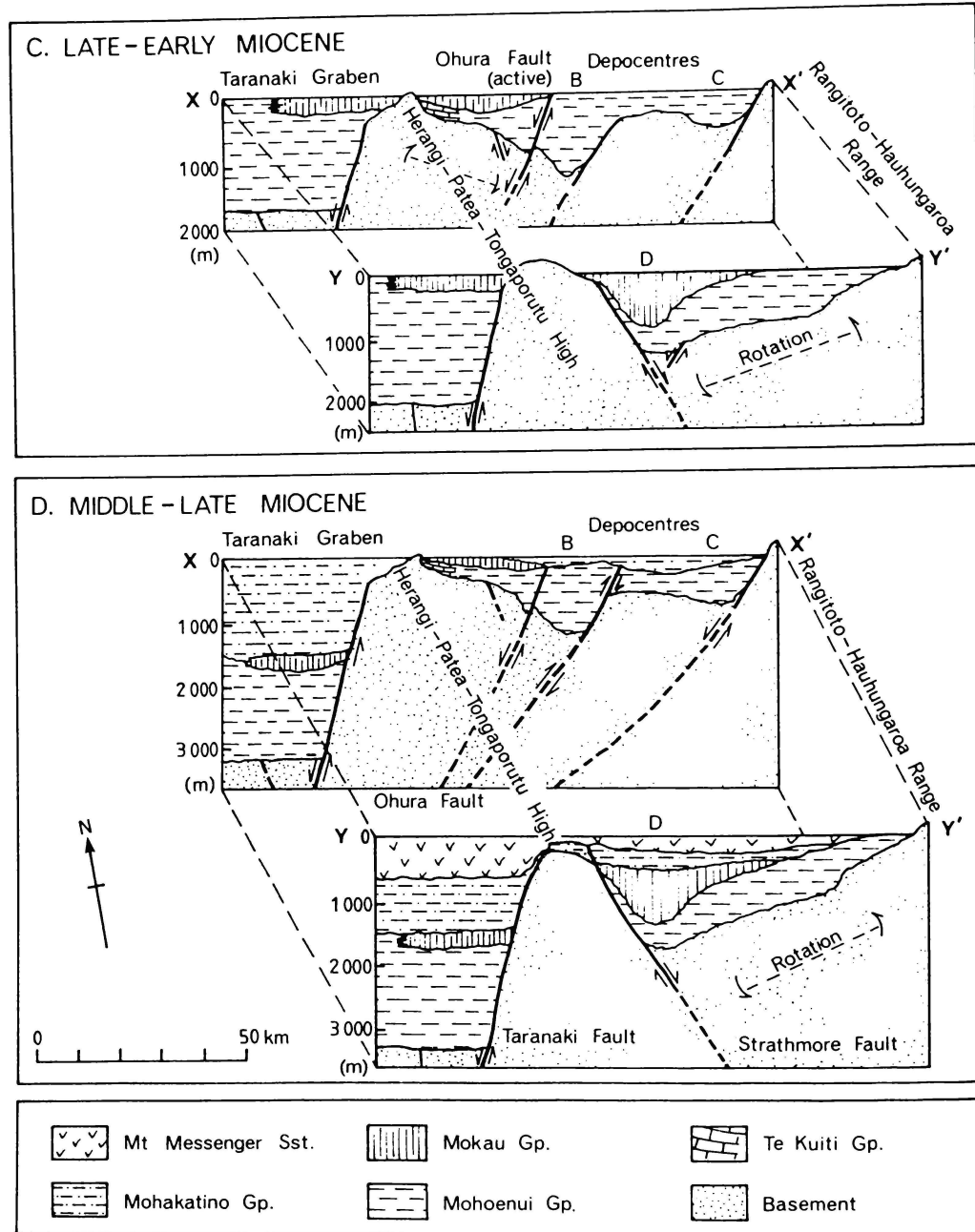


Fig. 14 Cross-sections showing the inferred early to late Miocene structural evolution of the North Wanganui Basin by collapse of the rift shoulder adjacent to the Taranaki graben. The two stages shown here follow on from Fig. 14 and correspond to diagrams C and D in Figs 11 and 12.

half-angle graben developed by the clock-wise rotation about a north-south axis of a 50 km wide block, with the upturned edge being the Herangi High (Fig. 13B). Rotation of this block occurred between the Taranaki Fault and the west-dipping segment of Fault Z. Depocentre C and the submerged basement high separating it from depocentre B also originated by rotation of a basement block. However depocentre D may have had a different origin. The shape and gradient of the isopachs suggests that the controlling fault lay between the Patea -Tongaporutu High and the sub-basin, and logically, subsidence was achieved by anticlockwise rotation of a basement block in this case "hinged" to the east. This suggests that Fault Z is a scissors fault (zone) in the sense of an along strike change in the attitude and direction of downthrow. Two lines of evidence support this origin of depocentre D : (1) Hunt (1980) inferred from gravity data the occurrence of a fault (Strathmore Fault) along the eastern margin of the Patea-Tongaporutu High, and (2), the isopach gradients (Fig. 11) do not support the notion of a fault on the eastern side of depocentre D, and this is confirmed by the gravity data (Hunt, 1980). If, as suggested, this fault dips east beneath depocentre D, the subsidence at D should not be coupled to movement of the Patea-Tongaporutu high, in the way that depocentre B is coupled to the Herangi High (Fig. 14A). Indeed, it is noticeable that the Patea-Tongaporutu High became buried in the late Miocene, perhaps because no part of that block was differentially loaded, whereas the Herangi High remained emergent.

That subsidence of depocentre B was coupled to latest Oligocene-Miocene uplift of the Herangi High is corroborated by a 30° shallowing of dip through the Te Kuiti Group, Mahoenui Group and Mokau Group at the eastern end of the Awakino Gorge (Nelson, 1973). This progressive change in dip upward through the sequence, and the associated facies changes, indicate wedging of the basin succession to the west. The

occurrence of mega-slumps in shelf sequences of the Mohakatino Group (Henderson and Ongley, 1923) on the flanks of the Herangi Range probably originate from tilting of the high and indicate that it was still being differentially uplifted in the middle Miocene. This was despite the fact that overall its subareal extent was decreasing.

The structural concept of North Wanganui Basin evolution, characterized by the collapse, landslide fashion, of high topography toward an adjacent rift trough (Taranaki Basin), is consistent with the stage of an extended continental rift system.

The growth faults inferred in the North Wanganui Basin are probably listric faults of the type which have now been found to bound tilt blocks in modern and former rift systems (Bally and others, 1981; Anderson and others, 1983; Cape and others, 1983). High quality seismic-reflection lines have shown that these faults, normal at the surface, become curved at depth and sole-out as subhorizontal structures at about 10 km near the mechanical discontinuity between the upper brittle crust and lower ductile crust. Not uncommonly the throw can vary along these faults (Moore and Davidson, 1978); this is clearly the case in the North Wanganui Basin. It is also not uncommon in rift settings for scissor faults to occur. One can only speculate about the dip of the faults at depth within the basement below the NWB, but if they are substantially curved, they probably intersect one another and the master Taranaki Fault at levels shallower than 10 km. This is similar to the fault pattern identified at depth in parts of the Rio Grande Rift (Cape and others, 1983).

#### DIRECTION OF RIFT PROPAGATION IN THE NORTH ISLAND SEGMENT

The direction of rift propagation in the North Island segment is revealed by the spatial and temporal differences in the degree of rift development. Section A-A' of Fig. 6 in the context of Fig. 2, shows that

near the Oligocene-Miocene boundary the initial rift trough, between the latitudes of Kawhia and Ohakune, developed into an expanded rift. In comparison, the region to the south between Ohakune and Nelson (section B-B') never developed past the stage of a central rift trough. In view of Vink's (1982) model of rift propagation, this pattern indicates a southward direction of propagation.

The expanded stage of rift development in the latitude of the NWB, in the context of the southward direction of rift propagation, predicts that there might have been the introduction of oceanic crust north of Kawhia's latitude. Coincidentally, large positive geophysical anomalies, in-line with the Taranaki Basin and north of Kawhia (Fig. 2), have been reported by Hatherton and others (1979), who considered them to be rift originated basaltic volcanics because of their large size and flat-topped shape. Other workers have considered them to be subduction derived volcanics (Hayward, 1979) on the basis of their proximity to early Miocene calc-alkaline volcanics in western Northland. However, their position and inferred age (late Eocene-Oligocene) strongly suggest that the more northern anomalies represent the centres of incipient seafloor spreading; the more southern anomalies of Hatherton and others (1979) may have a mixed rift and subduction origin.

The Cenozoic geology of western North Island north of the NWB corroborates the north to south direction of rift propagation. In South Auckland from Awakino to Port Waikato (Fig. 10), an extensive but thin Oligocene shelf sequence, amounting to several hundred metres, accumulated east of the northern extension of the Taranaki Fault (Kear and Schofield, 1959; Nelson, 1978). This succession accumulated in a northward deepening epeiric sea between structural highs, and except for a lesser amount of subsidence, is inferred to be tectonically equivalent to the North Wanganui Basin, and to have originated by collapse of the eastern rift shoulder. Thus the early Miocene pattern of an

expanded rift zone passing southward to a single rift trough (Figs 2 and 6), was evidently a later repetition, 100 km to the south, of the Oligocene setting where an expanded rift/in South Auckland, between the latitudes of Port Waikato and Awakino, lay north of the single rift trough of the Taranaki Basin. From the occurrence of late Eocene coal measures in half grabens beneath the Oligocene marine sequence, the expanded rift started to develop in South Auckland while the central trough of the Taranaki Basin was near the end of the infra-rift stage (Fig. 6).

#### AGE AND DEGREE OF RIFT DEVELOPMENT IN THE SOUTH ISLAND SEGMENT

Southland : an Oligocene extended rift system

The disposition of basins and structural highs in Southland (Figs 5 and 8) is analogous to the pattern in the Taranaki Basin-North Wanganui Basin section of the North Island rift segment. The Oreti Basin passed northwards into a basement terrane which never had a cover of Cenozoic marine rocks, just as the NWB passed southward into the Marlborough-Wanganui shield (Fig. 2). A structural ridge, the Longwood-Takatimu High, the equivalent of the Patea-Tongaporutu-Herangi High, separated the Oreti Basin from the combined Waiau-Te Anau Basin, which extended much further to the north, just as the Taranaki Basin extended further south than the NWB. The analogous pattern in Southland suggests a northward direction of rift propagation. In following current usage, the Waiau and Te Anau basins and their more northern equivalents (Turnbull and others, 1975) are collectively referred to as the Moonlight Tectonic Zone (abbreviated MTZ).

The MTZ rapidly subsided in the late Eocene-early Oligocene and,

unlike the Taranaki Basin, the basal beds were deposited directly on basement without evidence of a regional blanket of infra-rift coal measures (Fig. 8; D-D'). The occurrence of mass-emplaced breccias and conglomerates which accumulated in subareal and submarine fans, attest to the exposure and erosion of master fault scarps along the MTZ. That the MTZ was rapidly down-faulted in the Oligocene is also shown by the rapid change over a few kilometres from a 2 km thick fining-upward basinal flysch succession to basin margin sequences only tens of metres thick (Norris and others, 1978).

By way of comparison, the base of the adjacent Oreti Basin contains a thin late Eocene coal measure sequence, and accumulated an Oligocene succession of mainly calcareous siltstone lithologies. An interpretation of bore-hole data does however suggest the occurrence of a narrow and deeper fault-controlled sub-basin adjacent and parallel to the Longwood-Takatimu High, which was infilled with an early to middle Oligocene flysch succession (Hyden, 1980) (Fig. 8; D-D'). The Oreti Basin as a whole shallows to the east and has an asymmetrical form. Both the shallower depth of the Oreti Basin and its slightly younger age, together with the symmetrical form of the MTZ (Norris and Carter, 1980) suggest that the MTZ was the rift trough and that its rapid subsidence induced subsidence of the Oreti Basin by collapse of the rift shoulder.

Regional onlapping patterns and fining-upward trends show that the differential subsidence of the MTZ and Oreti Basin was accompanied in the late Oligocene-early Miocene by regional subsidence also involving the structural highs. One manifestation of this is that by the late Oligocene both the Fiordland and Longwood-Takatimu Highs were submerged and ceased to be the dominant source areas; a regional paraconformity developed within condensed sequences on the flanks of these highs (Carter and others, 1982). The regional subsidence was, however, accompanied by differential movement of the structural highs, and Norris and Carter (1982) concluded of them:

"Tilting of the blocks probably occurred so that the margins of the Fiordland and Takatimu blocks adjacent to the Waiau and Te Anau basins may have been uplifted." Such tilting adjacent to the central trough and in the context of regional subsidence is the pattern identified in the Taranaki-Wanganui region, and<sup>is</sup> that characteristic of continental rifting at the expanded rift stage. In this instance only the eastern shoulder collapsed; the Fiordland block persisted as a large intra-rift plateau.

#### Northern Solander Trough : transform versus rift tectonics

Norris and Carter (1980) have synthesized a history of Cenozoic sedimentation at the head of the Solander Trough from seismic profiles tied into interpretation of the PARARA-1 well log. They inferred that Balleny Basin seismic units 1 and 2 derived from west of the Alpine Fault, and that Solander Basin seismic units A and B (Eocene-middle Miocene) derived from the Fiordland Block, considered by them to have been dextrally displaced 20-30 km on the Fiordland Boundary Fault Zone (FBFZ).

Their evidence rests critically upon the inferred directions of sediment supply; these are taken to pass outward from the thickest part of each seismic sequence. There are two problems with their interpretation of disappearing source areas. The notion that a source area lay west of the Alpine Fault throughout the Eocene-middle Miocene is not supported by the Cenozoic stratigraphy of south Westland, west of the Alpine Fault. There, a brief late Oligocene-earliest Miocene unconformity is bracketed by deep-marine lithologies, which for the Eocene-middle Oligocene are characterized by foraminiferal limestones and calcareous mudstones, both indicative of distant source areas (Nathan, 1977; 1978a). The second problem relates to the age of the Solander High and the source of units A and B in the Solander Basin (Fig. 5). If the Solander High was a structural high during the Eocene-middle Miocene, units A and

B cannot have derived from Fiordland because the Solander High would have lain directly between this source and the site of deposition. Therefore Norris and Carter (1980) preferred the Solander High to have been uplifted during the mid-late Miocene through a formerly enlarged Waitutu-Solander basin. However, no seismic evidence was presented to show that this high was uplifted after deposition of unit B, and in fact their seismic profiles show that it is a primary feature.

Both these problems are eliminated if one interprets the basins and highs as originating in a continental rift setting within which there was no subsequent transcurrent displacement. The seismic profiles (Fig. 9, B205, B211, Norris and Carter, 1980) show that the Balleny Basin is an asymmetrical basin where the succession thins towards the Big River High by the sequential overstepping of units 1, 2 and 3 toward the east. This, together with the observed angular discordance between units 2 and 3, are consistent with the rotation of a basement block such that the Big River High was the upturned edge and source area. This model not only implies the opposite direction of sediment transport, but also attributes the decreasing thickness of successive seismic units to the reducing area with time of the structural high which was gradually inundated as a consequence of regional subsidence. This pattern of basin development is essentially that of an extended continental rift system as earlier outlined.

The asymmetrical shape in seismic sections of the Solander High, and the sequential onlapping of units A, B and C onto its western flank (Fig. 7, D197, D201, D203, Norris and Carter, 1980), are also suggestive of the clockwise rotation of a basement block to form the Waitutu Sub-basin and concomitantly raise this high as a source area. This is also supported by the angular discordance between each of units A, B and C. The larger Solander Basin also has an asymmetrical form, and the

Stewart Island Shelf and the Mid-Bay High were probably the major source areas.

The Eocene age and the coal measure to shallow marine lithologies of seismic unit A in the Solander-Waitutu basins, determined by correlation with the stratigraphic log and interpretation of PARAPARA-1 exploration well (Norris and Carter, 1980), suggest that an infra-rift phase of subsidence and sedimentation preceded rapid subsidence and flysch deposition. This initial rift development preceded initial subsidence of the MTZ. The oblique NW-SE trend of the Hump Ridge-Mid bay High (Fig. 5) was probably an initial and persistent basement threshold between the MTZ and the Solander-Waitutu basins.

Westland : an inter-plateau section of the rift system

The identification above of Eocene-Oligocene rift development to the north and south of Westland logically suggests that this region should also have evolved by crustal extension / at the same time. The Papanoa Basin is the only basin where there is sufficient information to reconstruct the style of basin development. The isorank pattern (Suggate, 1959) (Fig. 7), the thickness distribution of basin sequences (Wellman, 1948; Gage, 1952), and the facies distribution of fault scarp-derived interbedded breccias and conglomerates (Laird and Hope, 1968), together indicate (Laird, 1968) that the Papanoa Basin comprises two half angle grabens, each downfaulted along the same fault zone but in opposite directions, scissors fashion. The position of the hinge is indicated by the saddle in the isorank pattern (Fig. 7). The along strike changes in both the dip direction and throw of this fault zone (Papanoa Tectonic Zone, PTZ), are identical to those inferred for Fault Z in the North Wanganui Basin (Fig. 11). Depocentres B and D are viewed as tectonic equivalents of the North and South Papanoa basins. Moreover, just as Fault Z developed in the direction

of rift propagation to form depocentre D after B (Fig. 11), there is good evidence that once active faulting started in Westland (late Eocene-Oligocene), it migrated northward along the PTZ also in the direction of rift propagation. Whereas the interbedded breccias and conglomerates are late Eocene in age throughout most of the PTZ, they are of early Oligocene age in the northernmost part of the North Paparoa Basin (Laird, 1968; Germane, 1976).

The change in dip direction of the PTZ and its more western location suggest that the North and South Paparoa basins flanked the central parts of the rift. The Victoria Basin sequence is so highly eroded that confirmation that it was the equivalent of the MTZ or the Taranaki Basin can only come from the geology of the Murchison Basin, a depocentre along strike to the north (Figs 7 and 8, C-C'). Although the Murchison Basin sequence is now steeply dipping and reverse faulted, the regional mappability of groups shows that it was formerly a major middle Eocene to late Miocene basin which accumulated at least a 3500 m thick sequence (Fyfe, 1968; Suggate, 1976) (Fig. 9).

Detailed, though regionally restricted, stratigraphic and sedimentologic studies have identified a unity of basin axis and basin margin tectonostratigraphic events reminiscent of the relationship between the MTZ and its margins (Crooks and Carter, 1976; Carter and others, 1982). Murchison Basin deposition started with the middle to late Eocene infra-rift accumulation of a thin transgressive coastal fluvial to shallow shelf sequence that typically blankets much of Westland but clearly laps onto basement highs (Fig. 8, C-C'). The sudden early Oligocene introduction of turbidites into the quiet shelf environment, the subsequent transition to submarine slope conditions, and the abundant evidence for slumping, indicate and age the rapid onset of basin subsidence and thus of boundary fault movements associated with active rifting. On the

structural high (rift shoulder) marginal to the basin in the west, an angular unconformity between the Eocene infra-rift sequence and overlying Oligocene shelf limestones, together with the occurrence of mass-transported fault-derived breccias and conglomerates (Fig. 8, C-C'), show that the faulting was accompanied by basement tilting (Kear, 1954; Carter and others, 1982). The dominance of biogenic and authigenic deposits on the structural highs and the local hardground development, attest to the low terrigenous input in the middle to late Oligocene, which is consistent with submergence of the structural highs in response to regional subsidence following the rapid and differential subsidence of the adjacent basin. This tectonosedimentary pattern of events is identical to that in the MTZ except for the additional development of an infra-rift sequence (Fig. 8).

With the reversal of 480 km of Alpine Fault displacement, the Murchison-Victoria basins lie some 50 km to the west off the trend of the central rift troughs of the Taranaki Basin and MTZ (Fig. 2). That a well developed infra-rift sequence can be universally distinguished from active rift phase deposits in Westland, but not in the MTZ, suggests that this off-rift displacement is real, and that different parts of the South Island rift segment, now either side of the Alpine Fault, responded differently to the initial crustal extension. Both the off-trend displacement and infra-rift subsidence probably relate to the occurrence in Westland of an earlier late Cretaceous rift system (Laird, 1980). Laird (1968) showed that the PTZ was also the site of late Cretaceous half-angle graben sedimentation and basic volcanism, which more recently he has interpreted as part of a failed rift that intersected the West Coast west of Fiordland and extended northwards into the Western Platform. The mid-Cenozoic reactivation of late Cretaceous structures was clearly easier than developing new crustal structures. It follows that the lesser strength of the late Cretaceous structures also explains

their earlier failure, thereby facilitating the infra-rift subsidence in Westland despite its more northern location than the MTZ.

NW Nelson : the persistence of an intra-rift plateau

The cover rocks of NW Nelson range from middle Eocene to middle Miocene and are mainly confined to the synclinal valleys that flank the margins of uplifted basement anticlines and domes (Fig. 7) (Bishop, 1971; Grindley, 1971, 1980). Non-marine coal measure deposition commenced in half-angle grabens, now the Takaka and Aorere valleys, in the middle Eocene (Couper, 1960), and was followed in the late Oligocene by the deposition of a regionally transgressive limestone (Leask, 1980). The occurrence of the shallow marine Takaka Limestone as outliers upon the Haupiri Dome indicates that this plateau was only briefly submerged during the late Oligocene to mid-early Miocene, and for most of the life of the rift system resisted subsidence.

This transgressive sequence is not however the tectonostratigraphic equivalent of the infra-rift transgressive sequences in the Westland, Solander or Taranaki basins. (1) One difference is the occurrence of a greensand facies at the base of the Takaka Limestone, which may indicate an hiatus of the type described by Carter and Landis (1972). (2) The Nelson succession does not contain the progression of depositional environments typically found, for example, in Westland : coastal fluvial (Brunner Fm.), bay beaches (Island Fm.), coastal lagoons (Kaiata Fm.), longshore sand bodies (Little Totara Fm.), and marine shelf (Crooks and Carter, 1976). (3) The transition to marine conditions in Nelson is characterized by the introduction of bioclastic limestones; in Westland and Taranaki it occurs via the clastic Kaiata Fm. (4) In the Aorere Valley, early to middle Oligocene non-marine breccias and conglomerates which are indicative of active faulting precede the marine deposits

(Leask, 1980), whereas breccias unconformably follow the transgression in Westland. Thus the Takaka Limestone is the tectonostratigraphic <sup>bioclastic (calcarenitic)</sup> equivalent of the basin margin/limestones in Westland (Whitecliffs Fm.), rather than the earlier micritic transgressive limestone in Westland (Port Elizabeth Fm.; Crooks and Carter, 1976) (Fig. 8, C-C'). Furthermore, the regional subsidence which induced transgressive deposition of the Takaka Limestone, was equivalent to, but <sup>some</sup> 10 My later than, the regional subsidence in Westland which accompanied rapid basin subsidence and has been attributed to the expanded rift stage. This subsidence was also later by about 5 My than the initiation of rapid subsidence in the Taranaki Basin.

These differences highlight the lesser development of the rift system in NW Nelson compared with other regions to the north and south. Moreover, they indicate that most of NW Nelson remained emergent even at the peak of rift development. During the Oligocene, parts of it may even have been uplifted; an intra-Oligocene disconformity of regional extent occurs on the southeast side of the main plateau (Germane, 1976).

#### THE SOUTH ISLAND PATTERN OF RIFT DEVELOPMENT IN RELATION TO THE DIRECTION OF RIFT PROPAGATION

By comparison with the North Island segment of the rift system, the South Island segment is considerably more complicated. It comprises two intra-rift plateaux, one in NW Nelson which blocked the continuity of the deep basins, and another in Fiordland which was surrounded by deep basins (Fig. 2). In addition, some of the basins sustained infra-rift subsidence for up to 10 My before the initiation of active basin subsidence, while the MTZ notably did not. This pattern of rift development is however directly comparable with a model of continental rift propagation by Courtillot (1982), who considered the case of a series of locked zones in the initial stage of rifting. In the context of this model, Fiordland and NW Nelson are viewed as the locked zones

that resisted the infra-rift stage of subsidence, while the Westland basins and Balleny-Solander basins were the regions of rift nucleation with infra-rift subsidence. The occurrence of the MTZ indicates that the Fiordland locked zone was eventually breached, but because this was not the case in NW Nelson, a south to north direction of rift propagation is indicated.

The Courtillot (1982) model of continental rift propagation predicts an equivalent amount of horizontal extension across the locked zones as across the rift nucleation sections. In view of the propagation of rifting towards NW Nelson from two directions, the question arises of why this region, and to a lesser extent Fiordland, persisted as plateaux. By comparison with the Rhenish Shield, which blocks the Rhinegraben, the reason may relate to the basement composition. Illies and Baumann (1982) attributed the coherent uplift of the Rhenish Shield to the ductile, tectonically incompetent behaviour of its metamorphic basement, which thinned by stretching, and unloaded the subcrustal lithosphere thereby triggering thermal expansion and consequently isostatic uplift. Apart from the occurrence of granitic plutons, Nelson and Fiordland largely have a high grade metamorphic basement, and therefore may have responded in a similar manner to the Rhenish Shield. The stratigraphic evidence that the NW Nelson plateau resisted subsidence until the late Oligocene, fully 20 million years after infra-rift subsidence started in Westland and Taranaki, was outlined in the last section. That this shield may actually have been uplifted like the Rhenish Shield is more difficult to prove, but some evidence of this was noted earlier.

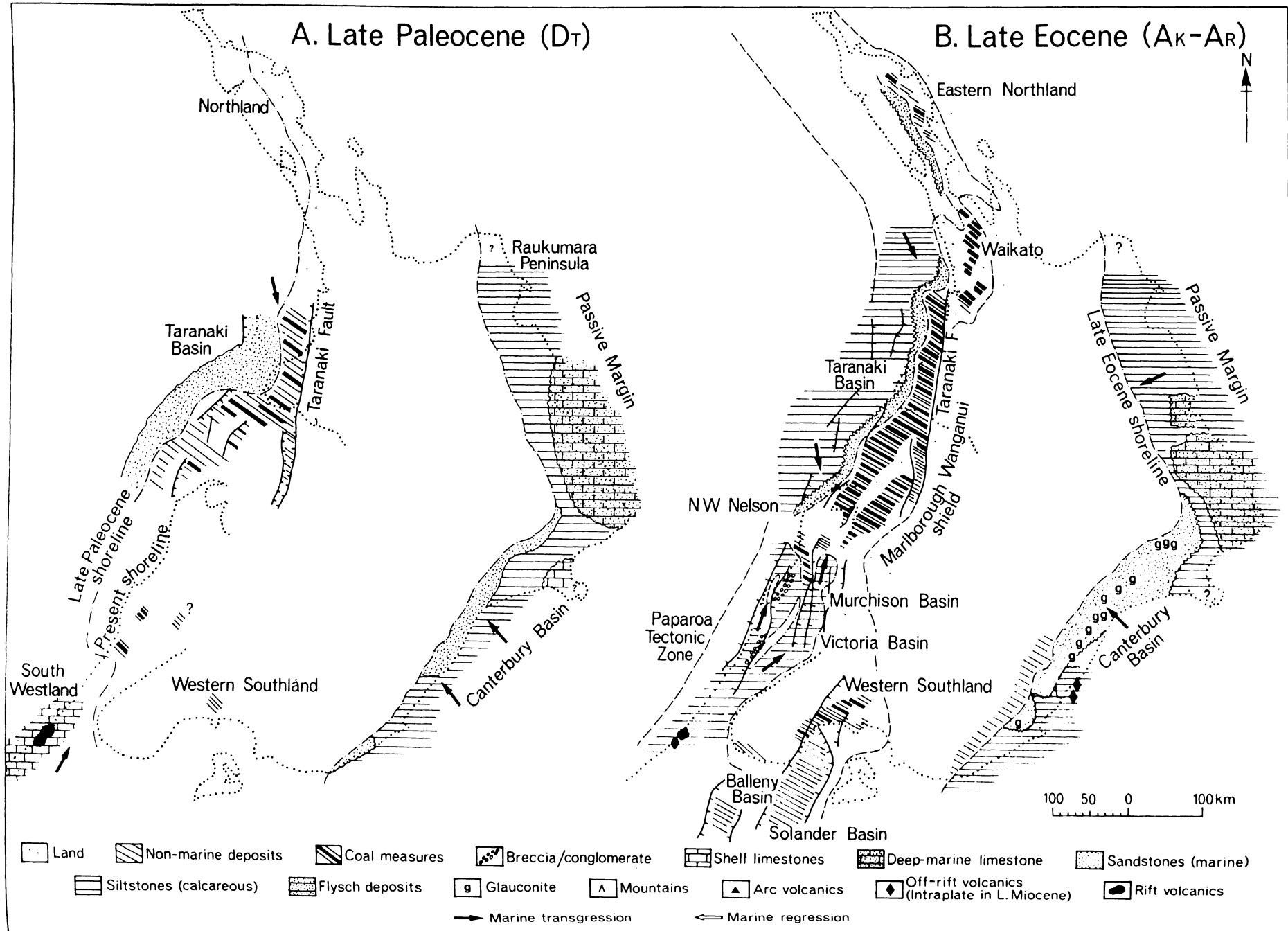
While a lithological control may be a compelling reason for the persistence of the infra-rift shields in the South Island, there is not enough change in basement type between, for example, NW Nelson and Westland to cause such a difference in response to the Cenozoic tensional

stress. Because Laird's West Coast Rift System involved Westland and not Fiordland or NW Nelson, it is proposed that the late Cretaceous crustal stretching and related fracturing pre-conditioned the crust in Westland to brittle failure, and thus pre-disposed it to subsequent basin development. Late Cretaceous crustal stretching may similarly explain the Eocene-Oligocene subsidence of the Western Platform, and hence why the western margin of the North Island rift segment was not as topographically pronounced as the eastern margin (Fig. 2).

#### PALEOGEOGRAPHIC SUMMARY OF RIFT DEVELOPMENT : IMPLICATIONS FOR THE AGE OF ALPINE FAULT INCEPTION

A series of three maps summarize the paleogeographic development of the rift system in the context of the pre-Alpine Fault configuration of New Zealand, and a fourth after 150 km of Alpine Fault displacement (Fig. 15). The paleogeographic development is recorded by way of the distribution, lithologic character and depositional environments of the mainly sedimentary cover rocks. The coherent patterns of Paleogene sedimentation shown by the first three maps corroborate the adopted shape of New Zealand at that time.

The Paleogene deposits in western New Zealand (Fig. 15A) are mainly non-marine coal measure lithologies, except in South Westland where deep-marine foraminiferal limestones and submarine basaltic flows and volcanic breccias of alkaline affinities accumulated (Nathan, 1977). Although the non-marine deposits accumulated where the rift system later developed, their deposition was probably controlled by basement irregularities inherited from the earlier late Cretaceous phase of rifting. The marine transgression in South Westland probably relates to isostatic subsidence at the edge of the subcontinent, induced by lithospheric cooling following seafloor spreading in the Tasman Sea which separated it from the thermal



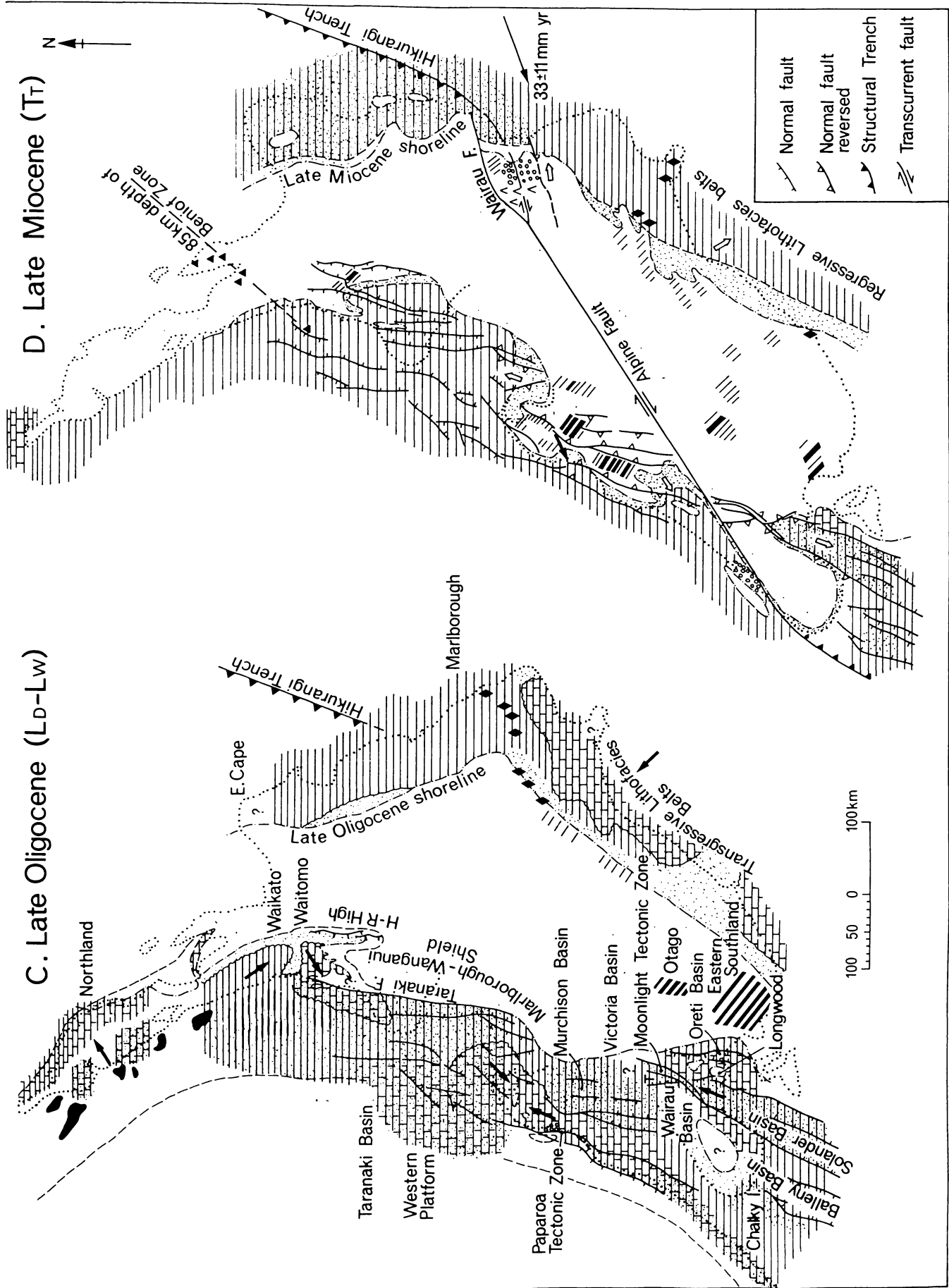


Fig. 15 A series of four maps showing the paleogeographic and paleotectonic development of New Zealand through the Cenozoic. See text for discussion. Lithofacies distribution partly after Stevens and Suggate (1978) and Pilaar and Wakefield (1978). 85km depth contour of the Benioff Zone after Kamp (1984).

anomaly at the spreading centre.

By the late Eocene there had been 20 My of infra-rift subsidence in Westland and shallow marine seas had transgressed northward into the Murchison and Paparoa basins, although intervening basement ridges may have still been emergent. Consequently, the extensive middle Eocene coal measures are not shown on Fig. 15B. Active late Eocene faulting in the Paparoa Tectonic Zone is evidenced by breccias and conglomerates. By the late Eocene a thick infra-rift mainly non-marine succession with coal measures had also accumulated in the Balleny and Solander basins. The Eocene basalts in South Westland, by comparison with the Paleocene basalts, are more alkaline, less differentiated, more voluminous and the sites of extrusion are further north (Nathan, 1977). In the middle to late Eocene the hydrocarbon productive fluvio-deltaic coal-bearing Kapuni Formation accumulated through infra-rift subsidence in the Taranaki Basin; its thickness demands considerable movement on a well defined Taranaki Fault at that time. Economically important coal measures also accumulated in north-south trending half grabens controlled by pene-contemporaneous basement faulting in the Waikato Basin (Kear and Schofield, 1978) and in eastern Northland (Kear, 1959); their northeastern location with respect to the Taranaki Basin heralded the Oligocene development of an expanded rift system in the more northern latitudes.

By the end of the Oligocene active subsidence had clearly formed deep troughs and the accompanying regional subsidence had inundated many of the intra-rift source areas, such as the rift shoulders, and consequently limestone deposition<sup>had</sup>/became widespread (Fig. 15c). The Marlborough-Wanganui Shield can have been the only important source area and probably supplied flysch sediments north to the Taranaki Basin, east to the Murchison Basin, and south to the Moonlight Tectonic Zone. Shallow marine skeletal limestones and volumetrically minor phosphorites

and glauconites accumulated on the current swept rift shoulders and intra-rift shields in clear waters above and away from the submarine canyons funnelling terrigenous detritus to the basins. Calcareous oozes accumulated in deeper water west of the basins which trapped the terrigenous material. The basalt volcanics in the northern part of the rift, considered to be indicative of incipient spreading, were probably emplaced in the late Eocene and Oligocene.

The Paleogene sedimentation patterns in eastern New Zealand are in sympathy with the concept of a rift system to the west. Kingma's (1974) Eastern Basin of eastern North Island and Marlborough accumulated mainly deep-marine fine-grained terrigenous deposits with calcareous oozes in the southern part. The deposits became increasingly calcareous and glauconitic into the Oligocene, and this probably reflects a combination of the diminishing elevation of the land to the west, and the partial reversal of drainage back to the west as the rift expanded. The Paleogene deposits in the Canterbury Basin are quite different to those of the Eastern Basin, and accumulated in shelf depths. The regional transgression started in the late Cretaceous (Wilson, 1963) and may be due largely to isostatic subsidence following rifting in the Bounty Trough (Fig. 1). An impressive feature of the transgression is the regular sub-parallel displacement of the shoreline to the northwest. This suggests that the sea migrated up a gently southeasterly tilted basement surface. In the Eocene-Oligocene this surface may have been additionally tilted by the effects of rifting in the fashion of Bott and Mithen's (1983) model; the shoreline may have been migrating to the hingeline. The concept of a rift system in the west, and as a consequence a southeasterly tilted paleoslope in Otago and Canterbury, <sup>can</sup> explain the conundrum perceived by Turnbull and others (1975) of Oligocene lacustrine deposits only 10 km east of coeval basinal flysch deposits in the Moonlight Tectonic

Zone.

Whereas the trend everywhere through the Eocene and Oligocene was towards subsidence and transgression, exemplifying a unity of geologic development, the early Miocene marked the time when this trend was reversed, and the rift system was progressively disrupted (Fig. 15D). This change parallels one in eastern North Island, where the once unified Eastern Basin became differentiated and kneaded into numerous and discrete basins by subduction accretion (van der Lingen and Pettinga, 1980; Pettinga, 1982), and in Marlborough, where olistostromes formed as a result of basement faulting and uplift (Prebble, 1980).

There is a very definite pattern to the disruption of the rift system. It started and became most pronounced in Westland, and subsequently its effects were progressively imprinted later in time away to the north and south. Disruption started in the early Miocene in Westland, as marked by a widespread post-Oligocene to mid-early Miocene unconformity; the time break ranges up to the late Miocene in South Westland adjacent to the Alpine Fault (Nathan, 1978a), but is not present north of the Alpine Fault in the Murchison Basin. This unconformity together with the change from limestone to clastic sedimentation, records a major crustal reorganization such that the former basins were everted and became the structural highs and the former highs became the new depocentres. The attitude of the normal faults active during the rift phase determined the direction of overthrusting; the reoccupation of these faults indicates compression and crustal re-thickening in the opposite direction to the earlier extension. By the late Miocene the continued compression in Westland had initiated marine regression from the short-lived Miocene depocentres (Fig. 15D).

The early Miocene unconformity did not extend northwards into NW Nelson, and the first indication of rift disruption there was the

mid-early Miocene change from Takaka Limestone to Tarakohe Mudstone deposition. Evidently, this region was still in an extensional mode while compression was active in Westland. Further north in the Taranaki Basin the/direct effects of compression were delayed until the late Miocene, and as discussed earlier, the amount of uplift progressively decreased northwards. In Southland, now south of the Alpine Fault, the same pattern is evident with a progression from completely everted basins (northern MTZ c.f. PTZ), to uplifted and compressed basins (Waiau c.f. Murchison Basin), to rift basins still in the marine realm (Solander c.f. Taranaki Basin).

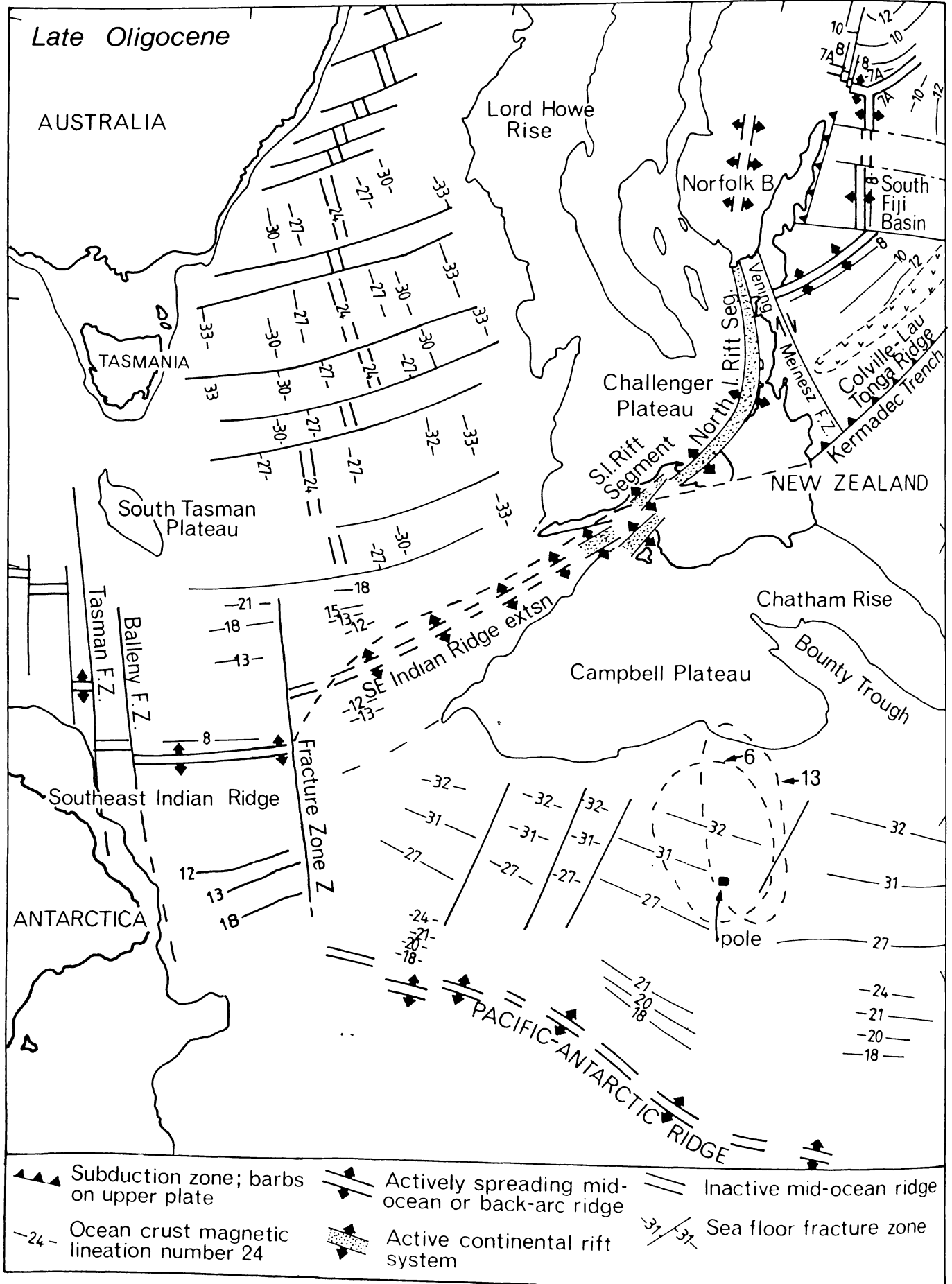
#### Age of Alpine Fault inception

The age and continuity of the rift system through western New Zealand in relation to the trend of the Alpine Fault unequivocally precludes pre-Miocene Alpine Fault displacement.

The evidence that disruption of the rift system started in Westland adjacent to the Alpine Fault, and that the age and degree of disruption symmetrically decreases away from this fault, would date the inception of the Alpine Fault as early-early Miocene, about 23 My BP.

#### RELATIONSHIP OF THE RIFT SYSTEM TO CONTIGUOUS SEAFLOOR SPREADING

The differential degree of rift development through western New Zealand and the directions of rift propagation strongly suggest that in the Paleogene oceanic spreading centres propagated towards the northern and southern parts of the subcontinent. A new interpretation of the history of seafloor spreading in the southwest Pacific confirms this prediction (Fig.16), and shows that the South Island segment linked with the south-east Indian Ridge, and the North Island segment linked with the Norfolk Basin spreading centre. This interpretation is different to others (Molnar and others, 1975; Weissel and others, 1977) because it is



based on different constraints. Specifically, (1) that there has been only  $\approx$  500 km of dextral displacement through New Zealand, and (2), that the displacement started in the early Miocene.

Figure 16 illustrates the plate tectonic setting at anomaly 7 time (26 My B.P., late Oligocene) near the peak of rift system development. It is reproduced from Kamp (1985) where the details of the maps construction are given, and where the implications for New Zealand of the relative plate motions leading up to and past the late Oligocene are fully discussed. The following discussion is based on that paper.

#### Southeast Indian Ridge linkage

The main feature of the SW Pacific plate tectonic setting at An 7 time is the propagation of the SE Indian Ridge into New Zealand. A major characteristic of the magnetic anomaly pattern of the South Tasman Sea

Fig. 16 Plate tectonic reconstruction of the southwest Pacific at magnetic anomaly 7 time (26 My BP), showing how the South Island segment of the rift system was linked to the Southeast Indian Ridge, and how the North Island segment was linked to the Norfolk Basin back-arc spreading centre. See text for discussion.

is a magnetic unconformity defined by the different trends of An 24 and An 21 lineations (Weissel and Hays, 1977). This unconformity indicates a dramatic change in the orientation of seafloor spreading within the space of 5 million years. Weissel and others (1977) considered for no apparent reason that the set of east-west oriented lineations 21-12 immediately south of this unconformity were too far east to have been generated at an extension of the Southeast Indian Ridge. Like Molnar and others (1975), they preferred these lineations to have been generated by oblique spreading at a failed arm striking north from a triple ridge junction involving a linked SE Indian and Pacific-Antarctic Ridge.

In this reconstruction (Fig. 16) the magnetic lineations 12 and 13, now in the Emerald Basin lie opposite the lineations 18-12 south of the unconformity, and together they indicate that a spreading centre must have lain between them. These symmetrically placed anomalies define an eastwards thinning wedge of Eocene and Oligocene crust naturally aligned with the Southeast Indian Ridge, though mildly offset on fracture zones. It is proposed that when this ridge finally broke through between Australia and Antarctica, it rapidly propagated eastwards into southern South Island. It possibly exploited a major east-west fracture zone that offset the earlier north-south trending Tasman Sea spreading centre. Subsequently (An 7-An 6), the Southeast Indian Ridge became further offset on the fracture zones and linked with the Pacific-Antarctic Ridge (Fig. 1). That this linkage was delayed until An 7-An 6 time is shown by the great disparity in spreading rates on these ridges for the interval between An 24 time to An 7-An 6 time (Cande and Mutter, 1982, c.f. Weissel and others 1977). However, these ridges have had comparable spreading rates since An 7-An 6 time.

There is good correlation between the age of ocean crust produced at the Indian Ridge adjacent to New Zealand and the age of rifting in the South Island segment of the rift system. It is difficult to judge the age of the oldest seafloor adjacent to the rift (Fig. 16), but it is probably of An15-An 13 age. This corresponds with the late Eocene-early Oligocene age of active rift subsidence (Fig. 7); the infra-rift subsidence occurred at a time (middle Eocene) when seafloor was being created (An 18) further west (Figs 7 and 16). A corollary of the rift propagation models is that rifting should cease once seafloor spreading stops. Significantly, rifting ceased in the late Oligocene in the South Island segment about the time the youngest seafloor (An 7) was introduced adjacent to New Zealand.

#### Norfolk Basin linkage

The North Island segment of the rift system lies at the southern end of the western Pacific collage of island arcs, trenches and marginal basins known collectively as the Melanesian borderlands (Coleman and Packham, 1976). There is good magnetic and stratigraphic evidence that the South Fiji Basin formed during the Oligocene by back-arc spreading marginal to the Tonga-Kermadec arc-trench system. Magnetic anomaly lineations 12 to 7A have been widely mapped (Watts and others, 1977; Davey, 1982; Malahoff and others, 1982), and locally anomaly 13 has been identified (Malahoff and others, 1982), indicating seafloor spreading involving a triple ridge junction from 36 to 25.5 My BP. Although this indicates the occurrence of an extensional regime to the north of New Zealand, it is not directly linked to the rift system. Unfortunately the magnetic anomaly pattern of the Norfolk Basin (Malahoff and others, 1982) has not yet been analyzed. That the Norfolk Basin originated by rifting and spreading has been consistently inferred (Coleman and Packham, 1976; Crook and Belbin, 1978), and Davey (1977, 1982) has presented

seismic reflection profiles showing the rifted basement morphology of both its western and eastern margins.

In the absence of firm age control, the age and origin of the Norfolk Basin has been inferred from tectonic models based on the age and structure of the South Fiji Basin. Crook and Belbin (1978) and Davey (1982) have both postulated that spreading was contemporaneous with spreading in the South Fiji Basin, thus indicating an Oligocene age. The Norfolk Basin spreading is viewed by Davey (1982) and Ballance and others (1982) as a type of back-arc spreading resulting from the subduction of the eastern plate of the South Fiji Basin spreading centre beneath the Three Kings Rise volcanic arc. Davey (1982) considered that the Norfolk Basin extension did not pass southward into western New Zealand because he was unaware of "... large scale extension through New Zealand in the Oligocene ...." This paper has documented this evidence, and accordingly it is proposed that the Norfolk Basin linked with the North Island rift segment. Anomaly 12 to 7A seafloor spreading would exactly correlate with the Oligocene age of active rift subsidence and incipient seafloor spreading in the rift system.

#### SUMMARY AND CONCLUSIONS

The evidence of a 1200 km long continental rift system of middle Eocene to early Miocene age through western New Zealand has been documented. It comprised a 100 to 200 km wide zone of 2-4 km deep troughs and half angle grabens bounded by normal and possibly listric faults. In the Neogene and Quaternary this rift system was obliquely dislocated by the Alpine Fault and tectonically overprinted by compression originating at the Australia-Pacific plate boundary.

Four phases of rift development have been identified: (1) A 10 My infra-rift phase of slow subsidence in broad depressions or half grabens

characterized by the accumulation of coal measures, and subsequently, shallow marine transgressive lithofacies. (2) An active phase of subsidence which in as little as 2 to 3 My created steep-sided central troughs of slope to bathyal depths in which submarine fan deposits accumulated. Faulting was mainly localised on master fault zones at the trough margins. (3) An expanded rift phase, characterized by the collapse of the basement shoulders marginal to the central troughs, and the creation of an expanded zone of tilt blocks and half grabens up to 2 km deep, in which flysch deposits or shelf limestones and mudstone accumulated. In the South Island this phase followed the start of phase 2 by only 2-3 My, but in the North Island it followed by 10 My. Although the edges of tilt blocks were differentially uplifted, this occurred within an expanded zone of regional subsidence in response to crustal stretching. The regional subsidence submerged many of the terrigenous source areas and permitted the widespread Oligocene development of skeletal shelf and deep-marine foraminiferal limestones. Phase 4 involved the incipient introduction of oceanic crust to the rift axis, and only occurred in the northern part of the rift system.

From the spatial distribution of these phases of rift development it is evident that the rift system had a northern and a southern segment. The North Island segment was the simpler one, and the late Oligocene south to north arrangement of phases 2, 3 and 4 indicate a southward direction of rift propagation. This pattern is identical to that predicted by Vink's (1982) model of rift propagation. By contrast, the South Island segment comprised two locked zones which developed into intra-rift shields flanked by sections of rift nucleation. The South Island segment and its development are directly comparable with Courtillot's (1982) model of rift propagation, and indicate a south to north direction of rifting. Intra-rift subsidence was restricted

to the rift nucleation sections, but the active rift subsidence of phase 2 occurred in the breached Fiordland locked zone at the same time as it occurred in the rift nucleation sections. The occurrence of alternate locked and nucleated zones is attributed to a combination of the factors of basement composition and inherited crustal structure. The age of rift development in the two segments was slightly different. Whereas each of the transitions from phases 1 to 2 to 3 occurred at the same time in the South Island segment, there is a perceptible southward migration of these transitions in the North Island segment. This is evident for the 2 to 3 transition, which is of early Oligocene age between Port Waikato and Awakino, and occurred in the middle Oligocene in the Taranaki Basin; the rapid subsidence of western Northland occurred in the late Eocene-early Oligocene (Hornibrook and others, 1976). This rift system, like the Bay of Biscay margin, was not preceded by doming and was accompanied by only minor volcanism.

The northern segment of the mid-Cenozoic rift system was linked with a seafloor spreading centre in the Norfolk Basin, and the southern rift segment was linked with the Southeast Indian Ridge after it broke through between Australia and Antarctica, and before it linked with the western end of the Pacific-Antarctic Ridge, about which spreading was rejuvenated in the early Miocene. The New Zealand setting may be a unique example where active spreading about a mid-ocean ridge was linked via a continental rift system with an active marginal basin spreading centre.

The age and continuity of the rift system precludes any pre-Miocene transcurrent displacement on the Alpine Fault. An early Miocene age of fault inception of approximately 23 My BP is supported here by the age and pattern of disruption of the rift system which began adjacent to the Alpine Fault. Therefore, the Australia and Pacific plates were

linked via the New Zealand subcontinent until 23 My BP. Consequently it is not valid to resolve through New Zealand the relative motion between these plates which appears to be indicated before 23 My BP by the changing pole positions (Molnar and others, 1975; Weissel and others, 1977; Stock and Molnar, 1982).

In the context of the late Oligocene shape of New Zealand adopted here, the concept of a western rift system provides a geotectonic framework which unifies and explains the complex patterns of New Zealand's early and middle Tertiary structure, stratigraphy and sedimentary geology (Fig. 15). Moreover, the documentation of a north-south trending rift through the New Zealand subcontinent establishes that there were two different ages of rifting, one in the late Cretaceous and the other in the mid-Cenozoic, and that both have contributed to the near complete late Oligocene submergence of the subcontinent.

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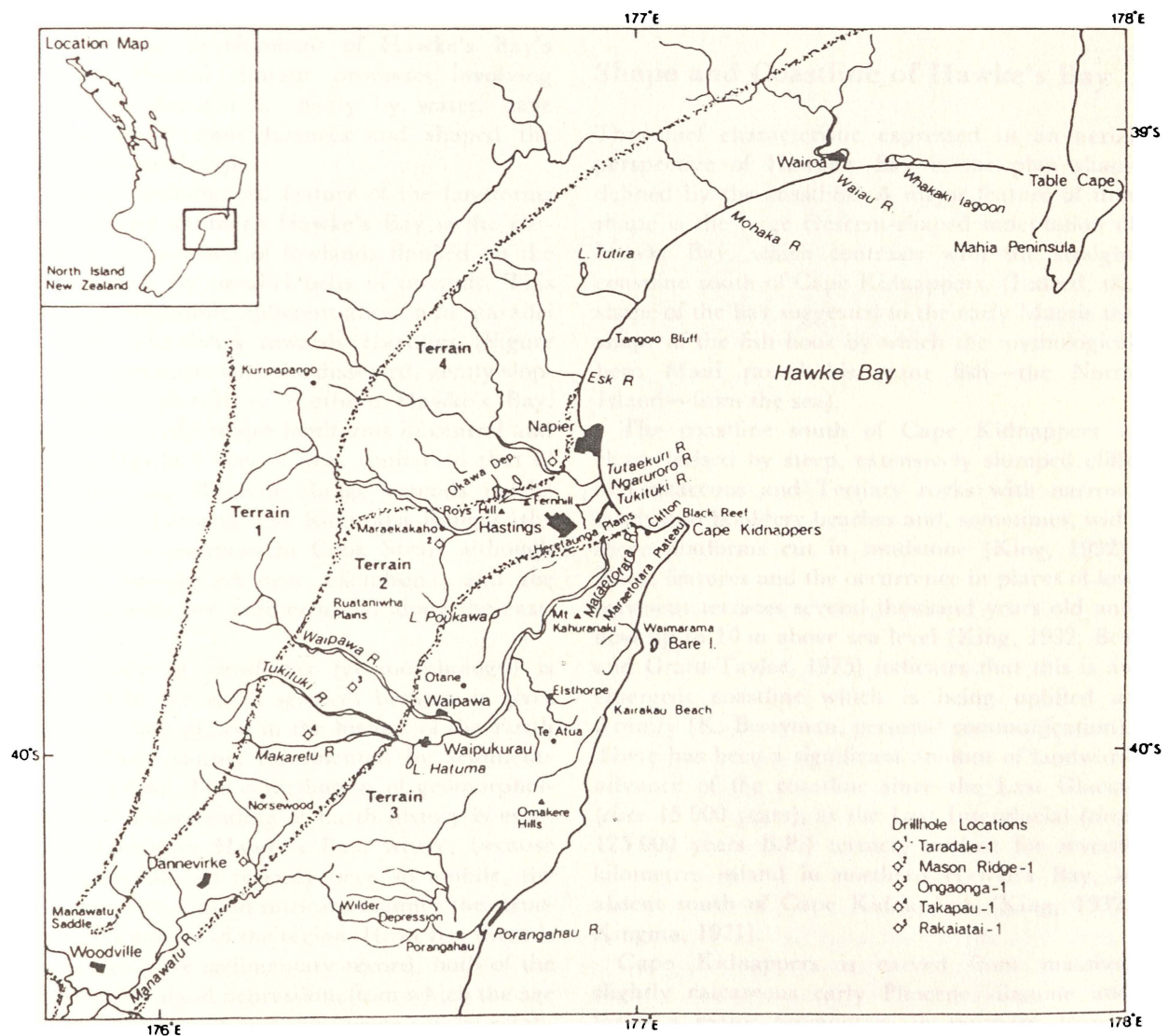
## PAPER 2

Landforms of Hawke's Bay and their origin: a plate tectonic interpretation

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# 12 Landforms of Hawke's Bay and their Origin: A Plate Tectonic Interpretation

P.J.J. KAMP



**Figure 12.1** A map of localities referred to in the text. The boundaries of the landform terrains are shown as stippled lines.

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The landforms of Hawke's Bay—mountains, plains, and coastal uplands—are the expression on the surface of the Earth of crustal forces caused by the interaction and subduction of the Pacific Plate beneath the eastern North Island. The large scale of the topography attests to the magnitude of the forces involved, and the recent age of land formation. An indication that these forces are still active was the occurrence of fault displacements during the 1931 Napier earthquake, reinforcing the importance of tectonism as the dominant factor influencing development of Hawke's Bay's landforms. Humid climatic processes involving erosion and deposition, chiefly by water, have modified the tectonic features and shaped the detail of the landscape.

The most pronounced feature of the landforms of central and southern Hawke's Bay is the pattern of a central belt of lowlands flanked on the west and east by parallel belts of uplands. This marked topographic differentiation and parallel alignment diminishes towards Hastings (Figure 12.1) and contrasts with the dissected, gently sloping, uplifted plateau of northern Hawke's Bay. The pattern of the major landforms in central and southern Hawke's Bay is thus similar to that of Wairarapa: the Ruahine Range extends to the SSW as the Tararua and Rimutaka Ranges, the inland plains continue to Cook Strait although they are interrupted near Eketahuna, and the coastal uplands are uninterrupted along the eastern margin.

The study of landforms (geomorphology) is important in the earth sciences because it gives access to a late period in the history of the Earth that is often scantily documented by sediments (Cotton, 1926). The contribution of geomorphology to an understanding of Earth history is especially relevant in Hawke's Bay, where, because the country has so recently been so mobile, the landforms reflect in an intricate manner the structural development of the region. However, there is also an extensive sedimentary record, both of the uplands and inland depression, from which the age and pattern of uplift and subsidence can be established. Thus, in Hawke's Bay, because of the particular geological and geomorphological setting, there is an outstanding opportunity to study in

one locality the spatial and temporal interrelationships of landforms, structure, and sedimentation—a rock cycle. Moreover, the rock cycle can be related to a driving force—lithospheric plate interaction. Interpretation of high quality geophysical and geodetic data accords with geological interpretations that Hawke's Bay lies at the northern end of an obliquely convergent plate margin that bisects the still largely submerged New Zealand subcontinent.

### Shape and Coastline of Hawke's Bay

The chief characteristic expressed in an aerial perspective of Hawke's Bay is the plan shape defined by the coastline. A major feature of that shape is the large crescent-shaped indentation of Hawke Bay, which contrasts with the straight coastline south of Cape Kidnappers. (Indeed, the shape of the bay suggested to the early Maoris the shape of the fish hook by which the mythological hero Maui raised his giant fish—the North Island—from the sea).

The coastline south of Cape Kidnappers is characterised by steep, extensively slumped cliffs of Cretaceous and Tertiary rocks with narrow, sandy and bouldery beaches and, sometimes, wide shore platforms cut in mudstone (King, 1932). These features and the occurrence in places of low wave-cut terraces several thousand years old and now up to 10 m above sea level (King, 1932; Beu and Grant-Taylor, 1975) indicates that this is an emergent coastline which is being uplifted at 2 mm/y (K. Berryman, personal communication). There has been a significant amount of landward advance of the coastline since the Last Glacial (*circa* 15 000 years), as the Last Interglacial (*circa* 125 000 years B.P.) terrace, evident for several kilometres inland in northern Hawke's Bay, is absent south of Cape Kidnappers (King, 1932; Kingma, 1971).

Cape Kidnappers is carved from massive, slightly calcareous early Pliocene siltstone and forms a major promontory in southern Hawke Bay. Along the coast between Clifton and Black Reef the magnificently exposed mid-Pleistocene Kidnappers Group outcrops as westward dipping.



**Plate 12.1** A view of the coastal section between Black Reef and Clifton (extreme right). The gently tilted strata forming cliffs 100 m high are of middle Pleistocene age. (Photo: M.J. Selby)

alternating pumice beds, conglomerates, and fossiliferous siltstones in cliffs 100 m high (Kingma, 1971; Beu and Grant-Taylor, 1975; Kamp, 1978), (Plate 12.1). A Last Interglacial wave-cut and folded terrace, first described by King (1932), unconformably cuts across the eastern part of the group, rising from 140 m to 210 m from Cape Kidnappers to 4 km inland. Further westward, the terrace correlates with a wave-cut unconformity within the Kidnappers Group and between the upper two formations (Kamp, 1978). A terrace of similar age and origin, now tilted and gently folded and reaching a maximum height of 180 m above sea level, occurs at Mahia Peninsula (Lewis, 1971; K. Berryman, personal communication).

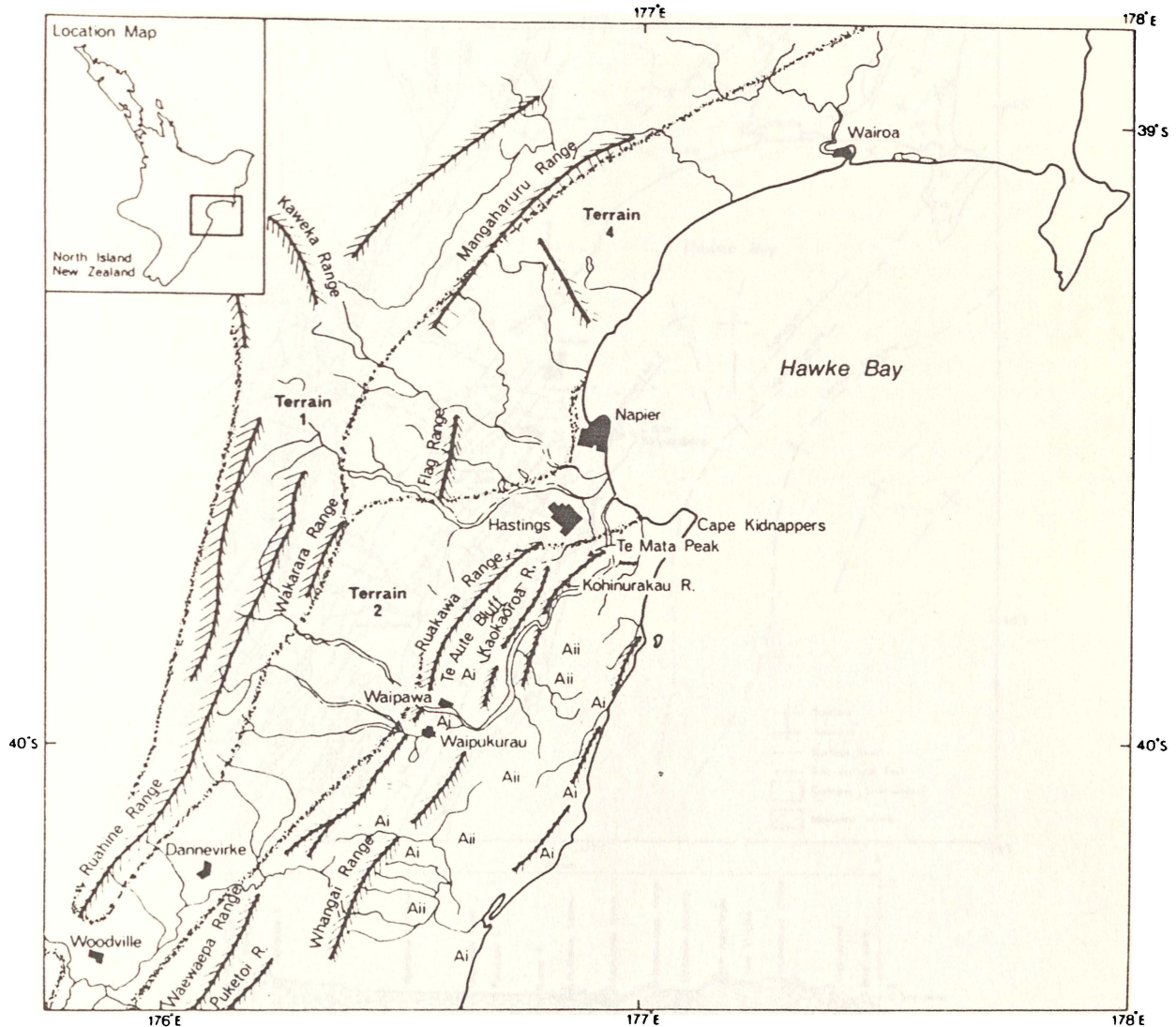
Four limestone promontories, one each at Black Reef, Napier Hill (at Napier City), Tangoio Bluff, and Mahia Peninsula, cause irregularities in Hawke Bay's coastline (Figure 12.1). Between these promontories the coastline is a smooth arcuate shape, especially north-east of Tangoio Bluff

where it is backed by uplifted early Pleistocene mudstone cliffs 200 m high.

### Landform Terrains of Hawke's Bay

On the basis of topography alone, four distinctive geographically separate landform terrains are identified in Hawke's Bay (Figure 12.2): Terrain 1 comprises the axial ranges in the west; Terrain 2 consists of plains and low hills; Terrain 3 is made up of the extensive hill country along the eastern margin; and Terrain 4 comprises the uplifted and dissected plateau of northern Hawke's Bay. These landform terrains can also be characterised by combinations of particular rock types and ages, and by geological structures (Figure 12.3). The intimate association of geology with particular landforms indicates the nature of the tectonic setting and the degree and recent age of tectonism.

Denudation processes have shaped the detail of the landforms of Terrains 1, 3, and 4, while

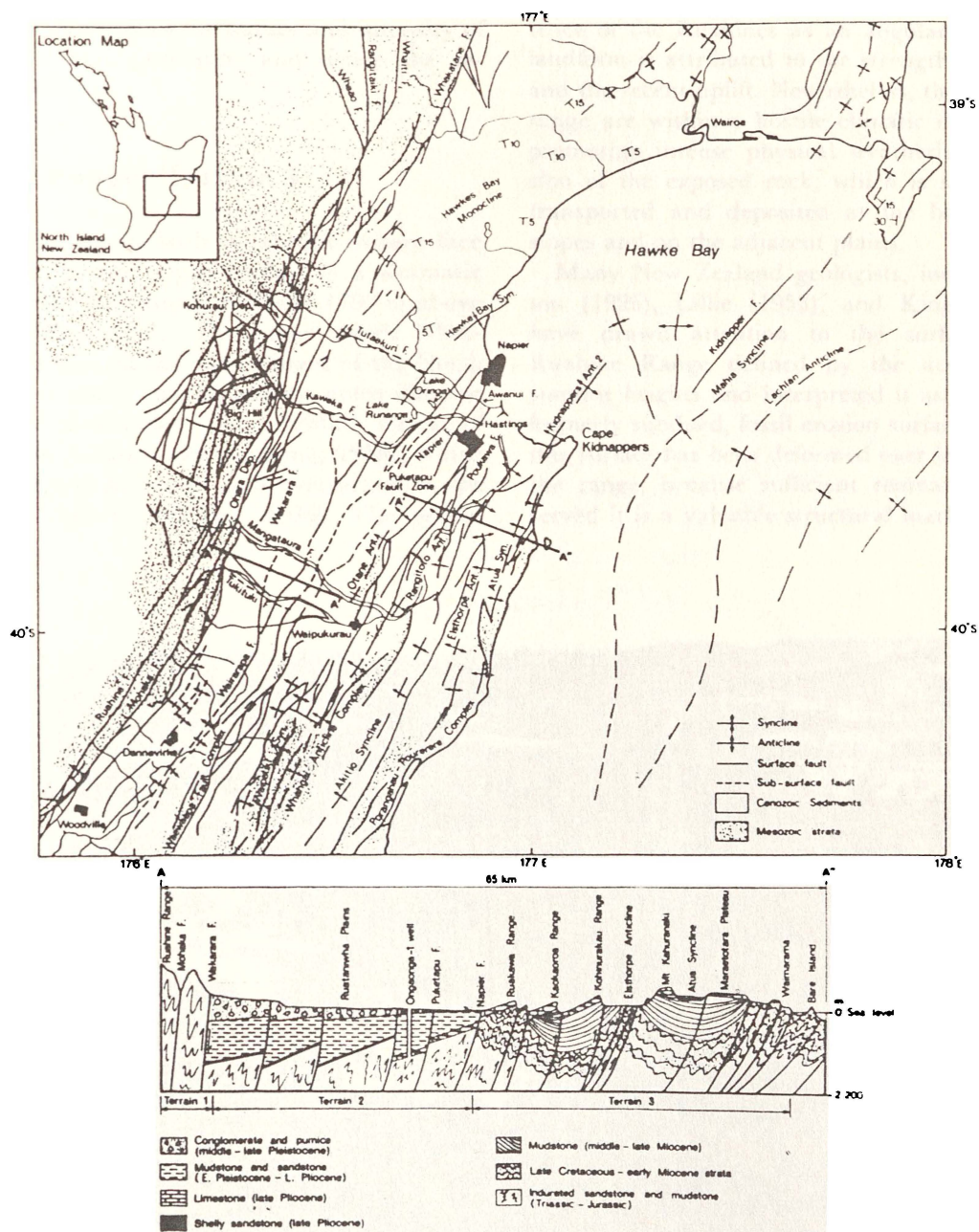


**Figure 12.2** A map of the main ranges and uplands in Hawke's Bay. The approximate positions of Sub-terrains 3Ai and 3Aii are also shown.

sedimentation of the products of denudation has determined the nature of landforms in Terrain 2. The processes of denudation are influenced chiefly by the complex interplay of rock type (lithology), geologic structure, climate, and time available for denudation. Lithology influences landform development by virtue of rock strength or resistance to erosion. Structure influences landform development directly by folding and dislocation of

the Earth's surface, and indirectly by determining the outcrop pattern of different lithologies. The factors of climate and time may either mask or accentuate the influences of lithology and structure; in Hawke's Bay there has been sufficient time for the processes of denudation to accentuate differences of rock type and structure, but insufficient time to obliterate them. The proportional influence of each of these factors in any of

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**Figure 12.3** A map of Hawke's Bay structure and a generalised cross-section (not to the same scale). The map shows the pronounced NE-SW regional structural trends onshore and offshore in central and southern Hawke's Bay. This contrasts with the Hawke's Bay monocline further to the north-east, and the rectangular to rhombic pattern of faulting at the northern end of the Ruahine Range. The cross-section emphasises the importance of post-Pliocene reverse faulting, especially in determining the attitude of the limestone strata. The map and cross-section were drawn from data in the following sources: Lillie, 1953; Grindley, 1960; Kingma, 1962; Leslie and Hollingsworth, 1972; Beu and Grant-Taylor, 1975; Clark, 1976; Lensen, 1977; Kamp, 1978; van der Ling and Pettinga, 1980.

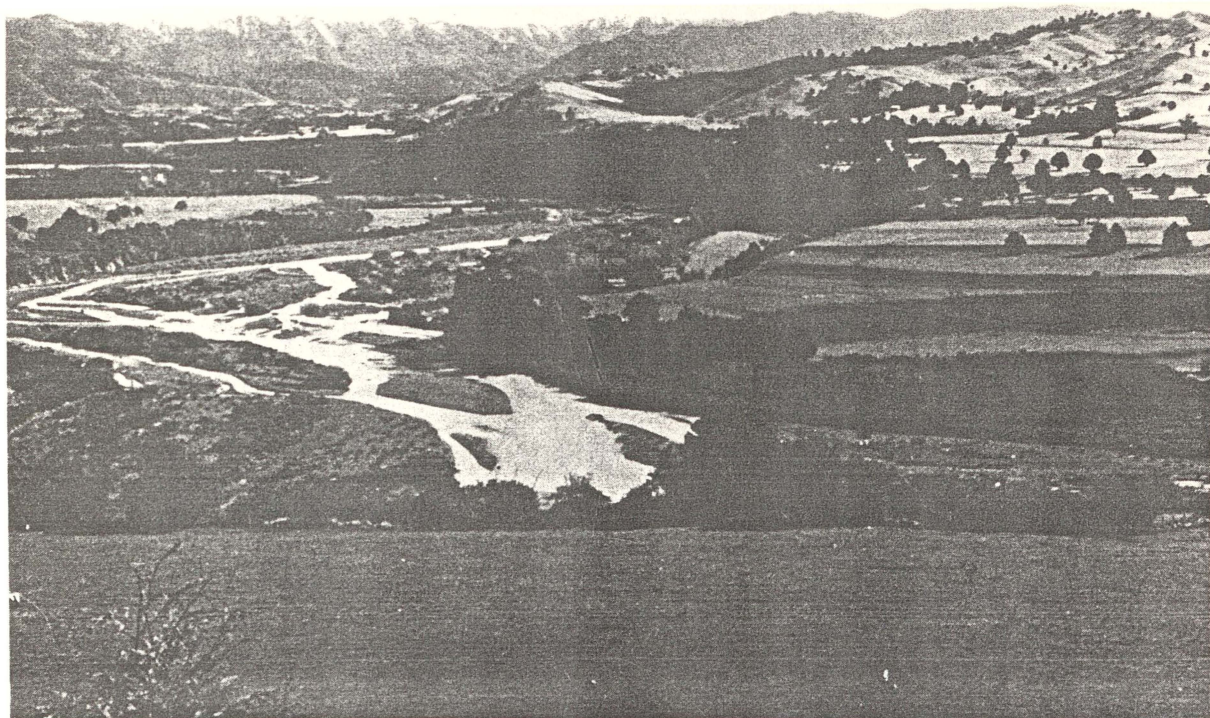
the terrains determines the nature and intensity of the denudational processes, and hence the resulting landforms.

### Ruahine Range: Terrain 1

The Ruahine Range with its abrupt eastern face and gently domed upper surface is a dramatic landform with an altitude of 1000–1700 m above sea level (Plate 12.2). The range trends NNE-SSW and is part of the axial ranges of the North Island. It is made up of largely unfossiliferous alternating sandstones and argillite strata of Triassic and Jurassic age (Kingma, 1959), which are now highly deformed and overturned to the north-west (Spörli and Bell, 1976). The persis-

tence of the Ruahines as an angular upstanding landform is attributed to the strength of the rock and the recent uplift. Nevertheless, the tops of the range are within a hostile climatic environment, promoting intense physical weathering and erosion of the exposed rock, which is subsequently transported and deposited at the base of steep slopes and on the adjacent plains.

Many New Zealand geologists, including Cotton (1926), Lillie (1953), and Kingma (1959), have drawn attention to the surface on the Ruahine Range defined by the accordance of summit heights and interpreted it as an uplifted, formerly subdued, fossil erosion surface. Although this surface has been deformed over large parts of the range, because sufficient remnants are preserved it is a valuable structural marker that can



**Plate 12.2** A view looking up the Waipawa river and along the Mangataura Fault (immediately left of centre; see Figure 12.3) towards the snow-capped Ruahine Range in the distance. The Wakarara Range forms the skyline on the right and extends to the centre of the photograph where it is bounded by the Mangataura Fault. Remnants of the high Salisbury Terrace occur in the middle distance on the right, and low terraces of the Ruataniwha Plains form the subhorizontal terraces in the right foreground. (Photo: M.J. Selby)

be used to study the nature, intensity, and direction of crustal stresses that have formed this terrain.

The fossil erosion surface defines a dome (Grant-Taylor and Hornibrook, 1976), produced by folding of the strata in two directions, one along the range and the other across the range. Lillie (1953) demonstrated that near Manawatu Gorge the erosion surface and overlying late Cenozoic sediments were folded into an anticline with an axis running along the range (NNE-SSW). Cotton (1926), among others, pointed out the occurrence of a pronounced sag in the vicinity of Manawatu Saddle (Figure 12.1), where the range is only 150 m above sea level (see also Chapter 11). North of Manawatu Saddle the south-dipping erosion surface initially rises steeply to 1000 m over a horizontal distance of 12 km and then more gradually to the top of the dome (1733 m). North of the dome the erosion surface gradually descends to 800 m near Kuripapango. The change in height of the erosion surface along the range defines an anticline with an axis trending across the range. Since the dome is elongated in a NNE-SSW direction, compression directed across the range has been much greater than compression directed along the range.

North of Manawatu Saddle, large-scale vertical displacements on steeply dipping reverse faults (Figure 12.3) have fractured the NNE-SSW trending anticline, upthrown the western flank, and produced the abrupt eastern face. Several long faults, principally the Ruahine and Mohaka Faults, have been involved, probably arranged *en échelon*. The amount of throw on the fault planes has varied along the fault traces and Lillie (1953) suggested that these were scissor faults with least upthrow near the Gorge and increasing displacement northward. The maximum vertical displacement of greywacke basement is about 3000 m, which includes about 1300 m of surface expression and 1700 m of subsurface displacement (Leslie and Hollingsworth, 1972), (Figure 12.3). There is also evidence of active transcurrent movement on these faults. Horizontal movement on both the Mohaka and Ruahine Faults is shown by displaced channels of streams and exceptionally well-developed fault facets on the Ruahine

Fault near Big Hill, produced by the offset of spurs (Kingma, 1957a).

In the north-eastern region of Terrain 1 the faulting is extremely complex (Kingma, 1962) and, correspondingly, the landforms are more diverse. The Wakarara Range (Plate 12.2), 1013 m at its highest point, is separated from the northern Ruahines by the Ohara Depression (Figure 12.3), 20 km long and 3 km wide. The northern part of the range is lower and smooth, corresponding to remnants of the erosion surface. Southward the range is higher and presents a saw-toothed profile. Up to 2000 m of early Pleistocene marine sediment is preserved immediately adjacent to the eastern margin of the Wakarara Range where, at the Eaton Thrust, greywacke basement overlies these young sediments (Kingma, 1957a). From consideration of structural evidence Kingma concluded that the Wakarara Range had been thrust SSE along the Mohaka Fault after the early Pleistocene.

The northern Ruahines are separated from the Kaweka Range by a depression in the vicinity of Kuripapango. This comprises the NE-SW trending Kohurau Graben which is bounded in the east by the Ruahine Fault Zone and elsewhere by the arcuate Kaweka Fault (Kingma, 1957b), (Figure 12.3). The occurrence of marine late Pliocene and early Pleistocene strata within the depression indicates that the Kuripapango Saddle was an important strait connecting Hawke's Bay and Wanganui Basin until the end of the early Pleistocene (Kingma, 1957b; Beu *et al.*, 1977). Kingma (1957a) suggested that, analogous to horizontal displacement of the Wakarara Range on the Mohaka Fault, Big Hill had been transported SSW on the Ruahine Fault Zone (Figure 12.3). Such large-scale horizontal displacements are supported by a structural analysis by Lensen (1958), who showed that the 'horst and graben' topography of the Wakarara Range and Ohara Depression was also a consequence of lateral displacements on the Mohaka and Ruahine Faults.

There are presently two models for the origin of the Ruahine Range; one suggests horst development (Kingma, 1957c), and the other posits initial anticlinal upwarping along a NNE-SSW axis, followed later by reverse faulting (Lillie,

1953). The former model implies major vertical displacements on faults bounding both the eastern and western sides, while the latter implies asymmetric uplift chiefly on eastern boundary faults. Since there are no pronounced fault lineaments and no evidence of recent faulting along the western margin of the Ruahine Range (Speden *et al.*, 1978), symmetrical horst development can be excluded. Rather, the western side is probably a slightly faulted monocline, since inland from Taihape, Tertiary beds dip steeply off the range. On the other hand, Lillie's model is supported by the occurrence of greater quantities of greywacke detritus, and its earlier appearance, in Hawke's Bay than in the Wanganui Basin.

### Inland Depression: Terrain 2

The Inland Depression is a belt of lowlands, comprising extensive terraces and low protruding hills, which extend north-eastward from Wairarapa to Hawke Bay. This Terrain conspicuously narrows from 20 km wide near Hastings to 12 km near Woodville (Figure 12.1). The western

boundary with the Ruahine Range is sharply defined by fault scarps and the eastern boundary is located at the base of the prominent dip-slopes of Terrain 3 (Figure 12.3). The topography gradually becomes more hilly in the north where it merges into Terrain 4. The northern extent of terraces is taken as the boundary between Terrains 2 and 4.

### Terraces

There are two main sets of fluvial aggradational terraces in addition to the modern terraces bordering the present river channels. The high terrace set occurs nearer the ranges and reaches an altitude of 500 m above sea level. In central Hawke's Bay Kingma (1971) mapped these as the Salisbury and Waharoa Terraces and recorded that they dip gently (5°) eastward. Lillie (1953) mapped the high terrace set in southern Hawke's Bay and named it the Maraharaha Cycle. Near Dannevirke this terrace set forms a dissected plateau 300 m above sea level with a south-west dip graded towards the Manawatu Gorge. From the slope directions of the high terraces it is evi-

**Plate 12.3** A view, looking northwards from Te Mata Peak, of the Heretaunga Plains (Terrain 2), Napier Hill (City), and part of Hawke Bay. The uplifted and tilted plateau of northern Hawke's Bay (Terrain 4) is evident in the distance. (Photo: M.J. Selby)



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dent that they formed after the present river systems were established. However, subsequently there were minor adjustments including a northward shift of about 8 km in the watershed of the Manawatu and Tukituki Rivers (Lillie, 1953).

The lower, younger terraces are more widespread than the high terraces and have noticeably formed at lower altitudes in the northern parts of Terrain 2. West of Maraekakaho the Pigsty Terraces border both sides of the Ngaruroro River and merge downstream into a single terrace that grades into the Heretaunga Plains (Kingma, 1971), (Plate 12.3). West and north of Takapau, the Waipawa and Tukituki Rivers and their tributaries have formed the extensive Ruataniwha Plains which gradually rise from 150 m near the eastern margin of Terrain 2 to about 500 m adjacent to the ranges. The Ruataniwha Plains appear to be a composite of as many as five separate terraces (Grant-Taylor in Speden, 1978), invariably composed of unsorted gravel. In southern Hawke's Bay the low terrace set surrounding Dannevirke and Woodville occurs at 230 m above sea level, 40 m above the present channel of the Manawatu River. It is composed mainly of greywacke conglomerate derived from the ranges, but locally along the eastern margin the deposits include argillite and limestone pebbles derived from Terrain 3. Most of the low terraces have a loess and tephra (volcanic ash) cover bed normally less than 1 m thick.

*Subsurface Geology of the Inland Depression*

The Inland Depression is filled with a thick pile of Pliocene-Pleistocene sediments (Figure 12.3) which contains a valuable record of the nature and sequence of events which occurred inside the basin and, perhaps more importantly, those events outside the basin which led to the formation of uplands. Interpretation of the record was limited by the scarcity of surface outcrops, but this problem has been partly overcome by the availability of information derived from subsurface seismic surveys and an oil exploration programme (Leslie and Hollingsworth, 1972), (Figure 12.1).

From drillhole data, the sedimentary sequence increases in thickness northward from Rakaiaitai-1

(664 m) to Mason Ridge-1 (1644 m), and from there becomes shallower eastward to Taradale-1 (1250 m). Across the basin the Pliocene-Pleistocene sediments capping the dip-slopes of Terrain 3 project beneath the surface and are progressively reverse downfaulted to a depth of 1700 m adjacent to the Ruahine Range (Clark, 1976), (Figure 12.3). Much of the intrabasin faulting is considered to have occurred during sedimentation, especially during the early Pleistocene, and not only affected the thickness of the sedimentary sequence but also the depositional environment (Clark, 1976).

An important regional unconformity is developed at the base of the depression. Late Pliocene sediments overlie Triassic-Jurassic greywackes in the south (Rakaiaitai-1, Takapau-1, Ongonga-1), and dipping middle (Mason Ridge-1) and early Tertiary sediments (Taradale-1) in the north. A period of major late Miocene-early Pliocene tectonism has been inferred from this unconformity (Katz, 1973; Clark, 1976). On the basis of stratigraphic and structural relations exposed in Terrain 3, Lillie also interpreted and subsequently emphasised (Lillie, 1953, 1980) the importance of late Miocene tectonism. This corresponded with the high point of sedimentation in the Cretaceous-Tertiary Geosyncline (Kingma, 1960), deformation and uplift of that succession (now exposed as Terrain 3), and a westward shift of the axis of subsidence and sedimentation to the Inland Depression. Hence the present structural pattern and the pattern of the associated landform terrains were established during latest Miocene to early Pliocene times.

Fossiliferous marine mudstones, sandstones, and thin coquina limestones of late Pliocene and early Pleistocene age account for most of the material in the depression and indicate that the basin was actively subsiding, and that a seaway existed there until the end of the early Pleistocene. In the middle Pleistocene, the strata suddenly became pumiceous and then conglomeratic, and were deposited chiefly in terrestrial environments including lakes and rivers. The basin, no longer marine, was slowly uplifting, but depositional landforms continued to form because of the large supply of detritus from the adjacent, more rapidly rising Wakarara and Ruahine Ranges. The com-

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bination of slow basin uplift and abundant sediment supply has developed a landform of dissected aggradational terraces where the successively younger terraces are progressively lower in altitude. Where there was not a continuous supply of sediment, such as in the northern part of Terrain 2 (and Terrain 4), processes of denudation formed a hilly topography in early Pleistocene sediments.

*Faulting, Folding, and River Directions*

The Inland Depression is faulted and folded into minor NE-SW striking anticlines and synclines (Figure 12.3), with dips generally ranging from 5° to 20° (Lillie, 1953). Two main fault systems occur—a dominant NE-SW system and a less pronounced NW-SE one. This deformation in the middle and late Pleistocene influenced river directions and thereby determined the areas of sedimentation. Because much of Terrain 2 is covered with Recent sediments and loess, there is little surface manifestation of faulting, but these faults have been identified in subsurface seismic surveys. Many of the towns and cities in Terrain 2 are situated on or about these faults; the Poukawa Fault, partly obscured by alluvium, trends beneath Hastings; and the Awanui and Napier Faults pass through Napier City (Figure 12.3).

The present courses of the main rivers follow in part, and accentuate, the NW-SE fault lineations. In central Hawke's Bay the Tukituki and Waipawa Rivers follow the Tukituki and Mangataura Faults respectively, south-east from the Ruahine Range to Waipawa and Waipukurau (Clark, 1976). Formerly, these rivers may have flowed further to the south-east and discharged into the sea near Kairakau Beach (Beu and Grant-Taylor, 1975), (Figure 12.1). Diversion northward of the Tukituki River was caused partly by elevation of the western limb of the New Rangitoto Anticline (Kingma, 1971) and partly by uplift along traces of the Puketapu and Napier Faults (Clark, 1976), (Figure 12.3).

Further north the Ngaruroro River follows the Kaweka Fault, which is downthrown to the north and mapped as a NW-SE arc from the Kaweka Range to Maraekakaho (Kingma, 1962). There it intersects the NE-SW trending Puketapu Fault Zone upthrown to the east. Uplift on this zone,

together with the occurrence of cemented limestones, formed a resistant barrier which restricted south-westward flow of the Ngaruroro River. Eventually it eroded a channel through the barrier and debouched into the Heretaunga Plains. About this time the Pigsty Terraces were formed by downcutting. Subsequently, renewed uplift on the Puketapu Fault Zone caused the river to flow along the fault trace and discharge, first between Roys Hill and Fernhill, and then north of Fernhill (Figure 12.1). Uplift on the eastern side of the Puketapu Fault Zone in late Pleistocene times also caused the gradient of some small streams to lessen, or even reverse, in their lower reaches and consequently Lakes Runanga and Oringa formed (Figure 12.3). Uplift also caused alluviation in the Okawa Depression. The effect of Recent folding upon river flow is also evident on the Heretaunga Plains north of Hastings, where uplift on the western side of the Poukawa Fault has caused the river channels in their lower reaches to narrow and change from a braided to meandering character. In 1931 compression of the Earth's crust (the Napier earthquake) caused a sudden uplift of 2 m which drained the Ahuriri Lagoon and caused the Tutaekuri River to discharge near Awatoto. After severe flooding in February 1934 this river was diverted to the mouth of the Ngaruroro River (Clark, 1976).

**Eastern Uplands: Terrain 3**

The eastern uplands form a belt of elevated country parallel to the Inland Depression and ranging in width from 20 km near Hastings to 40 km east of Dannevirke. This terrain comprises a varied physiography of a high plateau, limestone dipslopes, and broad synclinal valleys, all aligned to a pronounced NE-SW direction (Plate 12.4). The topography is normally higher than 150 m and rises to about 800 m.

The influence of lithology and geologic structure have been particularly important in influencing the development of landforms in Terrain 3. Broad synclinal and anticlinal folds, refolded into tighter folds and faulted along a north to north-east trend, characterise the structure of Terrain 3



**Plate 12.4** A view of the eastern uplands (Terrain 3) looking south from Te Mata Peak along the axis of the eroded Elsthorpe Anticline. Upper Pliocene, barnacle-rich limestones, outcropping in the foreground and right middle distance (Kohinurakau Range), form spectacular cuestas and westward dipping dip-slopes that can be correlated with subhorizontal limestones on the Maraetotara Plateau (extreme left). The isolated, upstanding block of Mount Kahuranaki forms the skyline left of centre. Silver Range is a hogback which occurs on the skyline in the centre of the photograph. (Photo: M.J. Selby)

(Figure 12.3) and determine the rock outcrop pattern. The anticlines are decidedly asymmetric; they always have longer and shallower dipping western limbs; and they have more steeply dipping eastern limbs that are frequently fractured by steeply dipping reverse faults (Lillie, 1953). Anticlines upwarp the strata and the overlying younger sediments have been stripped off, exposing the older sometimes more indurated strata. This effect is very evident in the Waewaepa Fault Complex, Whangai Anticline Complex, and Otane Anticline (Figure 12.3). Conversely, the formation of synclines downwarps the strata and promotes preservation of the younger and often softer sediments. A good example of this is the preservation of Miocene mudstones in the syn-

clines, especially the Akitio Syncline.

Important in the structure of Terrain 3 is the outcrop pattern of Mesozoic (Cretaceous) strata (Figure 12.3). Their surface distribution is limited to three semi-continuous NNE trending parallel belts of reverse-faulted NNE plunging anticlines. Cretaceous strata are conspicuously absent in the northern part of Terrain 3, but here the three belts continue along strike into Wairarapa.

Seismic profiling of the sea floor adjacent to Terrain 3 has shown that the prevalence on land of reverse-faulted anticlines and associated synclines continues offshore to the base of the continental slope (Lewis, 1980), (Figure 12.3). Hence, the land surface and the submarine surface have similar morphology and form one structural unit,

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irrespective of sea level, which no doubt indicates that they have developed in response to the same tectonic regime.

Three geomorphic sub-terrains are identified in Terrain 3 and informally named: soft mudstone sub-terrain (3A); limestone sub-terrain (3B); and indurated sandstone and argillite sub-terrain (3C). The nature of each sub-terrain is considered in turn.

*Soft Mudstone Sub-Terrain 3A*

Soft, easily eroded, and frequently slumped, mudstones are the dominant slope-forming materials in Terrain 3. The predominance of mudstone in the landscape is a manifestation of the persistence of mud sedimentation in the Cretaceous-Tertiary Geosyncline of Hawke's Bay (Kingma, 1960). There are two types of mudstone sub-terrains: one (3Ai) is developed in Cretaceous and early Tertiary bentonitic mudstones; and the other (3Aii) is formed in middle and late Tertiary sandier and, in places, stratified mudstones (Figure 12.3).

Sub-Terrain 3Ai occurs in three NNE-SSW trending belts: a western zone including the Whangai Range and extending north to Otane, and a narrow eastern zone comprising the coastal hills from Porangahau to Waimarama. The topography is formed of low hills, generally below 300 m and very susceptible to slope failure. The intensive slumping is promoted by the component of bentonitic clays (Lillie, 1953, 1980).

Bentonitic clays readily swell upon wetting and become very sticky and plastic, thereby facilitating downslope movement. Furthermore, the swelling property, together with alternate wetting and drying, rapidly disintegrates the rock into flakes, scales, and particles free to be moved downslope by fluvial processes. In this way Hawke's Bay's climatic regime, with its marked seasonal moisture deficit, provides favourable conditions for such weathering and denudation.

Discrete layers of bentonitic clay, identified in the field by their bright red and green hues, are especially prominent on the coast where they locally occur in beds 5 m thick (Lillie, 1953). In the steep coastal hills near Porangahau these clays, assisted by gravity, have produced an intensively

slumped topography. The mobility of bentonitic clays is further manifest in their ability to ooze-up fault planes. This occurs on the Mangatarata Fault south-east of Otane (Kingma, 1971).

Sub-Terrain 3Aii includes most of the mudstone country in the centre of the eastern uplands (Figure 12.2). The topography is formed of wide areas of dissected but rounded hillslopes, which from a distance give the appearance of a subdued landscape because the hills are contained within broad synclinal valleys, notably the Akitio Syncline (Figure 12.3). Streams meander considerably and form extensive marshes and small lakes (for example Lake Horseshoe) as they flow westward and northward along strike to the Tukituki River. In the south, the Porangahau River and its tributaries have eroded the Wilder Depression from within the Akitio Syncline.

Sub-Terrain 3Aii consists of sandy mudstones and alternating sandstones and siltstones of late Tertiary age. The coarser texture is considered to influence the processes of erosion and promote development of the rounded hillslope morphology.

*Limestone Sub-Terrain 3B*

Limestone landforms occur widely in Hawke's Bay north of Elsthorpe on the Maraetotara Plateau, and in a NE-SW trending belt west and south of Hastings, Waipukurau, and the Whangai Range. The spectacular cuestas and marked dip-slopes caused by the more resistant limestones give interest and diversity to the landscape which is otherwise dominated by mudstone hills (as in Sub-Terrain 3A). These limestones, mainly of late Pliocene and early Pleistocene age (Beu, 1978), give a clear record of the amount of Quaternary uplift and the style of post-depositional structural disturbance because they are stratigraphically highest in the sedimentary pile and are moderately resistant to erosion.

Long dip-slopes form the main ridges (Ruakawa, Kaokaoroa, Kohinurakau, Makara, Wae-waepa, and Puketoi Ranges) commonly rising to 400 m above sea level in the north and 700 m in the south (Figure 12.2). The direction of dip is always to the north-west, and the dip-slopes end in an abrupt, frequently reverse-faulted, eastern

face. The well-known Te Aute Bluff is such an escarpment. Any of the dip-slopes can be envisaged as a surface of the sea floor not too long ago.

These limestones are geologically unusual because they are largely composed of the remains of pink, subtidal barnacle plates and white mollusc shells (Kingma, 1971); barnacle limestones have rarely been reported from other localities on Earth. Some of the highest grade limestone outcrops in escarpments west of Otane and Waipawa, and the thickness of Pliocene sheets ranges from 3–300 m (Beu *et al.*, 1980). The origin of these sediments is attributed to shoaling of the seas caused by a combination of glacioeustatic sea level oscillations and basin uplift. Where the limestones were originally thinnest, corresponding to areas of early uplift, large areas such as that surrounding Elsthorpe have been eroded of limestone, thereby exposing the underlying late Miocene mudstone to geomorphic processes.

The limestone topography of the high Maraetotara Plateau, Craggy Range, and Mount Kahuranaki dominates the landscape east of the Tukituki River. In general the strata dip eastward at low angles, and consequently a karst topography of low, undulating hills has developed on the plateau, which is also cut by the deeply incised Maraetotara River. Mount Kahuranaki, an isolated block of late Pliocene sediment steeply rising 350 m above deposits of equivalent age on the underlying Maraetotara Plateau, is a geomorphic enigma and several explanations have been proposed (Kingma, 1971). The most recent and plausible is that it comprises a huge block, dimensions 3 km by 2 km, derived from the crest of the Elsthorpe Anticline and transported 2–3 km eastward upon a glide plane dipping 3°–4° east sometime after 2 My B.P. (Spörli and Pettinga, 1980). The scale of this movement illustrates the mobility of the eastern uplands (see Chapter 3 for a discussion of large-scale mass movement in this area).

### *Indurated Sandstone and Argillite Sub-Terrain* 3C

The prominent, steep hill country of the Waewaepa Range, Whangai Range, and the hills surrounding and extending north from Poran-

gahau are developed in more resistant, older, and more indurated sandstones and argillites (Lillie, 1953; Kingma, 1971). Greywacke similar to that of the Ruahine Range is dominant in the Waewaepa Range. However, it is the hard, white, and often flinty Cretaceous Whangai Argillite, named from extensive outcrops in the Whangai Range (Lillie, 1953), that forms most of the upstanding higher hills which contrast with the nearby low-slumped topography of Sub-Terrain 3Ai. East of Otane the westward dipping Whangai Argillite forms a prominent escarpment within a severely faulted anticline (Kingma, 1971).

Occasionally, beds of more indurated sandstone and mudstone with a higher carbonate content occur within the Tertiary mudstones. It is largely the attitude of these beds when they occur at the surface which determines the morphology. For example, in the vicinity of Omakere Hills, the relief consists of flat hill tops which provide a spectacular contrast with the nearby, steeply dipping hogbacks (Lillie, 1953). In this area, the alternating hard calcareous sandstones, thin limestones, and soft mudstones have been folded into a series of local synclines and anticlines. Correspondingly, along the hinge of the anticline where the sandstones and limestones are flat-lying, there are flat-topped hills; where the resistant beds are steeply dipping, hogbacks have formed. Silver Range (Plate 12.4), a pronounced hogback on the west flank of Elsthorpe Anticline, probably has a similar origin. It consists of a single, 20 m thick, indurated sandstone band within late Miocene mudstone dipping 50° west. To the north and south the hogback becomes less noticeable as the hard sandstone lenses out.

### *Rivers and Terraces*

Two consequent river systems rise in the uplands and transport sediment away from Terrain 3. One is the Porangahau River and its tributaries, and the other consists of several unconnected streams with short courses which flow in deeply cut valleys to the sea. At present the Porangahau system is entrenched within a group of high, accordant gravel terraces warped by folding and tilted by faulting. The entrenchment and renewed erosion,

especially of soft mudstones in the Akitio Syncline, is considered to result from recent and rapid uplift of the coast. Because the Porangahau River channel is now lower than the Tukituki River, the former is enlarging its catchment area at the expense of the latter.

### Northern Hawke's Bay: Terrain 4

Northern Hawke's Bay comprises an uplifted, gently dipping and dissected plateau of late Pliocene and early Pleistocene sediments (Plate 12.3). The plateau surface is defined by an accordance of summit heights; on the coast north of Napier the surface is 300 m above sea level, rising westwards to 1000 m above sea level at the crest of the Mangaharuru Range, while west of Napier the surface is more typically 200 m above sea level. The strata and the plateau surface dip uniformly at 5° to 10° in towards Hawke Bay, defining the Hawke's Bay Monocline (Figure 12.3). Significantly, the strike of the beds rotates through 45°, from a north-east direction west of Napier, to due east near Wairoa (Grindley, 1960). As a result, a radial stream pattern converging towards Hawke Bay has developed upon Terrain 4 (Figure 12.1).

There is a gradational change in the nature and degree of dissection of Terrain 4 from north to south, and this is attributed chiefly to changes in rock type. North-east from Lake Tutira to Wairoa and beyond, the slopes are composed of mudstone that is easily incised by streams and moved down-slope as rotational and translational landslides. The instability of this country is well known and, although still a problem, is being contained by improved land use management techniques. North-east of Tutira, the early Pleistocene mudstone has been largely removed by erosion because of greater uplift, and late Pliocene coquina limestones, similar to those outcropping in Terrain 3, form a series of cuestas with dip-slopes facing the south-east (Beu *et al.*, 1980).

In the southern part of Terrain 4, hard, recrystallised, horizontally lying early Pleistocene limestones outcrop as prominent bluffs in a belt from Tangoio Bluff through Napier Hill and inland to

Maraekakaho. Napier Hill is an outlier that has persisted because a sandy siltstone unit is underlain and capped by more resistant cemented limestones. North-westward of Napier the limestones become thinner, more sandy and pebbly, and ultimately grade into conglomerates and siltstones. The cemented conglomerates are the more resistant beds and form the main dip-slopes such as Flag Range (Kingma, 1971).

Because there has been little post-depositional structural disturbance of the early Pleistocene strata of Terrain 4, the lateral changes across the basin, from conglomerate to mudstone to limestone, reflect the proximity to terrigenous source areas and the depositional environments in the basin prior to its uplift. Kingma (1959) named this early Pleistocene basin (essentially Terrain 4) the Petane Trough and estimated a maximum sediment thickness near Rissington (north-west of Napier) of about 3000 m. This corresponds with a pronounced, negative gravity anomaly (Robertson and Reilly, 1958). The basin extended south-westward into Terrain 2, where the sediments presently occur mainly in the subsurface. The basin was rapidly supplied with coarse and fine detritus from land near the present-day Kaweka Ranges. Despite rapid subsidence, in part controlled by active intrabasin faulting (Clark, 1976), almost equally rapid sedimentation ensured that a shallow marine environment persisted over large parts of the basin. The deepest marine conditions, where mud was chiefly deposited, existed north of Tutira, especially around the present Mohaka River mouth. The basin rapidly shallowed towards Napier, where limestone formed in near-shore and intertidal environments away from an abundant source of terrigenous sediment, probably in regions of strong tidal currents, and influenced by glacioeustatically induced sea level oscillations.

At this time (early Pleistocene) the Kaweka and Kaimanawa Ranges probably had a significant relief (Kingma, 1959) and greywacke gravel, now weathered and in places cemented, was deposited close to source, mainly in the western margin of the basin north of the Ngaruroro River (Kingma, 1971). Hence the distribution of the different early Pleistocene lithologies in Terrain 4 result mainly

from the sedimentary response to the tectonic environment.

The occurrence of Upper Nukumaruan (Lower Pleistocene) fossils in the uppermost strata of Terrain 4, and the absence of concentrated pumice horizons, suggests that sedimentation ceased just before the middle Pleistocene. The plateau surface is probably the uppermost surface of deposition, that is the sea floor, uplifted from an enlarged Lower Pleistocene Hawke Bay. Uplift was probably associated with movement on the Mohaka Fault, which occurs immediately east of the Mangaharuru Range and has controlled the development of a wide depression within which the Mohaka River presently flows north-eastward (Figure 12.3). Judging from the occurrence of an extensive terrace some 100 m above sea level on both sides of the lower reaches of the Mohaka River, and the presence of higher terrace remnants, broad valleys were initially cut within a topography close to sea level. A presumed Last Interglacial age for cutting of the 100 m terrace (Grant-Taylor and Hornibrook, 1976) implies accelerated late Pleistocene uplift and equally rapid incision to shape the landforms.

### Origin of Landform Terrains of Hawke's Bay

Although each landform terrain is topographically distinctive, the same geographic areas are distinguished by combinations of structural and lithological properties: Terrain 1 comprises strongly deformed and uplifted Mesozoic greywackes; Terrain 2 is made up of depressed late Pliocene-Pleistocene sediments; Terrain 3 comprises highly deformed Cretaceous and Tertiary mudstones and limestones; and Terrain 4 consists of late Pliocene and early Pleistocene mildly deformed but uplifted mudstones, limestones, and conglomerates. The coincidence of geomorphic expression and geology suggests a primary tectonic control on development of the pattern of landform terrains. The theory of plate tectonics (for example Dewey, 1972) is a convenient model to explain the reason for the importance of tectonism in Hawke's Bay. Initially the plate tectonic setting of Hawke's Bay

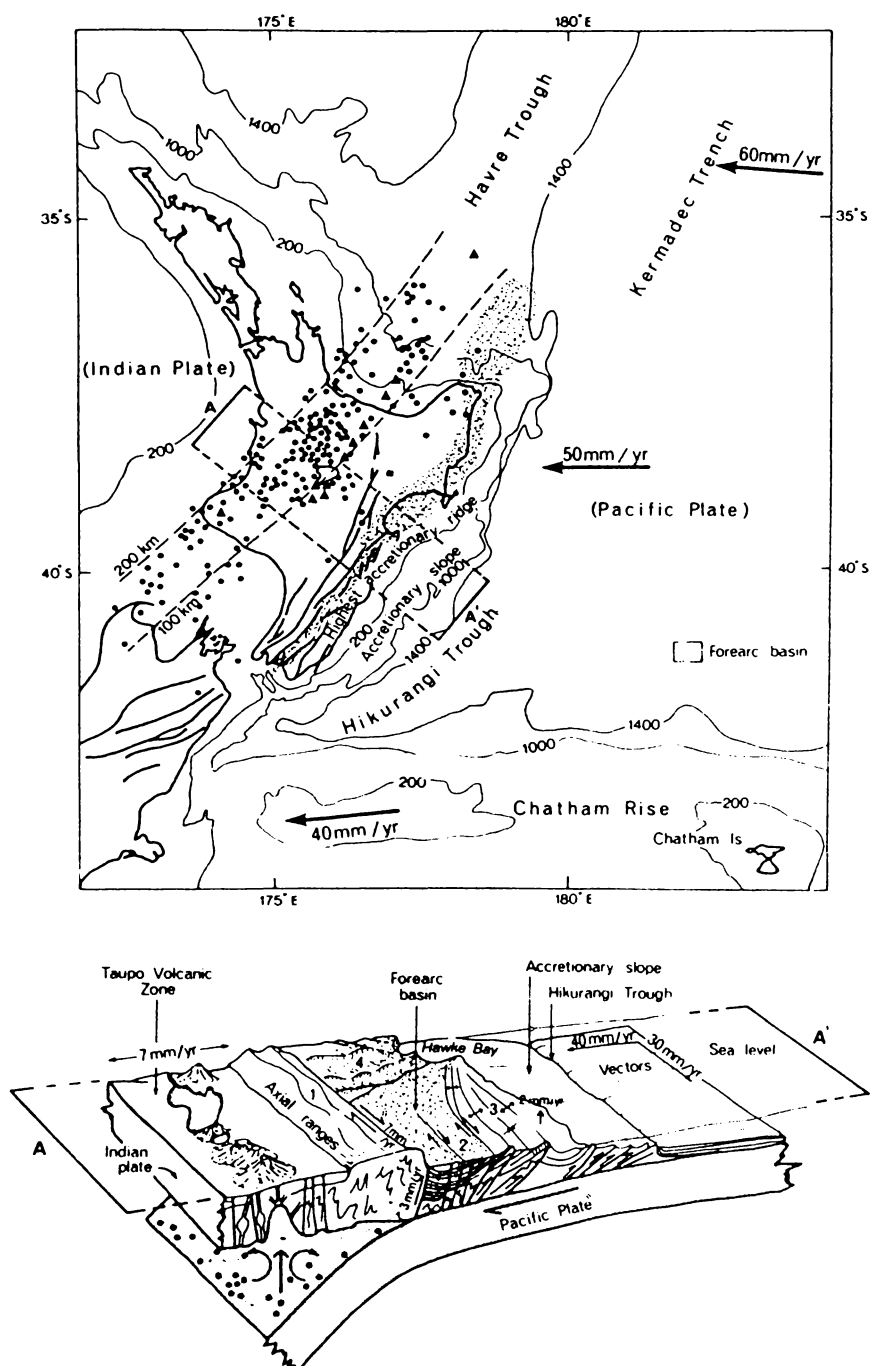
will be outlined, and then the origin of the landforms will be considered in this context.

### *Plate Tectonic Setting of Hawke's Bay*

New Zealand is bisected by a major lithospheric plate boundary that involves the Pacific Plate to the east and the Indian Plate to the west. The interaction of these plates has formed a north-west dipping subduction zone in the North Island (Figure 12.4), a transform fault system in the South Island, and a south-east dipping subduction complex south-west of the South Island (Stevens, 1980). A subduction zone has formed beneath the North Island because the plates are converging, and because the Pacific Plate comprises oceanic crust which is denser and can sink beneath the lighter continental crust. A subduction zone has not formed in the South Island chiefly because buoyant continental crust occurs on both sides of the plate boundary. The change to a south-east direction of subduction below the South Island is caused by differential rates of spreading of the Indian and Pacific Plates away from the Antarctic Plate.

The late Cenozoic folding and faulting that have accompanied regional uplift of the New Zealand land mass can be directly attributed to interaction of the plates. The zone of most intense crustal deformation occurs in a 70–100 km wide NE–SW trending belt from Hawke's Bay to Fiordland, named the Axial Tectonic Belt (Walcott, 1978a). The extent of the belt is defined by pronounced differential vertical and horizontal fault displacements, folding, and shallow earthquake activity. Hawke's Bay and Wairarapa occur at the northern end of this belt, immediately west of the Hikurangi Trough and south-east of the actively rifting Taupo Volcanic Zone (Figure 12.4).

The westernmost position of the Pacific Plate at the surface is the Hikurangi Trough, which forms the southern extension into New Zealand of the deep Kermadec Trench (van der Lingen, 1967; Lewis, 1980). For most of its length east of Hawke's Bay and Wairarapa, the Hikurangi Trough is a shallow, gently dipping, and sediment-filled bathymetric depression, but south-

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**Figure 12.4** A map and block diagram illustrating a plate tectonic interpretation of the structure and landforms of Hawke's Bay. The black dots on the map are earthquake epicentres believed to originate from the surface of the subducting plate (they are schematically positioned on the cross-section). The black triangles represent volcanoes. The bathymetric units are fathoms. The numbers 1,2,3,4 refer to the landform terrains. The map is modified from Walcott (1978a) and the cross-section is modified from Walcott (1978b) and Lewis (1980).

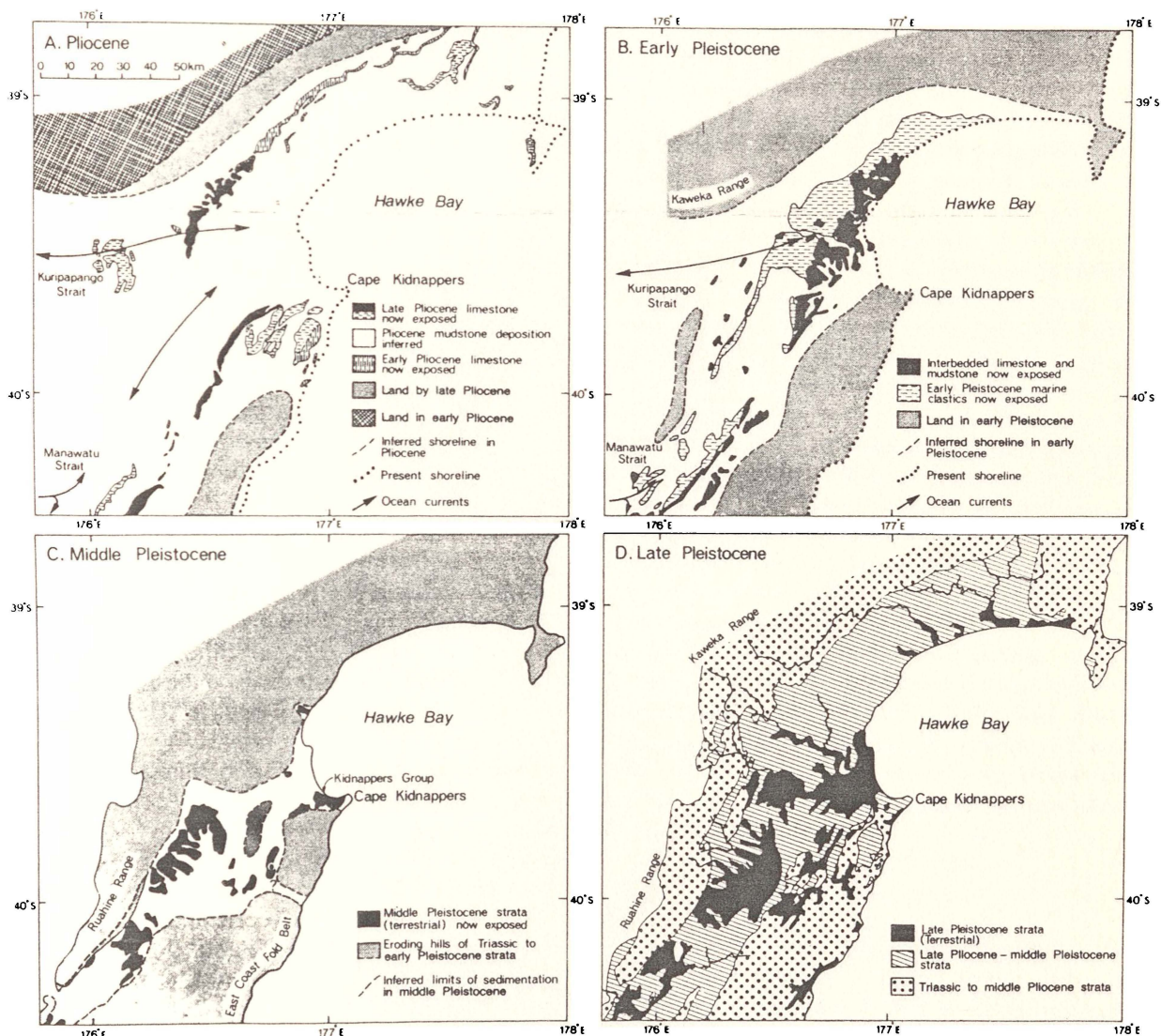
east of Cape Palliser it is considered to be a more east-west trending narrow transform boundary between the continental crust of Wairarapa and Chatham Rise (Lewis, 1980), (Figure 12.4). Westwards of the Trough the Pacific Plate is subducted beneath the North Island as a shallow dipping ( $12^\circ$ ) thrust for some 250 km, before it abruptly descends into the asthenosphere with a dip of  $50^\circ$ . Beneath the North Island the upper surface of the oceanic Pacific Plate is defined by the position of earthquake foci (Adams and Ware, 1977), (Figure 12.4); their distribution defines a plane striking  $N45^\circ E$ , parallel to the major structural and topographic trends in Hawke's Bay and Wairarapa. Beneath the eastern North Island and the continental shelf, the subducting plate occurs at only a few kilometres below the Earth's surface in the east, but up to 20 km below in the west.

On the basis of sea-floor spreading rates (Minster *et al.*, 1974) and geodetic data (Walcott, 1978a), the Pacific Plate, comprising Cretaceous oceanic crust (Molnar and Atwater, 1978), is believed to approach Hawke's Bay at 50 mm/y and Wairarapa at a lesser rate of 45 mm/y. Since the eastern North Island (Indian Plate) is inclined at  $50^\circ$  to the direction of Pacific Plate motion, the two plates converge obliquely and the rate of approach can be resolved into two vectors: one a compressive component of 40 mm/y normal to the coast near Cape Kidnappers, and the other a strike-slip component of 30 mm/y parallel to Hawke's Bay's coast (Walcott, 1978b). The approach of the plates becomes progressively more oblique in Wairarapa; correspondingly, there is an increase in the rate of strike-slip movement and a decrease in the rate of compressive movement. The Hikurangi Trough in the vicinity of Cook Strait is nearly parallel with the direction of motion and consists almost entirely of strike-slip movement.

Particular processes occur at a convergent margin where there is active subduction. The oceanic crust essentially acts as a conveyor belt delivering sea-floor sediments to the trench where they may be either subducted with the oceanic crust, or scraped off and accreted to the base of the overriding plate, or both. An interpretation of seismic data suggests that presently, at the

Hikurangi Trough, sea-floor sediments are being accreted to the base of the overriding Indian Plate (Lewis, 1980). With accretion of each new wedge, older wedges are thrust upward on reverse faults. This mechanism has been active off the eastern North Island for the last 15 My (Walcott, 1978b), and a wide, thick accretionary prism has formed that extends from the coast to the trough. The effect inland of the submarine accretion has been regional uplift of Terrain 3 (Figure 12.4) which began in the late Miocene with uplift of a ridge that now forms a line of coastal hills (van der Lingen and Pettinga, 1980). Further, the north-west-directed compression caused by the accretion deformed Terrain 3 and part of Terrain 2 into the characteristic structure of plunging, asymmetric, reverse-faulted anticlines and synclines. Reverse faulting, in particular, has brought strata as old as Cretaceous to the surface along discrete NE-SW trending belts in Terrain 3 (Figure 12.3). Thus the landforms there have developed within rocks of a wide variety of ages and lithologies.

Numerous long, dextral oblique-slip faults intersect the Earth's surface in Hawke's Bay, noticeably west of the intensively folded and faulted Terrain 3 (Figure 12.3). These faults presently accommodate most of the component of plate motion (30 mm/y) parallel to the trough. Both their age and the total amount of horizontal displacement across them is unresolved. Lensen (1958) estimated a rate of horizontal displacement of 7 mm/y on the Ruahine Fault; this amounts to 14 km in 2 My if his 10 000 year record is extrapolated back in time. Considering this rate of displacement and the number of major faults, there may have been as much as 50–70 km of horizontal displacement through Hawke's Bay during the last two million years. A constraint on the maximum amount of displacement is offered by the pattern of age and lithology trends in basement rocks of New Zealand (Bradshaw *et al.*, 1980); as much as 200 km, distributed across the faults and intervening rocks in the Axial Tectonic Belt, is possible. From these basement trends it is clear that the 480 km of displacement evident on the Alpine-Wairau Fault in the South Island cannot pass through the North Island. There are no firm constraints on the age of the oblique-slip faults,

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**Figure 12.5** A sequence of Pliocene and Pleistocene paleogeographic maps showing the development of Hawke's Bay landforms. Map A is modified from Beu *et al.* (1980). The distribution of early, middle, and late Pleistocene sediments is taken from New Zealand Geological Survey (1973).

but it is supposed that they are of late Cenozoic age. Because these faults are oblique-slip in character, the age of uplift (vertical component of displacement) may approximate the age of horizontal displacement; the Ruahine Range was lifted above sea level in the Lower Pleistocene (Figure 12.5) and therefore transcurrent movement on the present faults perhaps started about

1.5 My B.P. This does not preclude earlier displacement on now obscure and less continuous faults further east in Hawke's Bay (Ridd, 1964; Lillie, 1969).

The line of marked change in dip of the subducting Pacific Plate corresponds with the trend of the Taupo Volcanic Zone, a region of predominantly rhyolitic volcanism and normal faulting

which is considered to be actively rifting. This rifting has isolated northern Hawke's Bay and the north-eastern North Island as a microplate and caused it to rotate clockwise over and against the obliquely subducting Pacific Plate. The rotation probably caused the cessation of subsidence and sedimentation in the Petane Trough (Terrain 4) and initiated middle Pleistocene uplift which has persisted through to the present. Further, such rotation would cause an ENE-WSW oriented syncline to form in the vicinity of Hawke Bay, thus explaining its persistence in spite of surrounding uplift, and would explain why the pronounced NE-SW structural trend in the south-eastern North Island dies out in the Pliocene-Pleistocene strata of Terrain 4. Hence, different crustal forces operate in northern Hawke's Bay compared with the rest of Hawke's Bay and this largely explains the difference in structure and landform terrains.

### **Plio-Pleistocene Paleogeography of Hawke's Bay**

Given the landforms and geology of Hawke's Bay, and an explanation of their origin in terms of plate tectonics, the late Cenozoic development of the terrains is summarised by changes in the paleogeography established chiefly from the nature and distribution of Pliocene and Pleistocene sediments. Briefly, the history is one of differential uplift with progressive withdrawal of the sea, erosion, and subsequent deposition of the exposed sediments together with folding and faulting. This section should be considered together with the last section in Chapter 13.

#### *Pliocene (5–2 My B.P.)*

Pliocene limestones and mudstones occur widely at the surface in Terrains 3 and 4, and in the subsurface of Terrain 2 (Figure 12.5A). By the late Pliocene most of Hawke's Bay was below sea level, apart from the southern region of Terrain 3, and land in the vicinity of the Kaweka Ranges is shown by the inclusion of greywacke pebbles in adjacent limestones (Kingma, 1957b). Much of

the pattern of submarine uplift can be established from the age and thickness distribution of the limestones (Figure 12.5A), (Beu *et al.*, 1980). In Terrain 3 the limestones become progressively younger westward; this can be explained by an initiation of uplift near the present coastline and displacement of sedimentation westward as the uplift became more regional. Localised, but major, east-west changes of the order of 300 m in the thickness of the limestones (Kingma, 1971), suggest that the submarine uplift was accompanied by folding into NE-SW plunging synclines and anticlines. This deformation might have promoted the formation of limestones by the construction of current-swept and sediment-free anticlinal ridges, favourable for limestone production, and adjacent troughs of deposition. In Terrain 4 a similar trend of submarine uplift in the east brought Mahia Peninsula above sea level at the end of the Pliocene. In contrast, the western margin adjacent to the incipient Kaweka Ranges persistently subsided through the Pliocene. Although there is evidence of differential vertical movement and the accumulation of thicker late Pliocene sequences in the Ohara Depression (Kingma, 1957a), there is no evidence to suggest that much of the Ruahine Range was above sea level at that time (Beu *et al.*, 1980).

#### *Early Pleistocene (2–1 My B.P.)*

Early Pleistocene sediments are presently distributed extensively in Terrain 4, in the surface and subsurface of Terrain 2, and in the south-west of Terrain 3 (Waewaepa and Puketoi Range). By the early Pleistocene a belt of coastal hills existed from Cape Kidnappers to Cape Palliser (Figure 12.5B, also Figure 13.4B, page 266) and an ancestral Hawke Bay had been delineated. The early Pleistocene sediments have a marine origin and their distribution indicates the persistence of a major seaway southward to Wairarapa and westward through the Kuripapango and Manawatu Straits into the Wanganui Basin.

The mixed terrigenous and carbonate early Pleistocene succession resulted chiefly from the interplay of structural, eustatic, and sediment-supply controls on sedimentation. In the absence

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of much detail on the sedimentary environments, only broad statements about the structural influences can be made. The absence of early Pleistocene sediments at Cape Kidnappers (Kamp, 1978), the occurrence of shallow marine limestone beds throughout the sequence near Napier, and the great thickness of marine clastics in the Petane Trough north-west of Napier, show that the Pliocene pattern of uplift in the east and subsidence in the west intensified in the early Pleistocene. But, at the end of the early Pleistocene, subsidence ceased and the whole of Terrain 4 was gradually uplifted from the sea. Uplift of Terrain 4 was probably part of a more general change in Hawke's Bay from open Pliocene folding, chiefly in Terrain 3, to more widespread and tighter folding, giving way to reverse faulting and transcurrent faulting. Earlier in this chapter these structures were related to processes of subduction.

*Middle Pleistocene (1.0–0.1 My B.P.)*

The middle Pleistocene sediments, derived mainly from Terrains 1 and 3, accumulated chiefly in terrestrial environments (lakes and rivers), indicating that by this time the sea had withdrawn to about the present coastline (Figure 12.5C). In parts of Hawke's Bay these sediments have been folded, and they are characterised by pumiceous beds and greywacke conglomerates from which may be inferred the timing of major uplift of the axial ranges.

The pumice is derived chiefly from erosion of an unwelded pyroclastic flow deposit (ignimbrite) which flowed into Hawke's Bay from the Taupo Volcanic Zone about  $0.85 \pm 0.1$  My B.P. (Kamp, 1981). Non-eroded remnants of the flow deposit 1–4 m thick are preserved at isolated localities from Taradale to Dannevirke and are well exposed along State Highway 50 in the vicinity of Gwavas. The age is established from a fission-track date (Seward, 1975) for its deposition in the Kidnappers Group, where it was deposited over a coastal paleodune topography. There, the flow deposit immediately overlies a 0.85 cm thick shower-bedded airfall tephra that mantled the topography. The flow origin is indicated by the common inclusion of charred logs, and the poorly

sorted, compacted nature of the deposit. The identification of an ignimbrite in Hawke's Bay is important for many reasons: it explains the sudden influx of large quantities of pumice which were rapidly eroded and redistributed; it is a dated marker bed for correlating isolated middle Pleistocene deposits; and where it is involved in folding it provides a maximum age on the folding. Moreover, the ignimbrite has wider stratigraphic value in the North Island, and major volcanological significance. The largest known eruption from the Taupo Volcanic Zone of the same age range as this ignimbrite is the Ongatiti Ignimbrite (Hinuera stone) which outcrops extensively in the King Country and Waikato (Blank, 1965; Olissov, 1981) as a welded deposit.

During the middle Pleistocene, large gravel fans (the Salisbury and Waharoa Terraces) formed along the eastern margin of the Wakarara and Ruahine Ranges. These fans prograded as braided rivers westward into the Heretaunga Plains and south-westward to Dannevirke, which at that time was near the shores of a large shallow lake, centred about Woodville, that drained out through the Manawatu Gorge. Small lakes also formed within the growing synclines in Terrain 3 (Figure 12.5C). From the age and stratigraphic position of the ignimbrite within the alluvial fans, it is estimated that parts of the ranges started to shed large quantities of gravel about 1 My ago. Given the height of the ranges (1700 m), the rate of uplift would be a minimum of 1.7 mm/y which agrees with the rates estimated by Wellman (1967): 2–7 mm/y.

*Late Pleistocene and Holocene (0.1–0 My B.P.)*

The late Pleistocene and Holocene is the time when the detail of the landscape and soilscape developed and the drainage network was established in its present form, apart from minor changes in direction due to faulting and folding (Figure 12.5D). The extensive uplift initiated in the middle Pleistocene persisted through to the present. On the crest of anticlines at Cape Kidnappers and Mahia Peninsula the Last Interglacial terrace (125 000 years B.P.) has been uplifted

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200 m; from this, a regional uplift of at least 100 m is inferred for the late Pleistocene in Terrains 3 and 4. This uplift increased the scale of the topography, the main effect being stream incision and formation of slopes by mass and particle movement.

Finally, since about 40 000 years B.P. the landscape has been periodically mantled by tephra originating from the Taupo Volcanic Zone and locally derived loess deposits. These airfall deposits form the parent materials of many of the soils in Hawke's Bay (New Zealand Soil Bureau, 1968; Gibbs, 1980).

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## PAPER 3

Landforms of Wairarapa in a geological context

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# 13

## Landforms of Wairarapa in a Geological Context

P.J.J. KAMP and C.G. VUCETICH

South of Hawke's Bay, separated from Wellington by the Tararua-Rimutaka Ranges, the Wairarapa includes the bulk of the south-eastern corner of the North Island and is elsewhere bounded by the sea. It displays a mountainous topography and inland depressions near sea level. The landscape is largely of middle to late Quaternary age as a result of vigorous, and continuing, tectonic activity, with erosion of the rising ranges and uplands and deposition in the lowlands.

### The Nature and Uplift Rates of the Wairarapa Coastline

Despite the fact that the eastern coastline of Wairarapa intersects rocks of a wide range of ages and degrees of induration, the coastline is nearly straight and only interrupted by promontories at Castlepoint and Cape Turnagain. Moderately indurated Jurassic greywacke crops out west and north of Cape Palliser for 50 km and the coast is exceedingly rugged; nearly vertical cliffs back narrow bouldery beaches and rock platforms. Eocene argillaceous limestones that display complex folding, interpreted as resulting from submarine slumping (Waterhouse and Bradley, 1957), crop out at a number of south-eastern coastal localities and especially at White Rock. North of Flat Point the coast forms open bays, frequently with sandy beaches and rock-cut platforms, and with the country behind rising to 100 m or more, either as single bluffs or as a series of low slump scarps

(King, 1930). Castlepoint is a prominent headland (named the Castle by Captain James Cook) and reef composed of Pliocene mudstone and Lower Pleistocene limestone. The Castle is 162 m high with almost sheer sides and is joined to the mainland by a narrow ridge (Johnston, 1975). Together the Castle and reef define a small harbour.

The Wairarapa coastline is one of rapid emergence (King, 1930), shown by the extent and height of successive wave-cut terraces. Wellman (1969, 1971a) and Ghani (1978) have identified five late Quaternary uplifted marine benches from which they have established the nature and rates of coastal uplift.

The lowest bench, named after Turakirae Head where it is best exposed (see Plate 14.5, page 278), supports seven beach ridges composed of gravel and sand; the oldest is 6500 years and 25-m above sea level. The beach ridges are considered to have been deposited during the stillstands of sea level between a series of sudden uplifts that for the last two ridges are correlated with the 1855 and 1460 earthquakes respectively (Wellman, 1969; Stevens, 1969). Consistent changes in the height of the ridges along Turakirae Head show that a block of land west of the Wairarapa Fault is tilting progressively westward with each major earthquake. Holocene beach ridges also occur at Cape Palliser, Ruamahanga Valley, Oterei, White Rocks, and Glenburn (Wellman, 1971a, 1971b; Singh, 1971). At White Rocks the heights of the ridges at a number of profiles along the coast have been

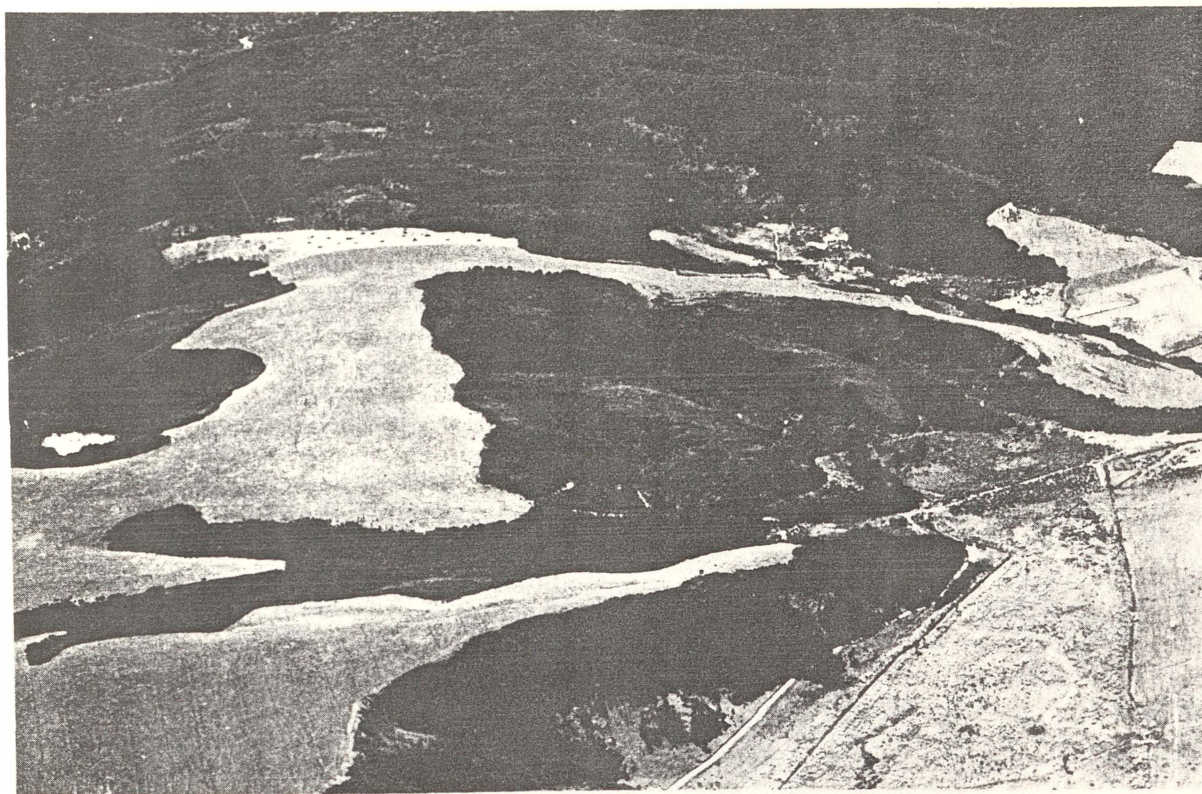
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measured by levelling at right angles to the coast. Although not all of the ridges are present at every locality, assuming that the rate of uplift at any one point has been constant, the data at White Rock shows that uplift is being accompanied by folding into two anticlines and a syncline. Uplift ranges from 2.6 mm/y for the anticlines to 1.1 mm/y for the syncline.

Four well-preserved, Last Interglacial marine benches, at variable heights up to 200 m above sea level and named the Eparaima marine benches, have been mapped from Flat Point around Cape Palliser and north to Bidwell Hill in the inland depression (Ghani, 1978), (Plate 13.1). The higher marine benches are generally poorly preserved, but a particularly well-preserved complete sequence cut in mid-Miocene strata occurs at Flat Point. Each of the Eparaima benches was

cut about the time of a stillstand in sea level during the Last Interglacial (Suggate, 1974) and, by comparison with dated terraces at Barbados and carbonate peaks in deep-sea cores, have interpreted ages from lowest to highest of 60 000, 84 000, 100 000, and 125 000 years. Confirmation of these approximate ages has been obtained from studies of the cover deposits; the terraces support three loess units and the uppermost unit contains the 20 000 year-old Kawakawa Tephra.

In regions where short-term Holocene data is available, the pattern and rate of folding and uplift is confirmed by a study of the spatial changes in elevation of the Eparaima benches. In inland Wairarapa where these Holocene data are not available, the Eparaima benches alone have provided data on uplift. It is concluded that on the marine benches, uplift rates range from



**Plate 13.1** An uplifted wave-cut terrace presumed to be 80 000 years old at this locality 2 km west of Lake Onoke. The terrace is outlined by the pasture and has been dissected by streams flowing from the Rimutaka Range (background). The terrace was 'cliffed' in the right foreground by the high sea level of 6000 years ago. (Photo: D.W. McKenzie)

0.75 mm to 4.0 mm/y for the growing anticlines, and from 0.5 mm to 2.2 mm/y for the growing synclines (Ghani, 1978).

### Landform Terrains of Wairarapa

Wairarapa is naturally subdivided into four dis-

crete terrains: Terrain 1 comprises the Tararua and Rimutaka Ranges; Terrain 2, the northern Pahiataua Basin; Terrain 3, the central Masterton Basin; and Terrain 4, the belt of eastern uplands (Figure 13.1). In northern Wairarapa Terrains 1, 2, and 4 are clearly the southern continuation of adjacent terrains in Hawke's Bay (Chapter 12).

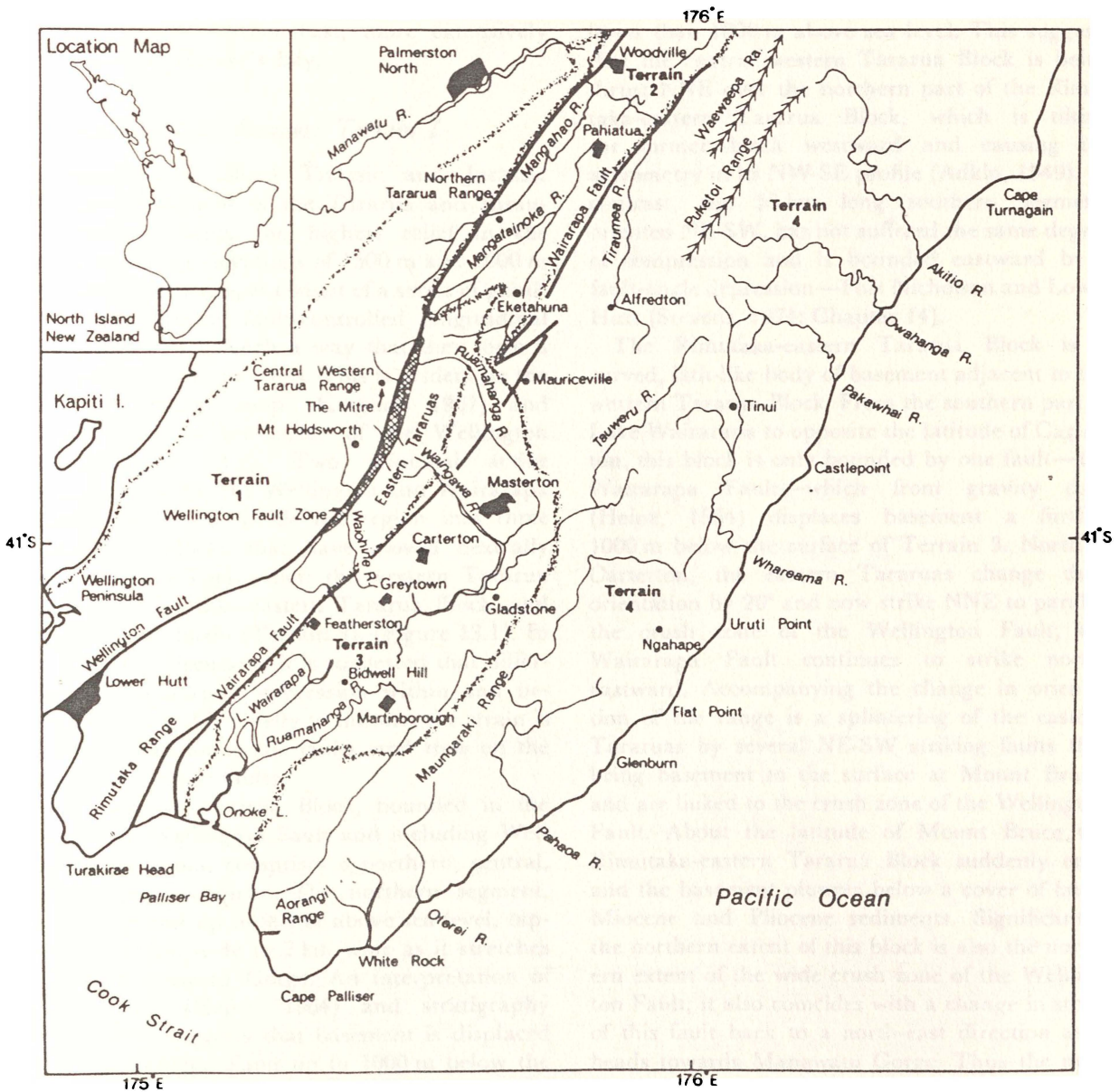


Figure 13.1 Locality map showing the boundaries of each landform terrain defined and described in the text.

However, Terrain 3 is separated from Terrain 2 by the Mount Bruce basement high, and although the two terrains are parallel, the former is displaced 20 km eastwards and occurs on the opposite side of the Wairarapa Fault. The more eastern position of the Masterton Basin is accompanied by a southward narrowing in the width of Terrain 4 and a concomitant widening in Terrain 1. Jurassic basement greywacke crops out in the eastern uplands, further east, more extensively than it does in Hawke's Bay.

#### *Tararua-Rimutaka Ranges: Terrain 1*

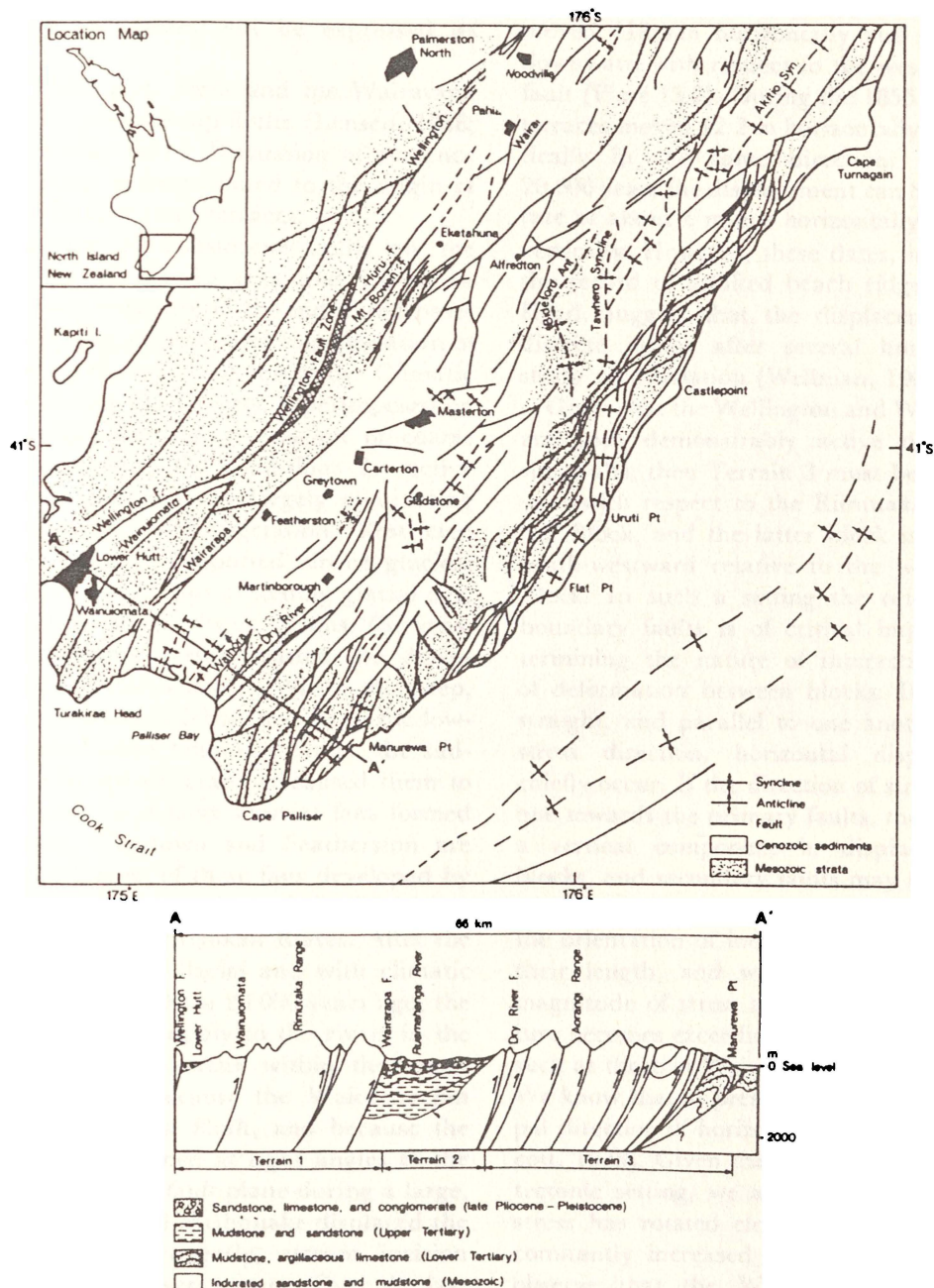
The pervasively folded Triassic and Jurassic greywacke basement of the Tararua and Rimutaka Ranges forms the highest relief in the district, reaching elevations of 1500 m and 1000 m respectively. The ranges consist of a series of parallel and subparallel fault-controlled longitudinal ridges, disposed in such a way that they form a wide arc convex to the west. This is evident on the 1:250 000 geology map (Kingma, 1967) and demonstrated by the strike of the Wellington Fault (Figure 13.2). Two principal active oblique-slip faults, the Wellington and Wairarapa Faults, define and divide the region into three independent blocks that have moved dextrally with respect to each other: the western Tararua Block, the Rimutaka-eastern Tararua Block, and the Masterton Basin (Terrain 3), (Figure 13.1). In the following discussion it is suggested that differences in geomorphic expression within and between blocks is due chiefly to the way the strain is accommodated along the faults, and thus on the strike of the major faults.

The western Tararua Block, bounded in the east by the Wellington Fault and including Wellington Peninsula, comprises a northern, central, and southern segment. The northern segment, 43 km long and up to 900 m above sea level, tapers from 12 km wide to 2 km wide as it stretches towards Manawatu Gorge. An interpretation of gravity data (Heine, 1964) and stratigraphy (Neef, 1974) suggests that basement is displaced on the Wellington Fault up to 1000 m below the surface of the Pahiatua Basin (Terrain 2). The 55 km long central segment of the western

Tararua Block has the highest elevation and contains the central portion of the wide arc referred to earlier. North north-east of the point of inflection, the Wellington Fault forms a wide zone (up to 2.4 km) of crushed rock, and across this zone there is a major difference in elevation of basement: to the west is the highest ridge, which extends from The Mitre to Mount Holdsworth, 1200 to 1600 m above sea level; while to the east, Blue Range is lower than 1000 m above sea level. This suggests that the central western Tararua Block is being thrust NNE over the northern part of the Rimutaka-eastern Tararua Block, which is tilting the former block westward and causing the asymmetry in its NW-SE profile (Adkin, 1949). In contrast, the 55 km long southern segment, oriented NE-SW, has not suffered the same degree of compression and is bounded eastward by a fault-angle depression—Port Nicholson and Lower Hutt (Stevens, 1974; Chapter 14).

The Rimutaka-eastern Tararua Block is a curved, lath-like body of basement adjacent to the western Tararua Block. From the southern part of Lake Wairarapa to opposite the latitude of Carterton, this block is only bounded by one fault—the Wairarapa Fault—which from gravity data (Heine, 1964) displaces basement a further 1000 m below the surface of Terrain 3. North of Carterton, the eastern Tararuas change their orientation by 20° and now strike NNE to parallel the crush zone of the Wellington Fault; the Wairarapa Fault continues to strike north-eastward. Accompanying the change in orientation of the range is a splintering of the eastern Tararuas by several NE-SW striking faults that bring basement to the surface at Mount Bruce, and are linked to the crush zone of the Wellington Fault. About the latitude of Mount Bruce the Rimutaka-eastern Tararua Block suddenly ends and the basement plunges below a cover of latest Miocene and Pliocene sediments. Significantly, the northern extent of this block is also the northern extent of the wide crush zone of the Wellington Fault; it also coincides with a change in strike of this fault back to a north-east direction as it heads towards Manawatu Gorge. Thus the morphology of the Tararua-Rimutaka Ranges, and their origin, seems to be related to the orientation

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**Figure 13.2** A map of Wairarapa's structure and a generalised cross-section (not to the same scale). The map is drawn from the geology map, Sheet 12 (Kingma, 1967), shows the pronounced NE-SW structural trends, and only samples the total amount of faulting in Wairarapa. The faults in the north-western and western regions are mainly oblique-slip Cenozoic faults. The interwoven lens-like faults along the coastal belt east of Alfredton are early and late Cenozoic open folds, which plunge to north and south oblique to the NE-SE structural trends. The location of the offshore anticlines and synclines are from Lewis (1980). The stippled area shows the extent of Mesozoic strata exposed at the surface.

of the principal faults, which in turn determines how much of the strain will be expressed as thrusting.

Both the Wellington Fault and the Wairarapa Fault are active oblique-slip faults (Lensen, 1958; Lensen and Vella, 1971). Discussion of evidence for active faulting is here limited to the origin of the Waiohine faulted river terraces.

A consequence of Pleistocene uplift on the boundary faults of the Tararua and Rimutaka Ranges has been exposure of the indurated basement to weathering, erosion, and transportation of the products to the adjacent lowlands. Climatic deterioration during glacial ages, superimposed on the uplift, accelerated the production of coarse detritus by enhancing the conditions for active physical weathering, and by largely eliminating the moderating effect of vegetation. Restricted areas of the Tararuas supported cirque glaciers during the last and perhaps preceding glacial age, as evidenced by fossil cirque basins (Stevens, 1974); solifluction processes assisted the down-slope mass movement of debris. Where the steep, sediment-charged rivers debouched on to the lowlands across the active boundary faults, the sudden reduction in stream gradient caused them to dump their loads, and large alluvial fans formed by aggradation. Greytown and Featherston are situated on the largest of these fans developed by the coalescence of smaller fans of the Waiohine, Waingawa, and Tauwharenikau Rivers. After the maximum of the Last Glacial and with climatic amelioration some 15 000 to 20 000 years ago, the reduction in sediment supply to the rivers in the ranges caused them to incise within the upper reaches of the fans. Because the Waiohine fan straddles the Wairarapa Fault, and because the edge of the terrace formed at right angles to the fault, movement on the fault plane during a large, immediately post-glacial earthquake displaced the original terrace. Subsequently, stream incision formed another, but lower, terrace. Over the last 20 000 years repeated fault movement and stream incision have produced six terraces that show measurable displacements. The amount of offset increases with terrace age, and the sequence provides a remarkable record of the progressive horizontal and vertical components of offset (Lensen

and Vella, 1971). The uppermost terrace has moved 118.5 m horizontally and 20 m vertically downward with respect to the western side of the fault (Plate 13.2). During the 1855 earthquake the terraces moved 12.2 m horizontally and 2.7 m vertically in the same direction. Over the last 20 000 years the displacement can be averaged to a rate of about 6 mm/y horizontally and 0.5 mm/y vertically. However, these dates, interpreted with the record of uplifted beach ridges at Turakirae Head, suggest that the displacement occurs as discrete jumps after several hundred years of strain accumulation (Wellman, 1969).

Given that the Wellington and Wairarapa Faults are both demonstrably active dextral oblique-slip faults, then Terrain 3 must be moving south-west with respect to the Rimutaka-eastern Tararua Block, and the latter block must be moving south-westward relative to the western Tararua Block. In such a setting the orientation of the boundary faults is of critical importance in determining the nature of interaction and degree of deformation between blocks. If the faults are straight, and parallel to one another and to the stress direction, horizontal displacement will chiefly occur. If the direction of stress is now oblique towards the primary faults, there may also be a vertical component in displacement of the blocks, and secondary faults may form parallel to the stress direction. If, in addition to the above, the orientation of individual faults changes along their length, and with time the direction and magnitude of stress also changes, then the structure becomes exceedingly complex, and landforms such as those in Wairarapa and Wellington result. We know that at present in Wairarapa the principal direction of horizontal stress is NE-SW (Walcott, 1978). Given the eastern North Island plate tectonic setting, we assume that the direction of stress has rotated clockwise with time and concomitantly increased in magnitude. Further, we observe that the Wellington Fault is curved. Hence, it is tempting to explain the differences in landforms and their origin in terms of these factors. For instance, the eastern Tararuas are being forced south-westward, but along a NNE-SSW segment of the Wellington Fault. The result is a substantial component of compression along this



**Plate 13.2** A view of the Waiohine terraces displaced by the Wairarapa Fault. The fault cuts across the apex of the fan from left to right (arrow) with terraces on the far side being uplifted to produce a scarp. (Photo: D.W. McKenzie)

segment of the fault, which is partially relieved by thrusting of the central western Tararuas over the eastern Tararuas, and partly by intense shearing to form the wide fault zone. This compression may also explain why basement has been uplifted to the surface at Mount Bruce, and why a series of *en échelon* faults have splintered the eastern Tararuas. The south-west trend of the Wellington and Wairarapa Faults south of the latitude of Carterton, thus nearly parallel to the stress direction and hence the lesser component of compression, perhaps explains the lower elevations of the Wellington Peninsula and Rimutaka Range and the occurrence of fault-angle depressions.

#### *Pahiatua Basin: Terrain 2*

The physiography from Eketahuna north to Woodville comprises two broad, terraced river

valleys and a low central ridge that maintains a separation of the parallel-flowing Mangahao and Mangatainoka Rivers. This pattern of landforms is caused by uplift of the eastern side of each of three steeply dipping north-east trending faults: the Wellington Fault, the Huru Fault, and the Mount Bowen Fault (Neef, 1974). These displacements have defined two fault-angle depressions, both tilted up to 20° to the west. The central ridge is the uplifted margin of the western depression in which the Mangahao River flows; the Mangatainoka River flows in the eastern depression. Downfaulted portions of both depressions have been infilled with mid-Pleistocene to Holocene fluvial sediments derived chiefly from the Tararua Ranges. Four aggradational surfaces have been mapped (Neef, 1974). The highest surface, at 300 m above sea level, is the oldest, now of limited extent and mainly preserved on the tops of

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hills west of Eketahuna. Two low-level terraces above the flood plains of the modern rivers are more extensive; they occur in all the major valleys. The Eketahuna Surface, upon which eastern Eketahuna is built, occurs at 250 m above sea level, and the more extensive Hukanui Surface at 220 m above sea level.

The Mangatainoka and Mangahao Rivers have both abandoned broad, east-trending, now misfit, valleys at Eketahuna and Hukanui (Neef, 1974). The Mangahao River abandoned the Hukanui misfit valley in the early Holocene, whereas the Mangatainoka River vacated the Eketahuna misfit valley before the Holocene. These changes in river direction are partly attributed to aggradation and river capture, and partly to active faulting. During the Holocene the rivers have incised their beds as much as 45 m below the Hukanui Surface to form minor gorges.

The sediments cropping out in the hills of the Pahiatua Basin are formed from a variety of rock types, but in general they are limestones and

muddy sandstones in the north and mudstones in the south. Prior to middle and late Pleistocene uplift and erosion, the limestones and sandstones were probably also present in the south.

*Masterton Basin: Terrain 3*

The Masterton Basin or Wairarapa Valley is a structural depression 77 km long and up to 20 km wide that plunges southward to Palliser Bay. The shallow but extensive Lake Wairarapa, merely 1.5 m above sea level, is evidence that the basin is still subsiding in the south-west; a trend inherited from the late Miocene-early Pliocene. Most of the hills in the basin occur to the east of the Ruamahanga River and are composed of folded and faulted mid-Pleistocene terrestrial deposits and older shallow marine sediments. To the west of the Ruamahanga River, younger and undeformed large, coalescing gravel fans have been constructed by the Tauherenikau, Waiohine, and Waingawa Rivers. The outward and upward

**Plate 13.3** A view of the confluence of the Ruamahanga and Waingawa Rivers, incised within the Waiohine Surface. The Ruamahanga River flows from left to right. The fine dissection and shallow mass movement failures in early Pleistocene sediments of Foster Hill are evident in the background. (Photo: D.W. McKenzie)



growth of these fans has forced the Ruamahanga River against the hilly topography of the older, now deformed fans (Plate 13.3).

Few continuous exposures are available to examine the transition from shallow, marine, early Pleistocene to predominantly terrestrial, middle Pleistocene sediments. There is one section in the east bank of the Hauhangaroa River on the flanks of the Maungaraki Range, and another near Gladstone, cut by the Ruamahanga River through the nose of a growing anticline. The former section exposes some of the oldest terrestrial sediments, of about one million years, including blue-grey lacustrine silt, lignite, and fluvial conglomerates most probably derived from the Aorangi Range (P. Vella, personal communication). Similar lithologies occur at Gladstone but seem to have been derived from the Tararua Range, transported by an ancestral Ruamahanga River, and deposited during the early phases of folding, which produced an asymmetrical NNE plunging anticline that now forms a pronounced ridge in the landscape (Kennett, 1964). Elsewhere, hills of middle Pleistocene sediments have been upthrown as much as 50 m along faults bounding them to the east, such as at Bidwell Hill and the hills immediately south-east of Martinborough.

The alluvial deposits that form the valley floor west of the Ruamahanga River have been subdivided into two groups (Vella, 1963a). The older—named the Bruce Group—is now limited to residuals a few square kilometres in extent. Remnants of the upper surface up to 470 m above sea level, and 180 m above the Ruamahanga River, are best preserved on hills east of the river, south-west of Mount Bruce. The Bruce Surface has been displaced 20 m by north-east striking faults, and slopes leading down from the surface are smoothly rounded as a result of solifluction processes and by deposition of loess.

At lower altitudes than the Bruce Group is a group of better preserved and more continuous aggradation surfaces called the Plains Group (Vella, 1963a). It includes the extensive, composite Waiohine fan of the central Wairarapa Valley (Figure 13.3) and a sequence of three terraces formed by the Ruamahanga River in the northern

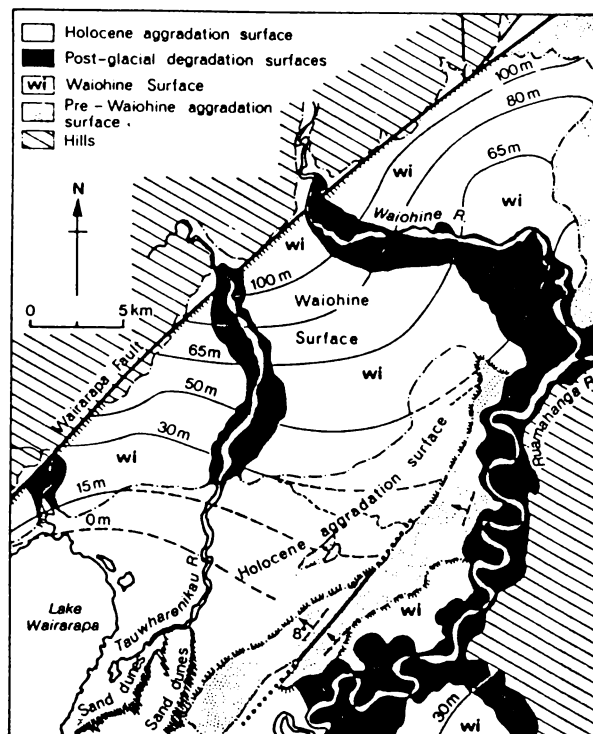


Figure 13.3 Waiohine Surface at Waiohine and Tauwharenikau Rivers, and at Ruamahanga River near Martinborough, showing areas still preserved and reconstructed contours at 15 m on the original surface (reproduced from Vella, 1963a).

part of the valley. The Waiohine Surface is stony, lacks the loess cover of the older surfaces, and is only slightly deformed; it is therefore taken to be slightly older than Holocene. It is believed to be the correlative of the younger of the three aggradational surfaces in the upper Ruamahanga Valley. The two higher terraces, about 280 m and 263 m above sea level, have slopes rounded by solifluction processes and loess deposition and therefore are older than the Waiohine Surface.

During the post-glacial period the rivers have incised within the earlier deposits (Plate 13.3, Figure 13.3), formed a Holocene aggradational surface around the southern margin of the fan, and partially infilled Lake Wairarapa. Six thousand years ago, when sea level may have been as much as a metre above present sea level, Lake Wairarapa was a large coastal embayment and

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sand dunes were constructed on its western shores.

*Eastern Uplands: Terrain 4*

The landforms of the northern segment of Terrain 4—broad elevated valleys and steep hill country up to 500 m above sea level—are similar to those in southern Hawke's Bay (Chapter 12), as the same structures and lithologies continue southward (Figure 13.2). Further to the south, however, Terrain 4 narrows and culminates in the mountainous Aorangi Range, 1000 m above sea level. Three sub-terrains are evident: the steplands developed in basement of the Aorangi Range; hill country, often rugged and deeply incised, composed of differentially indurated Cretaceous and



**Plate 13.4** An active alluvial fan at the base of the Aorangi Range. (Photo: M.J. Crozier)

Lower Tertiary rocks; and open elevated valleys and ridges of chiefly soft, sandy mudstone.

The Aorangi Range is cut by many steeply dipping, probably reverse faults that also have a transcurrent component of displacement (Figure 13.2). Movements on the fault planes have so crushed and shattered the moderately indurated greywacke that it is readily eroded and, under the influence of high rainfall combined with high rates of tectonic uplift, severe gully erosion can occur (Plate 13.4). Severe denudation has not been limited to the modern era; some rock fans formed during cooler episodes of the Last Glacial have been described from the Aorangi Range (Waterhouse, 1957).

The sub-terrain of differentially indurated Mesozoic and Lower Tertiary strata crops out along a broad coastal strip and in the Bideford Anticline (Figure 13.2). These sediments are strongly folded with dips of 50° to 70°. Steeply dipping faults have broken these strata into a series of splinters that form prominent, serrated dark-coloured hills which contrast with the surrounding low-lying, lighter coloured rocks. These ridges have been locally called 'taipos' (devils) and are prominent near Ngahape and Tainui. They are locally recognised for the thin infertile soils formed upon them and their susceptibility to severe sheet erosion.

Many of the landforms of the eastern uplands are developed in late Miocene to early Pleistocene soft mudstones, sandstones, and thin limestones. East of the Masterton Basin they form the Maungaraki Range, the extensive hillcountry centred about Alfredton, and the Tawhero Syncline. Slumping is widespread. Deep-seated slumping on failure planes parallel to bedding is common in the late Miocene interbedded sandstones and massive mudstones that dip at 20°, close to the axis of the Tawhero Syncline, in the high plateau-like country of the Whareama Valley. Johnston (1979) has mapped and described many of these slumps, which may be up to 3 km in length and 0.4 km wide and seem to be continuously moving. The slightly younger and sandier rocks further west are finely dissected with concave upper slopes and convex lower slopes; they are more susceptible to shallow failure and mass movement

(Plate 13.3), especially during extreme rainfall events such as those which struck Wairarapa in September 1977 (Crozier *et al.*, 1980).

### Origin of the Landform Terrains of Wairarapa

The pattern of the landform terrains of Wairarapa dates back to the Miocene and a change to a new tectonic regime that was accentuated, and in places modified, in the Pliocene and Pleistocene. During the late Cretaceous and early Tertiary a major marine basin, named the Eastern Basin by Kingma (1960), extended from Marlborough, through Wairarapa and Hawke's Bay, to at least the Gisborne district.

From the early Miocene onwards, the Eastern Basin was disrupted, by intrabasin folding and faulting, into numerous small basins and adjacent basement highs that ultimately involved the complete removal from much of Wairarapa of Upper Cretaceous and Lower Tertiary lithologies (Kingma, 1967). Consequently, Miocene to Pleistocene strata are predominantly clastic and coarser grained than Lower Tertiary lithologies; they represent terrestrial and shallow-to-deep marine depositional environments and, at least in the Tinui district (Johnston, 1979), were deposited in basins with structural trends oblique to the trends of underlying Upper Cretaceous and Lower Cenozoic strata. The axis of middle and late Miocene sedimentation lies within Terrain 4, specifically the Tawhero Syncline and Whareama Valley, and explains the origin of the interbedded sandstones and massive mudstones prone to slumping. In the late Miocene and early Pliocene the depositional axis shifted westward to form a linear depression; the southern part still persists today as the Masterton Basin (Terrain 3). In the vicinity of Eketahuna the former depression, now uplifted, appears to have been, in the early Pliocene, a narrow and deep fault-controlled trough (Neef, 1974). This trough rapidly shallowed in the late Pliocene, concomitant with a further and final westward shift in the axis of deposition to the present inland depression of northern Wairarapa (Terrain 2). The early Miocene dis-

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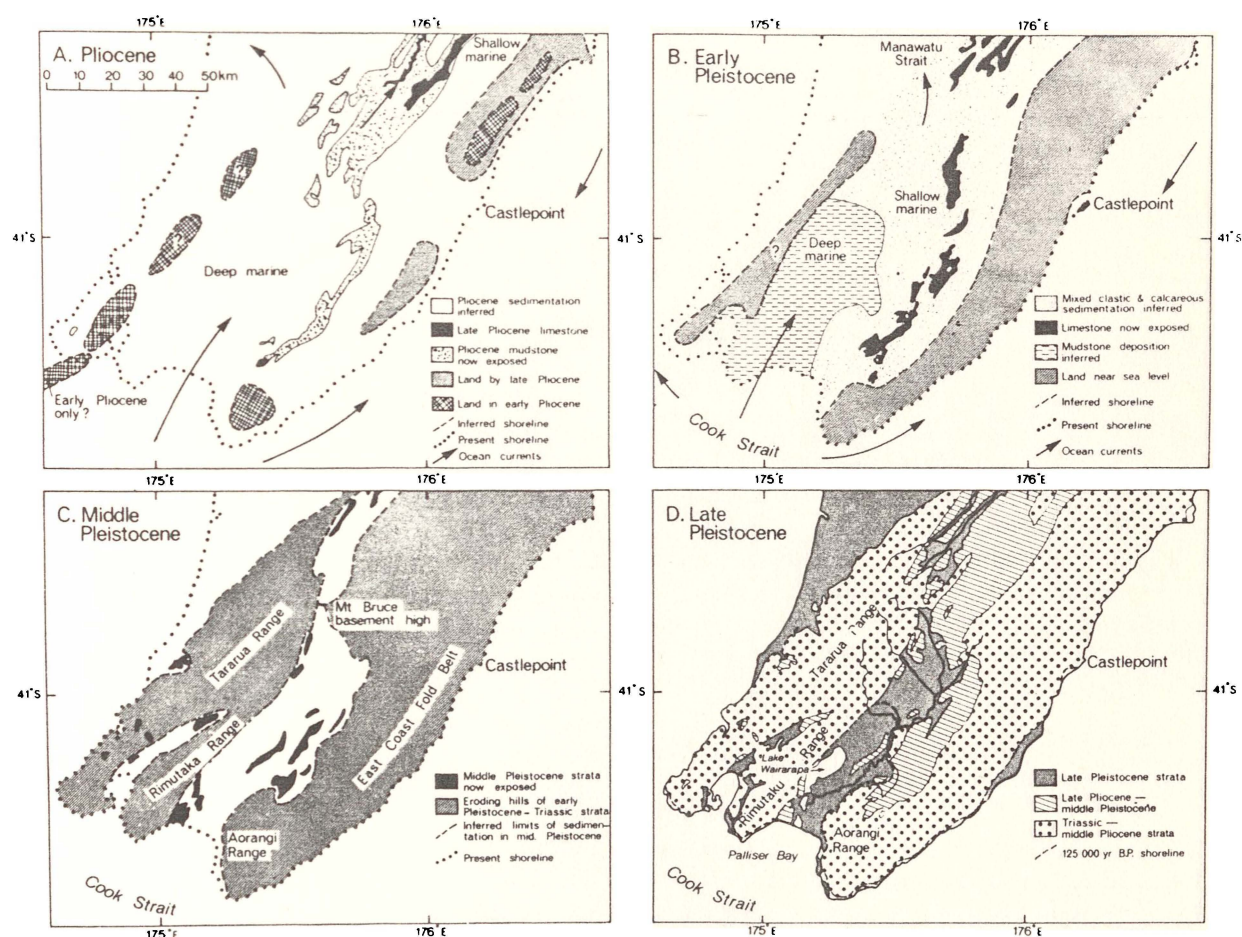
ruption of Wairarapa is attributed to propagation of the plate boundary through New Zealand. The successive westward shifts in the axes of mid-Miocene to Pleistocene deposition is attributed to the development of an accretionary prism in response to subduction at the Hikurangi margin. Although there is some evidence of pre-late Miocene dextral transcurrent movement through Wairarapa, and especially through Terrain 4 (Ridd, 1964; Lillie, 1969), transcurrent movement on the Wellington and Wairarapa Faults is considered to be chiefly of Pliocene and Pleistocene age.

By comparison with Hawke's Bay, basement greywacke strata are more evident in the landforms of Wairarapa, especially in the eastern uplands. This is related to a higher rate of Pleistocene uplift and erosion in Wairarapa, and to mid-Tertiary erosion that removed lower Tertiary strata as far east as the eastern uplands in Wairarapa. Thus in the Pleistocene, a reduced thickness of strata needed to be removed to re-expose basement.

### Pliocene and Pleistocene Paleogeography

By the late Miocene Wairarapa had been structurally differentiated into a western basement high, a central depression, and an eastern high. Changes in the Pliocene-Pleistocene paleogeography, diagrammatically summarised in Figure 13.4, trace the accentuation and modification of this pattern. The regional trend through the Pliocene and early Pleistocene is one of gradual uplift of the highs above sea level, decelerated subsidence in the inland depressions, and progressive withdrawal of the sea to the Masterton Basin. The middle and late Pleistocene is characterised by accelerated uplift, especially of the ranges, and terrestrial infilling of the inland basins.

A paleogeographic map shows the reconstructed physical geography at a particular time in the past, including such information as the distribution of land and sea, the depth of the sea, the directions of currents, and the distribution of bottom sediments. A series of paleogeographic

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**Figure 13.4** A sequence of Pliocene and Pleistocene paleogeographic maps showing the evolution of Wairarapa's landforms. Drawn from New Zealand Geological Survey (1973) and Vella (1963b). The age of Cook Strait is based on an interpretation of Grant-Taylor and Hornibrook (1964).

maps gives the evolution of a particular region. These maps (Figure 13.4) are reconstructions based on the nature and distribution of sediments now exposed on land, and the dating is based on the content of marine fossils or by correlation of climatic stages. Because the distribution of exposed and accessible Pliocene and early Pleistocene sediments is largely limited to the western margin of Terrain 4, the corresponding maps are chiefly interpretations, based on trends inferred from the exposed strata. No attempt is made here to incorporate into the maps the tens of kilometres of Plio-Pleistocene transcurrent displacement on the principal faults.

The Pliocene and early Pleistocene paleogeography of Wairarapa (Figure 13.4) complements that of Hawke's Bay (see Figure 12.5, page 250); with continued uplift, a Pliocene archipelago developed into a narrow seaway that extended from Hawke's Bay to Palliser Bay. The seaway became constricted in the vicinity of Mount Bruce in the latest Pliocene-early Pleistocene, and about 1.5 My B.P. flow ceased and independent drainage basins developed to the north and south. A marine environment persisted in the Masterton Basin until the middle Pleistocene, when, for a time, the basin was alternatively land and sea. During the middle Pleistocene the trend of basin

subsidence reversed and the adjacent, more rapidly rising, ranges shed detritus into the basin which built the floor above sea level. Consequently, the Last Interglacial shoreline only reached 50 km inland to Bidwell Hill, and 6000 years ago the shoreline was 20 km inland (Ghani, 1978).

Given the late Pliocene-early Pleistocene paleogeographic setting of the Masterton Basin—an inland sea shoaling to the north and east—one might expect some evidence to be preserved in the sediments of the effect of coeval, climatically induced sea level oscillations (Shackleton and Opdyke, 1976, 1977). Indeed, Vella (1963b) has described five repetitive late Pliocene-early Pleistocene sequences (cyclothem), each with a characteristic succession from mudstone to limestone with intervening unconformities. Vella attributed the origin of each unconformity-bounded cyclothem to sea level oscillations driven by climatic changes. While oxygen isotope analyses of calcareous foraminifera from the palaeomagnetically dated (Kennett *et al.*, 1971) Mangaopari Stream section (Devereux *et al.*, 1970), and from deep-sea cores (Shackleton and Opdyke 1976, 1977), show climatic oscillations of a higher frequency than the cyclothem described by Vella, implying that the cyclothem may be also responding to a tectonic factor, the principle is valid and is the subject of further work in progress.

The Tararua, Rimutaka, and Aorangi Ranges dominate the late Pleistocene landforms of Wairarapa, but their age is difficult to establish. Unequivocal evidence of a minimum age is offered by the coming of large quantities of greywacke conglomerates into the basins; conglomerates became the dominant depositional lithology in the latter part of the middle Pleistocene. An interpretation of an outlier at Makara (Grant-Taylor and Hornibrook, 1964) suggests that the Wellington Peninsula was uplifted after the early Pliocene, but no Pliocene or Pleistocene outliers have been located within the ranges to restrict the maximum possible age of uplift there. By extrapolation of the rate of vertical displacement on the Wairarapa Fault (0.9 mm/y) calculated from the Waiohine faulted terrace sequence, it appears that uplift above sea level began about one million

## Landforms of Wairarapa in a Geological Context 267

years ago. Because the actual rate of uplift may not have been constant, and may not have been at the rate calculated from the 20 000 year-old high Waiohine Terrace, uplift may have begun either before or after one million years ago. Perhaps most of the uplift has occurred, as suggested by Ghani (1978), in the last several hundred thousand years.

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## POSTSCRIPT TO PAPERS 2 AND 3

Papers 2 and 3 were written early in the course of the research leading to the thesis. In view of the subsequent findings in papers 4 and 8, it is necessary to modify three statements or conclusions made in papers 2 and 3.

In Paper 2, it was stated that the upper surface of the subducting oceanic Pacific Plate, at intermediate depths, is defined by the position of earthquake foci. This statement may have created the impression that the earthquakes originate at the interface between the plates. In paper 8 I show that at intermediate depths they most probably originate, rather, within the crust of the subducting plate. In addition, in Paper 2, I followed Adams and Ware (1977) in that the distribution of the earthquake foci define a plane striking N45°E that dips NW at 50°. In Paper 8 I show that the subducting plate is actually buckled rather than planar, and therefore it has variable dips along strike at intermediate depths.

At the time papers 2 and 3 were written, my understanding of the origin of much of the structure between the coastal ranges in Hawke's Bay-Wairarapa and the Hikurangi Trench, was that it originated through subduction accretion. It now appears that the structure of most of this region originated through imbrication and subduction kneading of a pre-existing passive margin succession; only the region from the present mid-slope position to the trench originated by the accretion of materials scrapped off the subducting lithosphere. Thus the question arises of the origin of the very broad zone of compression

that extends across to the Wanganui Basin, and involves the reverse faulting of greywacke basement? In paper 4 it is postulated that in addition to the effects of the episodic coupling of the subducting and overriding plates, this compression originates through the formation of a brittle-ductile mega shear zone through eastern North Island-Marlborough. This type of movement effectively extended (stretched) the east coast region in a NE-SW direction and concomitantly thinned it in a NW-SE direction.

In Paper 2 it was proposed that the East Cape block may have rotated clockwise as a microplate. Since Professor Walcott and his co-workers have published evidence for up to 62° of post-Oligocene dextral rotation of the east coast region, I now consider that the East Cape block was not a discrete microplate but that the rotation was accommodated within this region by brittle-ductile deformation (see Paper 4).

PAPER 4

Age and origin of the New Zealand Orocline in relation to Alpine  
Fault movement

Submitted to: Journal of the Geological Society of London.

Posted February 5, 1985.

AGE AND ORIGIN OF THE NEW ZEALAND OROCLINE IN RELATION TO ALPINE FAULT  
MOVEMENT

PETER J.J. KAMP

**SUMMARY:** The Alpine Fault, and the recurved arc structures (orocline) in the late Paleozoic-Mesozoic Rangitata Orogen, are two of the first-order structures of the New Zealand subcontinent. A commonly held view is that the orocline originated as a gigantic drag fold with Alpine Fault movement. However, in view of the post-Oligocene age of the Alpine Fault, this concept, involving a single recurved arc, cannot reconcile the two published sets of paleomagnetic data on tectonic rotations within the Rangitata Orogen and its cover rocks, which indicate at least  $62^\circ$  of dextral rotation during each of the Mesozoic Rangitata Orogeny and the late Cenozoic Kaikoura Orogeny. A new model postulates that there are actually two recurved arcs. The Western Arc has a multiple origin having formed initially during the late Triassic phase of the Rangitata Orogeny by the subduction accretion of the exotic Rakaia Terrane. It was accentuated during the late Eocene-Oligocene and the Plio-Pleistocene. The Eastern Arc formed with the late Cenozoic development of the Australia-Pacific plate boundary and it is viewed as a mega brittle-ductile shear zone that formed immediately northeast of the Alpine Fault. This solves the problem of the nature and location north of the Alpine Fault of the relative plate motion evident as 480km on the Alpine Fault. A major implication of this model, for plate tectonic

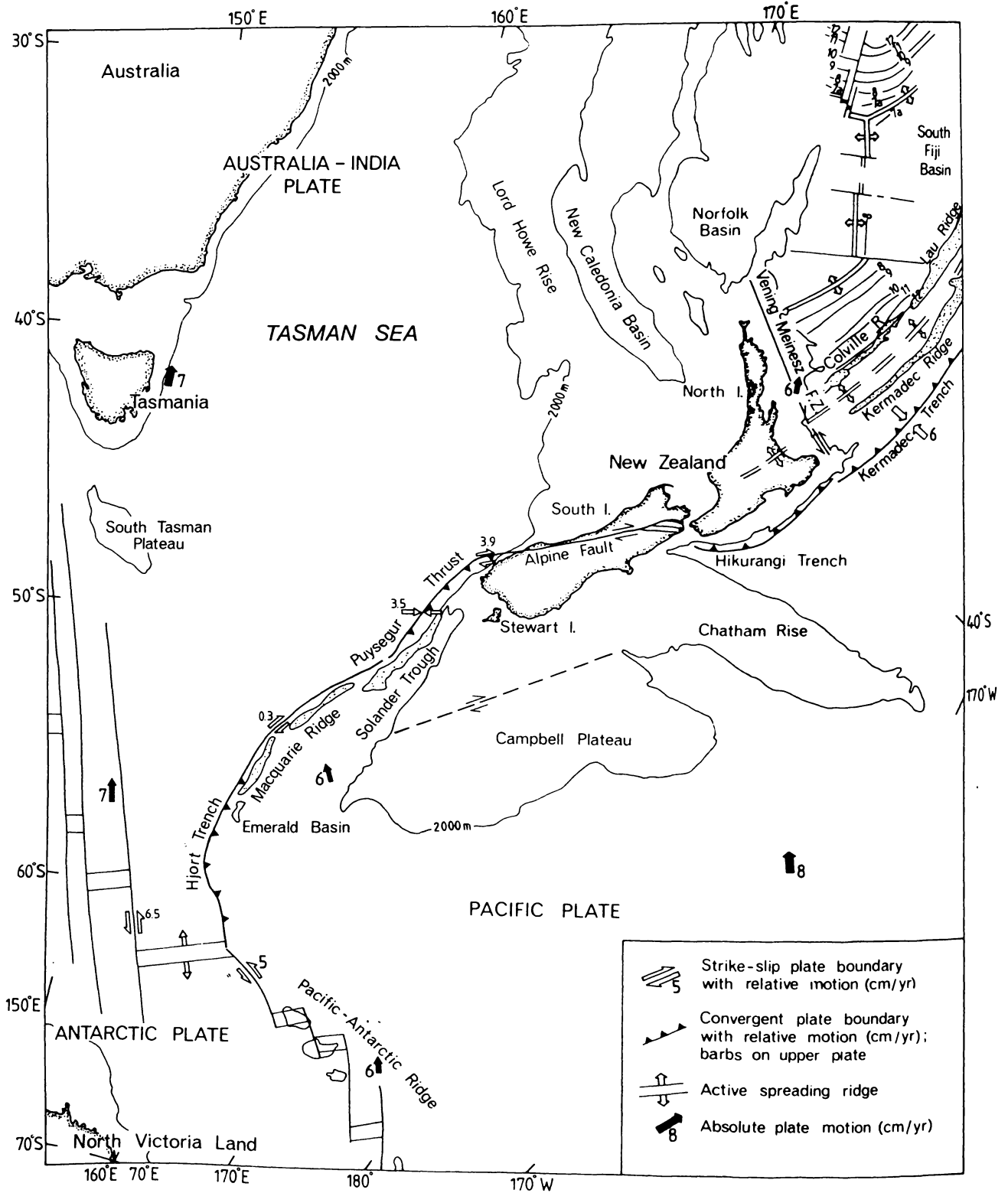


Fig.1 Plate tectonic map of New Zealand and the southwest Pacific showing the location and character of the Australia-Pacific plate boundary. reproduced from the Plate Tectonic Map of the Circum-Pacific Region-Southwest Quadrant (The American Association of Petroleum Geologists, Tulsa, U.S.A.).

reconstructions of the southwest Pacific, is that only approximately 500km of displacement has occurred through New Zealand, compared with the commonly adopted figure of 1000km.

Key words: New Zealand; Alpine Fault, shear zone, plate tectonics, southwest Pacific.

The Alpine Fault is a continental transform in the New Zealand sector of the Australia-Pacific plate boundary (Fig.1). Since the identification by Professor H.W. Wellman in 1948 of the 480km of dextral displacement on this fault, two problems critical to a more complete understanding of the geology of New Zealand have arisen. The first is the age of the fault's inception; the ages proposed to date range from the early Cretaceous (Suggate 1963) to the late Miocene (Wellman 1964). The second problem, and one which has received much less attention, is the nature and location north of the Alpine Fault proper of the relative plate motion evident as dextral displacement on the Alpine Fault. Figure 2 illustrates six recent treatments of this problem in regional tectonic analyses, from which it is evident that successive writers have assumed that the relative plate motion north of the Alpine Fault is expressed totally as fault displacements, that this displacement generally occurred on a simple extension of the Alpine Fault, and that the displacement occurred through eastern North Island.

The treatments in Fig.2 illustrate the simplest approach to the second problem, and importantly, they contradict three constraints offered by the onland geology:

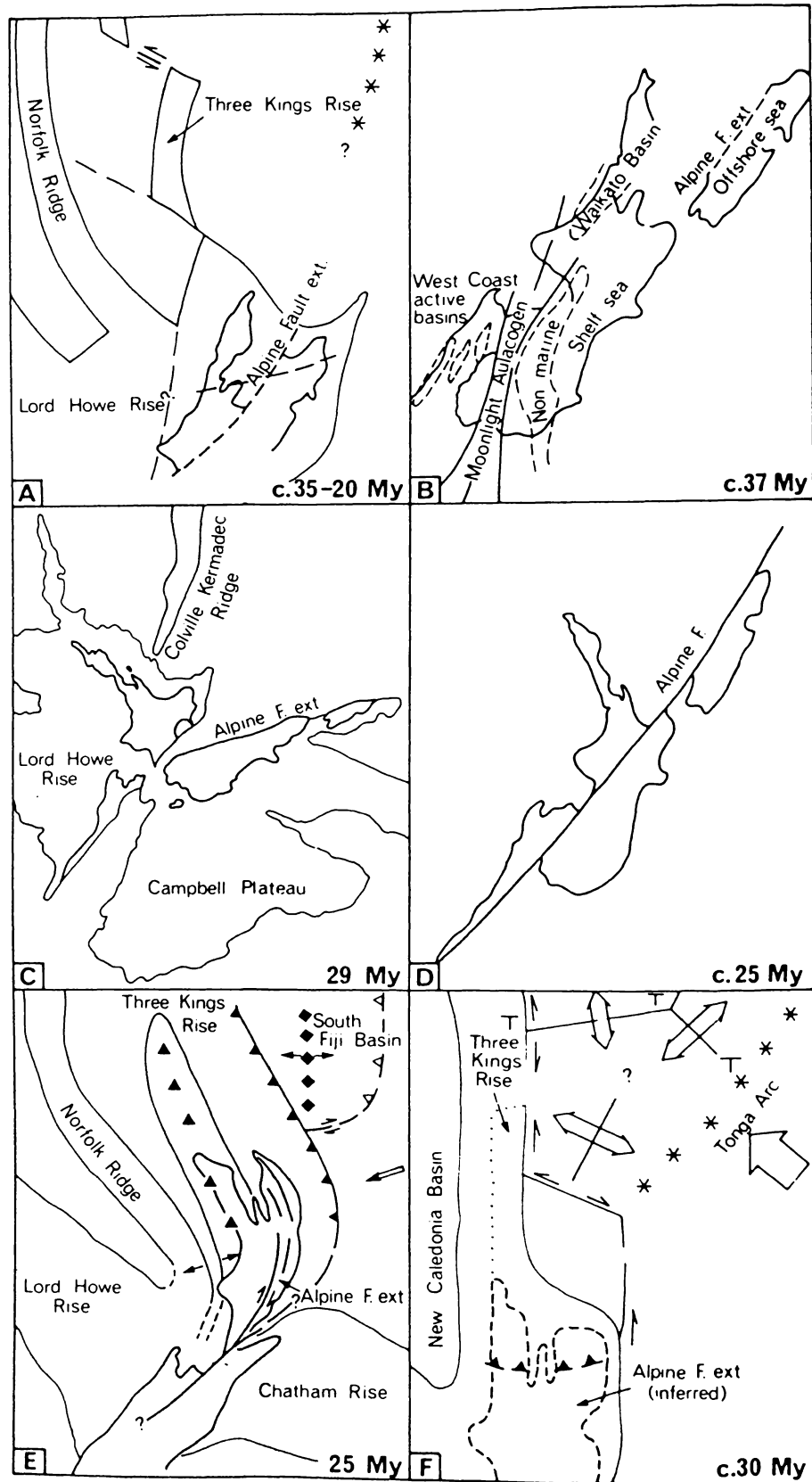


Fig.2 Middle Cenozoic reconstructions of New Zealand by previous workers showing the inferred nature and location north of the Alpine Fault proper of the relative plate motion evident as central displacement on the Alpine Fault. A from Ballance (1976); B, Carter and Norris (1976); C, Crook and Belbin (1978); D, Stevens and Suggate (1978); E, Cole and Lewis (1981); F, Ballance *et al.* (1982).

1. In plotting the distribution of each of the Rangitata basement terranes onto the Oligocene outlines shown in Fig.2, the present terrane distribution pattern (Bradshaw *et al.*1980) (Fig.3B) is further complicated; it should actually be simplified as a result of removing the deformation associated with the development of the late Cenozoic plate boundary.
2. It is difficult to identify sensible patterns in the Paleogene disposition of sedimentary basins, source areas and paleoshorelines if the Oligocene outlines in Fig.2 are adopted (Kamp 1985a).
3. The notion of a single fault extension through Marlborough and eastern North Island is inconsistent with the late Cenozoic pattern of deformation. The faulting is in fact distributed across a 70 to 100 km wide zone, and at present within this zone about half of the deformation is taken up as distributed strain (Lensen 1975; Walcott 1978a; Bibby 1981).

The problem of the nature and location of the relative plate motion north of the Alpine Fault is however just one symptom of a much larger problem: the age and origin of the recurved arc structures in the basement and cover rocks (Fig.3A). This oroclinal structure is generally viewed as a gigantic drag fold that formed just prior to Alpine Fault displacement (Fleming 1970; Hunt 1978)(Fig.4). However this origin is not upheld in an integral view of New Zealand geology, not only because it implies an extension of the Alpine Fault through eastern North Island as a single trace, but also because it is difficult to reconcile this origin with the two sets of paleomagnetic data (e.g. Grindley *et al* 1980; Walcott *et al* 1981) recording tectonic rotations within New Zealand.

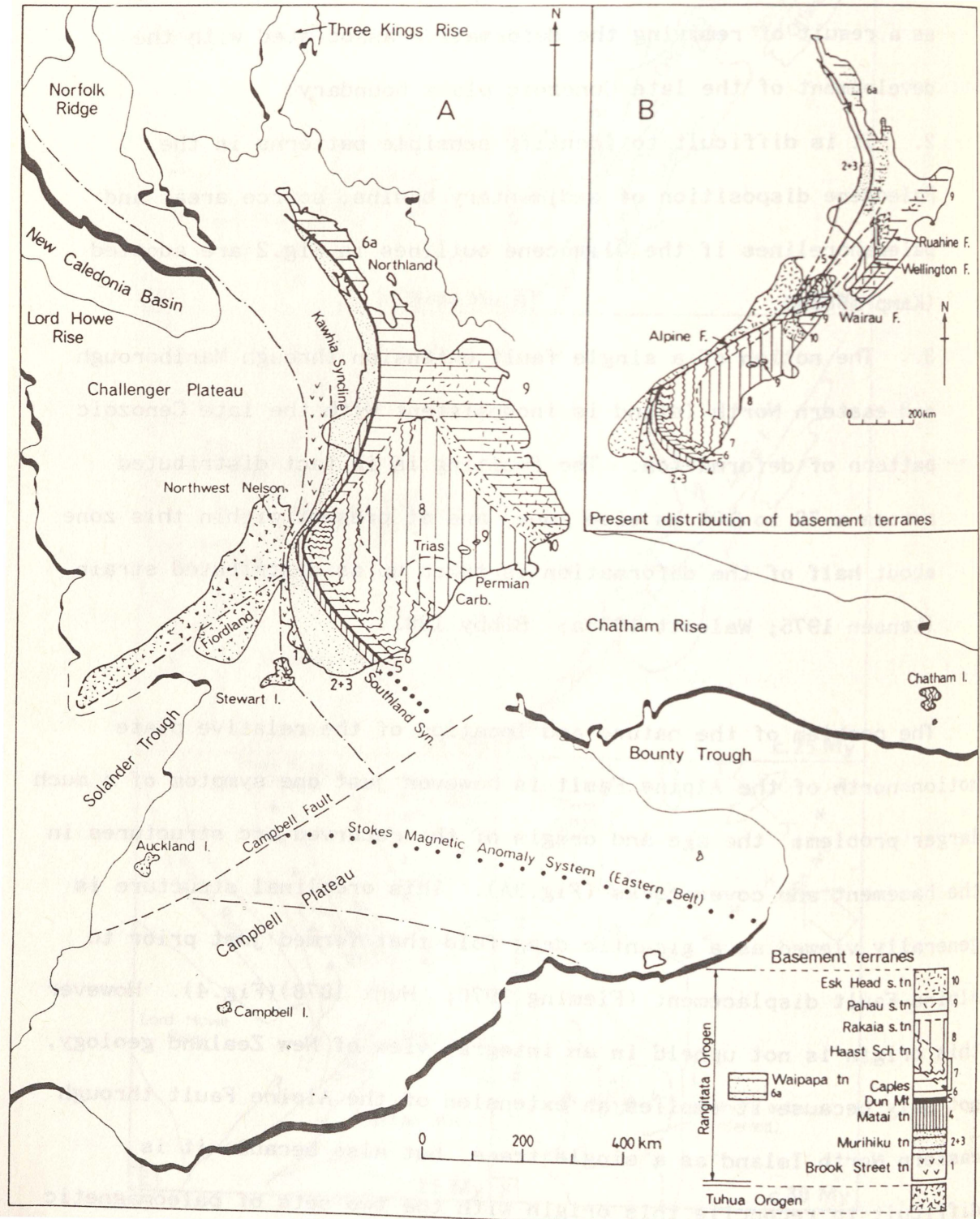


Fig.3 Sketch maps of the basement geology of New Zealand shown as a series of tectonostratigraphic terranes, at present (B) and for the early Tertiary (A). Modified after Bradshaw *et al.* (1980).

I take this opportunity to present a new model of the age and origin of the recurved arc structures in relation to Alpine Fault movement, and to explore its implications for the late Cenozoic structural development of eastern North Island and Marlborough. This model represents an attempt to reconcile the evidence for two widely different ages of recurved arc formation with a late Cenozoic age of Alpine Fault movement.

#### THE ALPINE FAULT IN RELATION TO THE RECURVED BASEMENT STRUCTURE

Macpherson (1946) first described the large S-shaped pattern of fold axes in the late Paleozoic-Mesozoic Rangitata Orogen (Fig 3B) as a recurved arc (orocline). This structure is most clearly expressed by the outcrop pattern and the associated geophysical signature of the Permian Dun Mountain ophiolite belt and the Permian-Triassic Brook Street magmatic arc (Hatherton 1966; Hatherton and Sibson 1970; Hunt 1978). New Zealand's plan shape largely reflects this structure, and Fleming (1970) and Davey and Christoffel (1978) have shown that it is a very prominent feature when the probable offshore extensions of the onshore terranes are considered.

Since the recurved arc of Macpherson is symmetrically bisected by the Alpine Fault with the same sense of displacement as the curvatures, a commonly held view is that it originated as a gigantic drag fold just prior to Alpine Fault inception. This concept, suggested by Suggate (1963), was first seriously applied to New Zealand by Fleming (1970), who adopted the view that the recurved arc was originally linear. Figure 4, which is taken from a subsequent

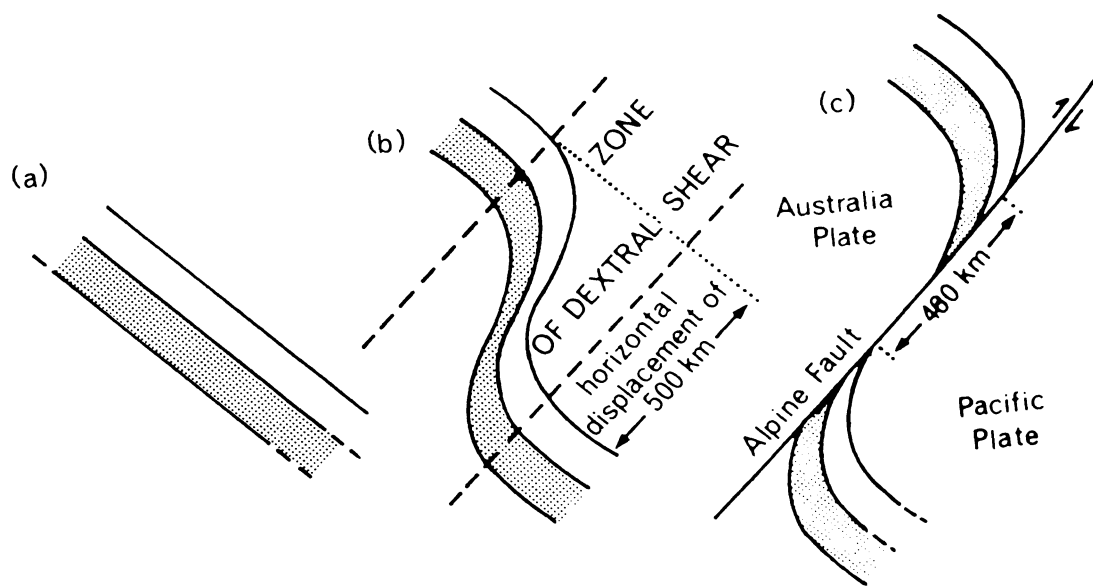


Fig.4 Sketch reproduced from Hunt (1978) showing how the western basement rocks of New Zealand may have been deformed in association with Alpine Fault movement.

paper by Hunt (1978), schematically illustrates this model of the inferred genetic relationship between the recurved arc and the Alpine Fault. It also shows a corollary of this relationship: there has been approximately 1000km of dextral displacement through New Zealand. Most of the recent plate tectonic syntheses of the southwest Pacific region have built this amount of displacement into their reconstructions (e.g. Weissel *et al* 1977; Crook and Belbin 1978).

A contentious geological issue in New Zealand is whether this model (Fig.4) applied to New Zealand during the late Mesozoic Rangitata Orogeny or during the late Cenozoic Kaikoura Orogeny. This depends upon the age of the initial and major lateral displacement on the Alpine Fault.

#### AGE OF ALPINE FAULT INCEPTION AND MAJOR DISPLACEMENT

To date three different ages of Alpine Fault inception and major dextral displacement have been proposed. An early Cretaceous Rangitata Orogeny age involving 360km of horizontal displacement (Suggate 1963; Grindley 1974), an early Oligocene age (Molnar *et al* 1975; Carter and Norris 1976), and an early Miocene age (Wellman and Wilson 1964; Kamp 1985).

Two lines of evidence are critical to the early Cretaceous school. The first relates to the present separation on opposite sides of the fault of early Cretaceous lamprophyre dikes considered to have been intruded as a linear dike swarm (Wellman, 1956; Grindley, 1963). Based on the early Cretaceous K-Ar ages of these dikes, Wellman and

Cooper (1971) suggested that 360km of the Alpine Fault's displacement pre-dated their intrusion and that the remaining 120km occurred during the late Cenozoic, Kaikoura Orogeny. The second line of evidence relates to the occurrence of mylonites close to the Alpine Fault which are partly intruded by lamprophyre dikes believed to be of mid-Cretaceous age (Reed 1964; Young 1968).

Cutten (1979) has recently carefully assessed the validity of these evidences, and concluded that neither support the notion of major Rangitata Orogeny displacement on the Alpine Fault. The sets of displaced dike swarms are evidently petrologically and geochemically dissimilar, and there are other dike swarms which provide other possible correlations. In addition, the southern set of dikes which intrude the Haast Schists may be too old owing to the possible presence of excess argon in the adjacent country rocks (Adams, 1981). The mylonite evidence is also dismissed by Cutten(1979) on the basis that some of the mylonites may have formed during an earlier phase of compression, followed by transcurrent shear at a later date parallel to the original mylonite band. In addition, Sibson *et al* (1981) have concluded that while lamprophyre dikes cut high-grade mylonites on the Fraser Fault, which lies adjacent to, and northwest of the Alpine Fault (Young 1968), no dikes actually intrude the Alpine Fault zone proper. Furthermore, their structural data indicate that all the fault rocks within the Alpine Fault zone, ranging from cataclasite to schist-derived mylonites, have been imposed during the late Cenozoic. An early Cretaceous age of Alpine Fault inception and major displacement is not accepted here.

The remaining options of the age of Alpine Fault inception lie near the Eocene-Oligocene boundary or the Oligocene-Miocene boundary.

Both of these ages are inferred from the stratigraphy and sedimentation patterns of mid-Cenozoic basins in the South Island (Waiiau-Te Anau; Paparoa-Murchison) which now lie on opposite sides of the Alpine Fault. The differences in age arise from different interpretations of the origin of these basins. Norris *et al* (1978) and Norris and Carter (1982) have viewed these basins as originating in a continental transform setting caused by initial movement on the Australia-Pacific plate boundary (Alpine Fault), whereas Kamp (1985a) attributes their origin and mid-Eocene to late Oligocene development to continental rifting, with subsequent (early Miocene) dislocation and disruption of this structure by Alpine Fault movement.

That the Eocene-Oligocene basins in western and southern South Island probably did not originate through transform displacement is based on the following: 1. The Alpine Fault clearly had a different (northeast-southwest) trend from that of the western zone of north-south trending basins. 2. The zone of basins extended for 800km northwest of the Alpine Fault. 3. The depocentres originated by normal extension rather than by transtension (Kamp 1985a). The early Miocene age of the Alpine Fault's inception is based (Kamp 1985a) on the widespread occurrence in the basins now adjacent to the fault in Westland of a post-Oligocene to Pliocene unconformity which originated tectonically (Nathan, 1978), together with a regional and persistent change from limestone to terrigenous sedimentation further from the Alpine Fault where the unconformities did not develop. Based on these arguments, an early Miocene age of Alpine Fault inception is adopted here, with all of the 480km of displacement taking place during the last 23 million years.

In view of the Neogene and Quaternary age of Alpine Fault movement, it appears that the orocline cannot have originated as a drag fold during the late Mesozoic. However, sound structural interpretations of regional and local synmetamorphic Rangitata Orogeny structures within the Haast Schist terrane indicate that much of the bending probably did occur during the Mesozoic (Grindley 1963; Cooper 1974). The regional pattern shows that as one passes northwestward from the Otago Schists into the Alpine Schists and up to the Alpine Fault, the synmetamorphic folds tighten-up and the fold axes are dextrally rotated into near parallelism with the fault. Within this pattern, Grindley (1974) has attributed the refolding (F2 deformation of Grindley 1963) of early nappes (F1 deformation) about steep axial planes in the Alpine Schists to earliest Cretaceous formation of the recurved arc. This phase was accompanied by amphibolite facies metamorphism.

In summary, the above reasoning suggests that the recurved arc, as defined by the more western basement terranes, probably formed during the Rangitata Orogeny, and that its displacement on the Alpine Fault occurred much later and during the Kaikoura Orogeny. Therefore, the bend in the western terranes cannot have originated as a drag fold with Alpine Fault movement.

The paleomagnetic method, in combination with appropriate age information, is a powerful means of determining the occurrence and age of tectonic rotations. Recently published paleomagnetic data gathered from widespread localities in New Zealand is now reviewed to more closely evaluate the relationship between the recurved arc structures and the Alpine Fault. On this basis the current model (Fig.4) is rejected and a new one is proposed, which, amongst other

implications, shows the nature of the relative plate motion northeast of the Alpine Fault.

#### Paleomagnetic data on tectonic rotations within New Zealand

Between 1977 and 1982 two sets of paleomagnetic data were obtained and published by two separate research groups working in New Zealand, both attempting to resolve the age of the recurved arc.

The first was obtained by Grindley and his co-workers (Grindley *et al* 1977, 1980; Grindley and Oliver 1979; Oliver *et al* 1979) from Mesozoic igneous rocks occurring within and upon western and southern parts of the basement orocline, and on both sides of the Alpine Fault (Fig.5). The restored paleolatitudes for each of the Mt. Somers (95 my B.P.), lower Buller Gorge (81 my B.P.), Chatham Islands (75 my B.P.) and Glenham Porphyry (230-190 my B.P.) localities show a consistent progression with age that defines the New Zealand mid to late Mesozoic Apparent Polar Wander Path. This path is consistent with the Australian APWP (McElhinny *et al* 1974) as the New Zealand subcontinent did not separate from Australia by seafloor spreading until 78 my B.P. (Anomaly 33; Weissel and Hayes 1977).

Assuming the maximum statistical uncertainty in mean declinations, both the Buller Gorge and Mt. Somers declinations, when compared with those of the Chatham Islands, indicate a maximum possible post-emplacement dextral rotation of 50°; the Glenham Porphyry locality is more tightly constrained at a maximum of 28° of dextral rotation. They have interpreted their data to support bending of the recurved arc chiefly during the Rangitata Orogeny.

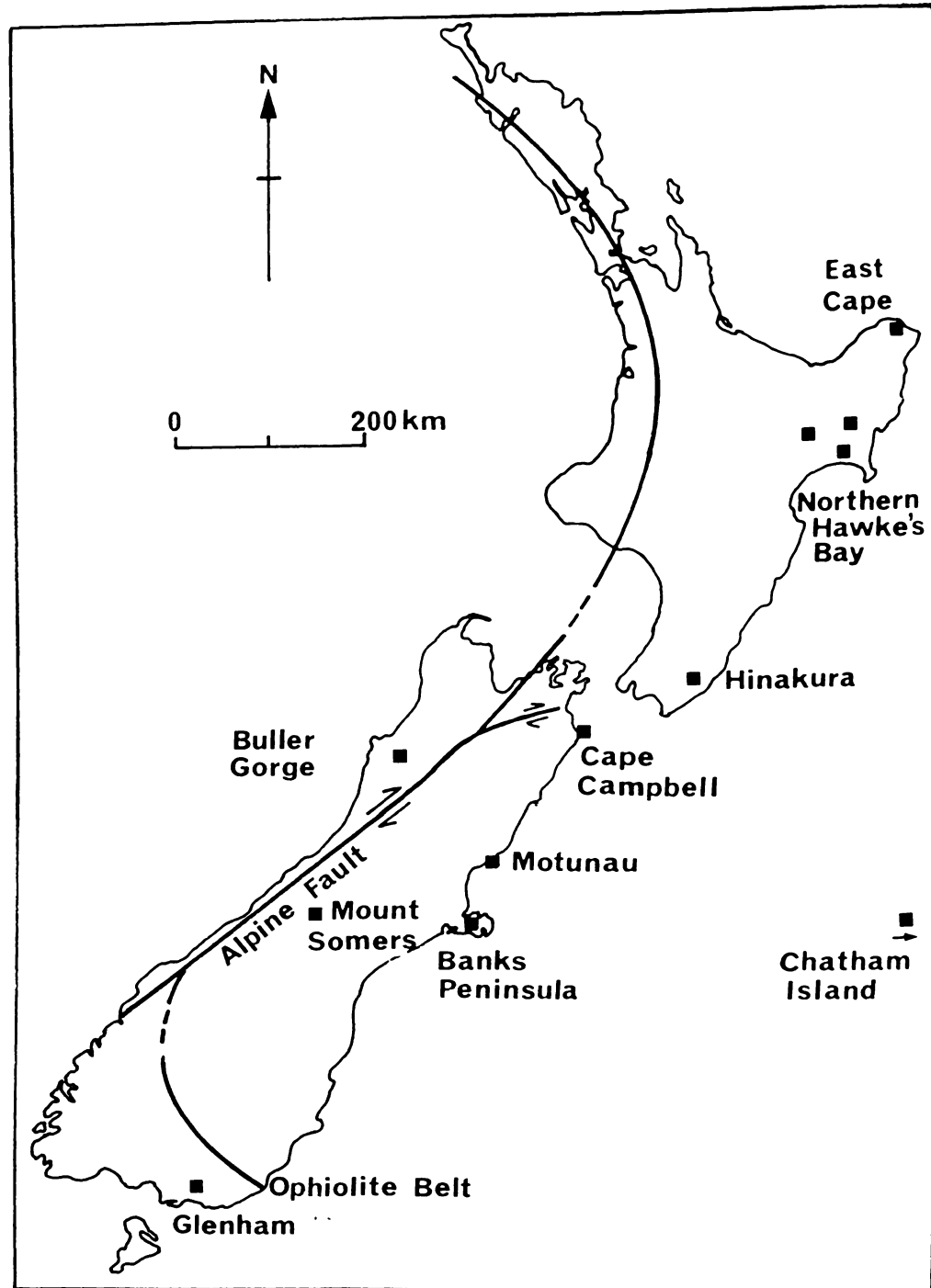


Fig.5 Map of New Zealand showing the localities sampled for paleomagnetic determination of the age and degree of tectonic rotation.

This conclusion is supported by the metamorphic and tectonic history of the Haast Schist terrane. As outlined earlier, Grindley (1974) considered that his F2 deformation in the Alpine Schists accompanied formation of the recurved arc and occurred during the metamorphic climax when the present isograd pattern was established. He also considered that the F2 deformation in the Alpine Schists was coeval with the latest F2 folding and greenschist metamorphism in Otago (Grindley, 1978). A recent programme of K-Ar dating of the Otago Schists has revealed 125-195 my B.P. ages for the lower grade metamorphic rocks (Adams 1981), which imply that the metamorphism had commenced by at least the Triassic-Jurassic boundary, and was followed by a 70 million year interval of cooling through uplift and erosion. Thus if Grindley's correlation of the F2 deformation phase in the Alpine Schists with the latest F2 deformation phase in the Otago Schists is valid, it follows from the K-Ar dates that the recurved arc formed at, or soon before, the Triassic-Jurassic boundary, consistent with the Glenham Porphyry paleomagnetic data. Later, it is suggested that the F1 and F2 deformations of the schists, their metamorphism, and the formation of the recurved arc in the western parts of New Zealand are linked by way of the middle to late Triassic collision of the exotic Rakaia (Torlesse) terrane with the more western Wakatipu arc-trench assemblage.

The second set of paleomagnetic data tracking tectonic rotations within New Zealand has been obtained by Walcott and his co-workers (Walcott *et al* 1981; Walcott and Mumme 1982) from late Cenozoic sedimentary strata which overlie basement in eastern North Island and Marlborough (Fig.5). Late Miocene rocks of the Tongaporutu Oppezone (6-11 my B.P.) at Cape Campbell and Hinakura have a stable

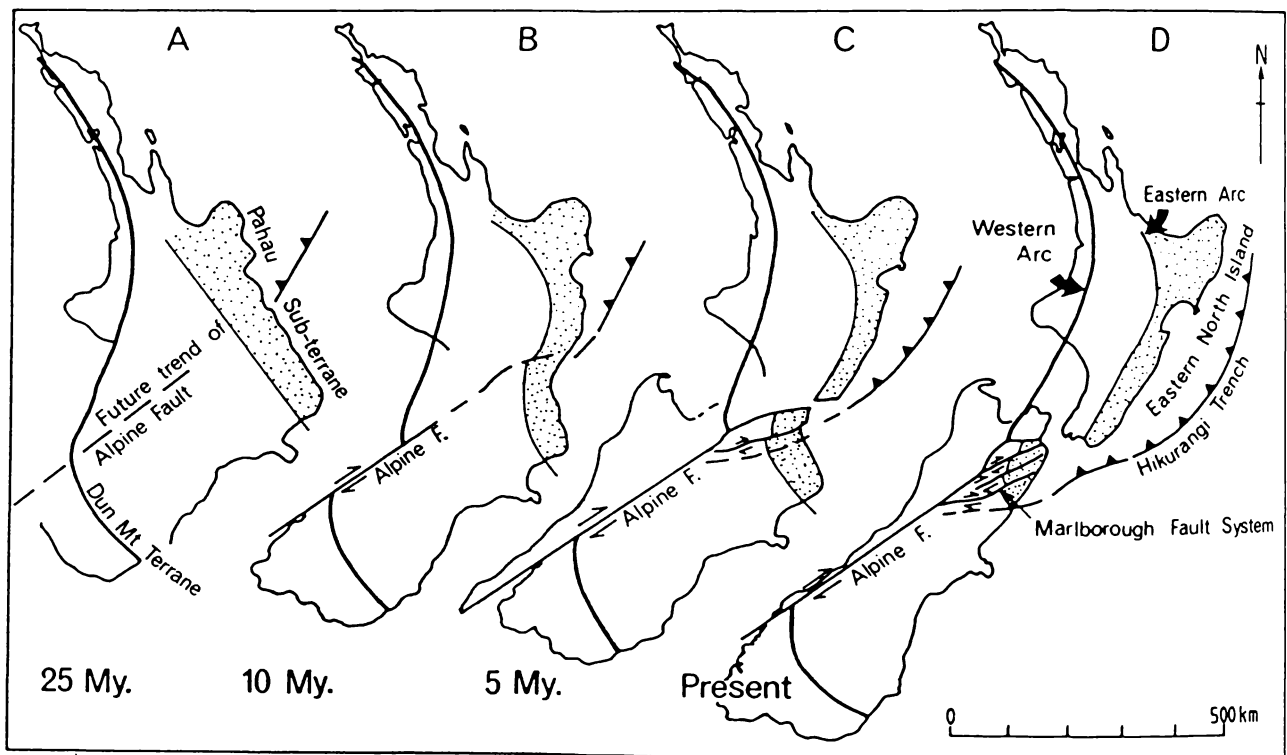


Fig.6 A new model, showing as a series of sketches, the postulated age and origin of the New Zealand recurved arcs in relation to movement on the Australia-Pacific plate boundary including the Alpine Fault sector.

direction of remnant magnetism which deviates  $20^{\circ} \pm 11^{\circ}$  and  $30^{\circ} \pm 8^{\circ}$  clockwise respectively from the present axial dipole field (Walcott *et al* 1981). By comparison, rocks of the same age and lithology further south at Motunau, and of similar age (8-9 my B.P.) but of volcanic composition at Banks Peninsula (Evans 1970), have essentially the same declination as the Earth's present axial dipole and indicate no tectonic rotation. The determination of the mean declination of older siltstones in Northern Hawke's Bay, mainly of middle Miocene age, has identified dextral tectonic rotations of as much as  $62^{\circ} \pm 23^{\circ}$ . These data imply a consistent increase in declination with time of  $4^{\circ}/\text{My}$  (Walcott and Mumme 1982). The subtraction of the change in declination due to the apparent polar wander of the Australian Plate, amounting to about  $1^{\circ}/\text{My}$  during the last 20 million years, gives a residual declination anomaly for the eastern North Island-Marlborough region of about  $3^{\circ}/\text{My}$  (Walcott 1984). From these data Walcott *et al* (1981) concluded that most, if not all, of the bending to form the basement recurved arc has occurred since mid-Tertiary times.

In the context of a single recurved arc the two sets of paleomagnetic data are incompatible - one indicates a Mesozoic age and the other a late Cenozoic age of formation. A more complicated model describing the origin of New Zealand's recurved arc structures and their relationship to the Alpine Fault is necessary.

#### **A new deformation model for New Zealand invoking two recurved arcs**

Figure 6 illustrates a new model of the ages and origins of the recurved arc structures in New Zealand and their postulated relationship to the late Cenozoic displacement on the Alpine Fault.

The model is constrained by the two sets of paleomagnetic data; a pre-Miocene bend is shown for the western terranes, represented by the Dun Mountain terrane, and a late Cenozoic bend is shown for the more eastern terranes of Marlborough and eastern North Island. The model is also constrained by an early Miocene age of Alpine Fault inception, and Stock and Molnar's (1982) estimate of the average rate of relative plate motion through New Zealand during the last 10 million years (33mm/y).

The model proposes that there are actually two recurved arc structures in New Zealand compared with the present concept of a single arc. The Western Arc comprises the elements of the Rangitata Orogen from the Brook Street terrane to the Haast Schist terrane, and the Eastern Arc comprises the Rakaia, Esk Head and Pahau sub-terrane (Fig.3). The model shows that during the late Cenozoic the pre-existing Western Arc was dislocated by movement on and near the Alpine Fault, while the Eastern Arc formed as a gigantic brittle-ductile shear zone northeast of the Alpine Fault. At present only the northwestern limb and the fault ruptured central portions of the Eastern Arc crop out on land; the southeastern limb is submerged as the Chatham Rise. An important feature of this model is that only 500km of relative plate motion is necessary to achieve both the observed 480km of dextral displacement on the Alpine Fault and the formation of the shear zone in the eastern North Island-Marlborough region.

#### Basement Considerations

In Fig.6 the dextral rotations measured in the cover rocks of eastern North Island are inferred to apply to the basement on the basis that the cover rocks are autochthonous. Notwithstanding the

occurrence of early and middle Miocene allochthonous sheets in the East Cape Region (Stoneley, 1968; Brothers and Delaloye, 1982; Mazengarb, 1983), this inference is most probably valid for the localities where the paleomagnetic samples were collected (Walcott *et al* 1981; Walcott and Mumme 1982). An independent means of assessing the autochthonous assumption and its implications may be offered by considerations of the basement itself.

There are two issues, one, that there is evidence in the basement of eastern North Island for dextral rotation, and two that it is of late Cenozoic age. The first issue is most probably valid as shown by the fact that over the large area of the Raukumara Peninsula where the cover rocks have been stripped, the dominant structural pattern is a pronounced dextral swing of at least  $55^\circ$  in the strikes of the major folds and faults (Kingma 1965). The second issue is more difficult to prove. One can however argue that the dextral rotation post-dates the bulk of the bending of the Western Arc, as follows.

Figure 3 shows that in the Bay of Plenty region the Pahau Subterrane lies adjacent to the Waipapa terrane. Although the nature of this contact is not known in detail, it is clear that the terranes 7 and 8, which all lie between the Pahau and the South Island equivalent of the Waipapa terrane, (the Caples terrane), are cut out in central North Island. This structural discordance suggests two generations of dextral rotation. This becomes even more evident in a map of the possible pre-plate boundary distribution of the basement terranes, such as the one presented by Bradshaw *et al* (1980), which is reproduced here in the context of the New Zealand subcontinent (Fig. 3B). Thus while considerations of the basement cannot precisely constrain the age of dextral rotations in eastern

North Island, they do show that the bending post-dates formation of the Western Arc, and most probably also post-dates the formation of the Pahau subterrane (i.e. post-early Cretaceous).

### Origin of the Western Arc

Since a drag-fold origin is not applicable to the Western Arc, an alternative mechanism for its formation is required. It is argued here that the Western Arc resulted mainly from a mid to late Triassic subduction collision of the Rakaia subterrane with the pre-existing arc to trench assemblage of terranes 1-6. While the exotic character of the quartzo-feldspathic detritus of the Rakaia subterrane is not in doubt, it is however worth noting that there is a major problem as to the source of this detritus (contrast, Landis and Bishop 1972; Andrews and Bradshaw 1973; Kamp 1980; Mackinnon 1983). A minimum age of the initial collision is given by the oldest K-Ar ages of the lowest rank metamorphic rocks which formed in the collision zone (Haast Schist terrane). Adams (1981) reports ages on such rocks as 195 my B.P. (Triassic-Jurassic boundary).

A striking feature of the distributions of the Rakaia and Haast Schist terranes is their coincidence with the portion of the Western Arc which is concave to the east (Fig.3). Conversely, where these two terranes feather-out, such as to the north, the Western Arc is convex to the east. This is strongly suggestive of a genetic link between accretion of the Rakaia subterrane, formation of the schist belt, and formation of the recurved arc. Much of the development of the Western Arc was probably at the expense of the volcanic arc to trench assemblage, and the pronounced "waist" in the Murihiku forearc basin which coincides with the inflection of the recurved arc is also viewed as a consequence of the collision.

Spatial trends in the ages of the terranes support the concept that a middle to late Triassic collision formed the Western Arc. For example, the Caples accretionary prism (Turnbull 1980) is only of Permian to early Triassic age (Turnbull 1979) near the point of inflection, but ranges up to Jurassic age (Kear 1960; Schofield 1967) in the North Island (equivalent to Waipapa terrane) where it was distant from the collision and subsequent uplift. In the Southland Syncline (Fig.3A), reductions in Jurassic succession thicknesses towards the northwest (McKeller and Speden 1978), together with a southeasterly directed component of along-slope regression (Carter *et al* 1978), indicate that the near complete absence of Jurassic strata in the northwestern two-thirds of the Syncline are due in large part to non-deposition consequent upon the late Triassic-Jurassic collisional eversion of the forearc basin. This interpretation is supported by a major metamorphic unconformity between late Permian Glaucophanic Schist Facies rocks and a thin inlier of late Jurassic Zeolite Facies beds in the Key Summit Syncline, located at the northwest end of the Southland Syncline. Grindley (1978) has correlated the lawsonite metamorphism, and the uplift indicated by this metamorphic unconformity, to the F1 deformation phase and associated metamorphism in the Haast Schists which predate the oldest K-Ar ages of 195 my B.P.

Although the initial collision of the Rakaia wedge with the subduction zone occurred in the Triassic, it was probably followed by an extended interval of subduction accretion and kneading, perhaps in an obliquely convergent setting (Wood 1978), which considerably thickened the crust. Bradshaw *et al.* (1980) suggest that following the collision, the trench was re-established further

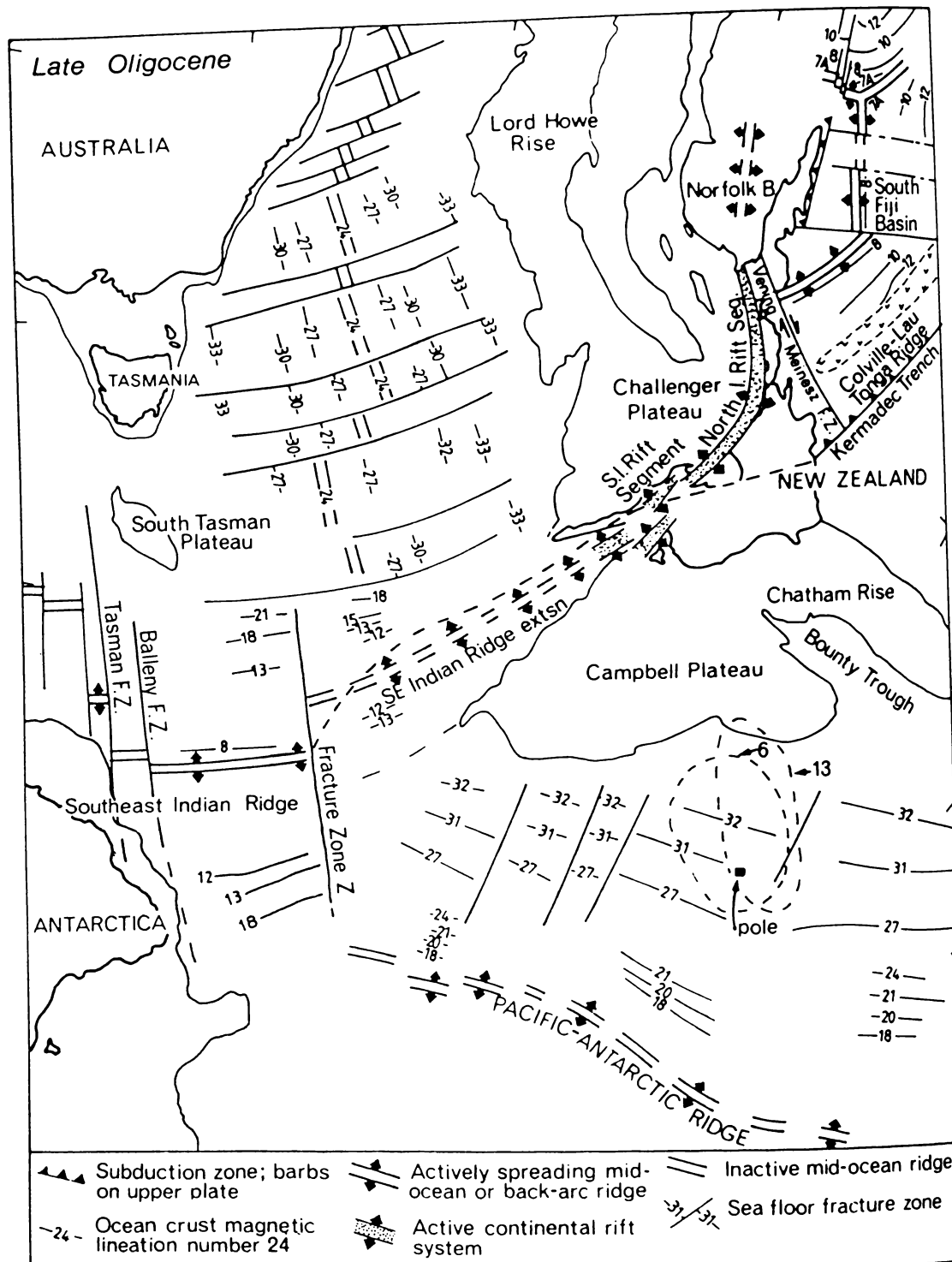


Fig.7 Plate Tectonic map of the southwest Pacific region for Anomaly 7 time (26 my B.P.; late Oligocene) After Kamp (1985b).

east, and the Pahau and Esk Head subterranean represent a later Jurassic-early Cretaceous subduction complex. The younger age of these terranes, together with the evidence that their accumulation followed a tectonic re-organisation, explains why they were not recurved as part of the Western Arc.

While the Western Arc is considered to have originated during the middle to late Triassic, this structure appears to have been accentuated during at least two further times. One occurred during the late Eocene and Oligocene, and the other during the Pliocene-Pleistocene.

An integration of the onshore and offshore geology of New Zealand has revealed the occurrence of a mid-Eocene to late Oligocene continental rift system through western New Zealand (Kamp, 1985a). The South Island segment of this rift system was evidently the response within the continental crust of New Zealand to the eastward propagation and spreading of the Southeast Indian Ridge (Kamp, 1985b). This ridge formed an eastward thinning wedge of Anomaly 21-7 oceanic crust between the Campbell Plateau and the older oceanic crust (An33-An24) of the central Tasman Sea (Fig.7). In a pre-Anomaly 21 (early Eocene) reconstruction, this wedge of seafloor must be removed; this is achieved by sinistrally rotating 25° the Campbell Plateau-Chatham Rise block relative to the Lord Howe Rise about a map centre at 44°S, 170°E. This reconstruction implies about 25° of tightening of the Western Arc during the late Eocene-Oligocene, and, at the same time, shortening within Marlborough-eastern North Island in a direction normal to the coastline. New paleomagnetic data of Mumme and Walcott (in prep.) from western North Island supports this age and amount of rotation of the Western Arc.

The Plio-Pleistocene accentuation of the Western Arc is confined to the ends of the arc adjacent to the Alpine Fault. Northern South Island is presently in a state of east-west compression which has originated from the continent-continent collision across the present plate boundary. While one manifestation has been uplift of the Southern Alps and Marlborough ranges, another has been east-west shortening. This shortening has caused 12° of dextral rotation of the portion of the Western Arc immediately north of the Alpine Fault bend (compare Fig.6 C and D). The portion of the Western Arc southeast of the Alpine Fault has probably also been accentuated as a result of drag on the fault.

In conclusion, the Western Arc is viewed as a multigenetic structure. Moreover, while it is convenient to consider the Western Arc as distinct from the Eastern Arc, at least to some extent they developed concurrently.

#### Origin of the Eastern Arc

The Eastern Arc is considered here to have originated during the late Cenozoic as a consequence of deformation accompanying the evolution of the New Zealand sector of the Australia-Pacific plate boundary. Figure 6 illustrates the postulated development of the Eastern Arc in this context. It shows that the relative plate motion, amounting to about 500km, was accommodated differently along different parts of the plate boundary zone. In central and southwestern South Island it was expressed chiefly as Alpine Fault displacement, but in eastern North Island and Marlborough the equivalent amount of relative motion was distributed as aseismic strain and fault displacement

across a much broader zone. The total amount of Alpine Fault displacement (480km) is equivalent to the lateral displacement of the ends of the Eastern Arc. The model further suggests that during the early and middle Miocene, the Alpine Fault displacement was almost wholly accommodated in eastern North Island-Marlborough as ductile shearing (Fig. 6B), but that during the late Miocene-Quaternary, the additional strain was relieved in the axial portion of the bend as brittle-ductile shearing, thus forming the Marlborough Fault System. To this extent the Eastern Arc may be viewed as a mega brittle-ductile shear zone. Differences in the rheology of the basement, and in particular the contrast in competence between the Tuhua Orogen and the Rangitata Orogen, is considered to be the main reason that the relative plate motion was expressed so differently along the plate boundary zone.

While the northeast margin of the subcontinent, initially between the developing Alpine Fault and the Hikurangi Trench (Fig. 6B) was progressively deformed as a mega shear zone, a slab of Pacific Ocean lithosphere was concomitantly emplaced beneath the northern limb of the shear zone (eastern North Island) and the rest of northern New Zealand (Kamp, 1984). Before the inception of the Alpine Fault, this slab was already dipping at a shallow angle to the northwest immediately northeast of northern North Island, as evidenced by the Oligocene age and orientation of backarc spreading in the South Fiji Basin (Malahoff *et al.* 1982). With the early Miocene start of relative plate motion through New Zealand, this slab was progressively displaced to the southwest beneath northern New Zealand at essentially the same rate as Alpine Fault displacement (Kamp 1984). It was possible for subduction to occur beneath a major part of the Eastern Arc, that itself was being displaced in the direction of the

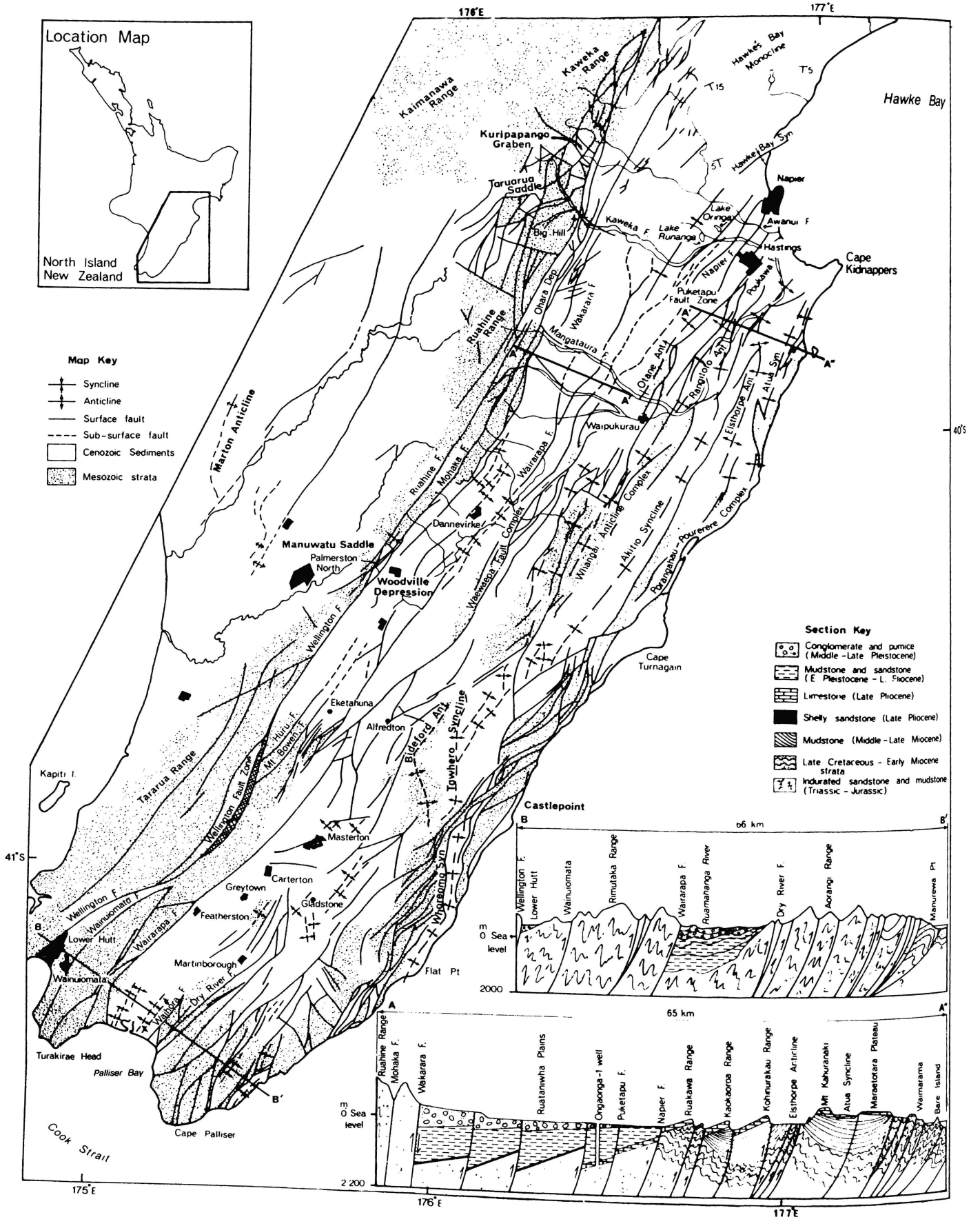


Fig.8 Structure of Hawke's Bay and Wairarapa in southeastern North Island. Data mainly from Grindley (1960) and Kingma (1962,1967).

relative plate motion, because only the southern portion (Marlborough-Chatham Rise) of this arc was displaced southwestward at a similar rate to the subducted slab.

#### Late Cenozoic structure and tectonics of eastern North Island in relation to the Eastern Arc

The preceding section implied that there has been two types of relative plate motion in eastern North Island. One type was expressed within the leading margin (continental crust) of the Australia Plate as the formation of a shear zone, and the other was expressed as a subduction thrust beneath the shear zone. The late Cenozoic structural and tectonic pattern of eastern North Island will therefore be the integral of these two types of relative plate motion which may well have reinforced one another. However, only the influence and control of subduction processes have thus far been considered in previous attempts to explain this structural and tectonic pattern. (e.g. Cole and Lewis 1981; van der Lingen 1982). The two major points listed below show that at least one other factor, suggested to be the formation of a shear zone within the leading margin of the Australia plate, must have contributed to the development of eastern North Island.

1. From the directions and rates of relative plate motion opposite eastern North Island (Walcott 1978a) a much greater compressive component normal to the coastline is anticipated in the more northern region (45 mm/y) than in the southern region (22 mm/y). However, in fact, the degree of crustal shortening normal to the coastline, as evidenced by the density of thrust faulting and folding (Fig.8) and the depth to basement (Fig.9A), is much greater in the south than in

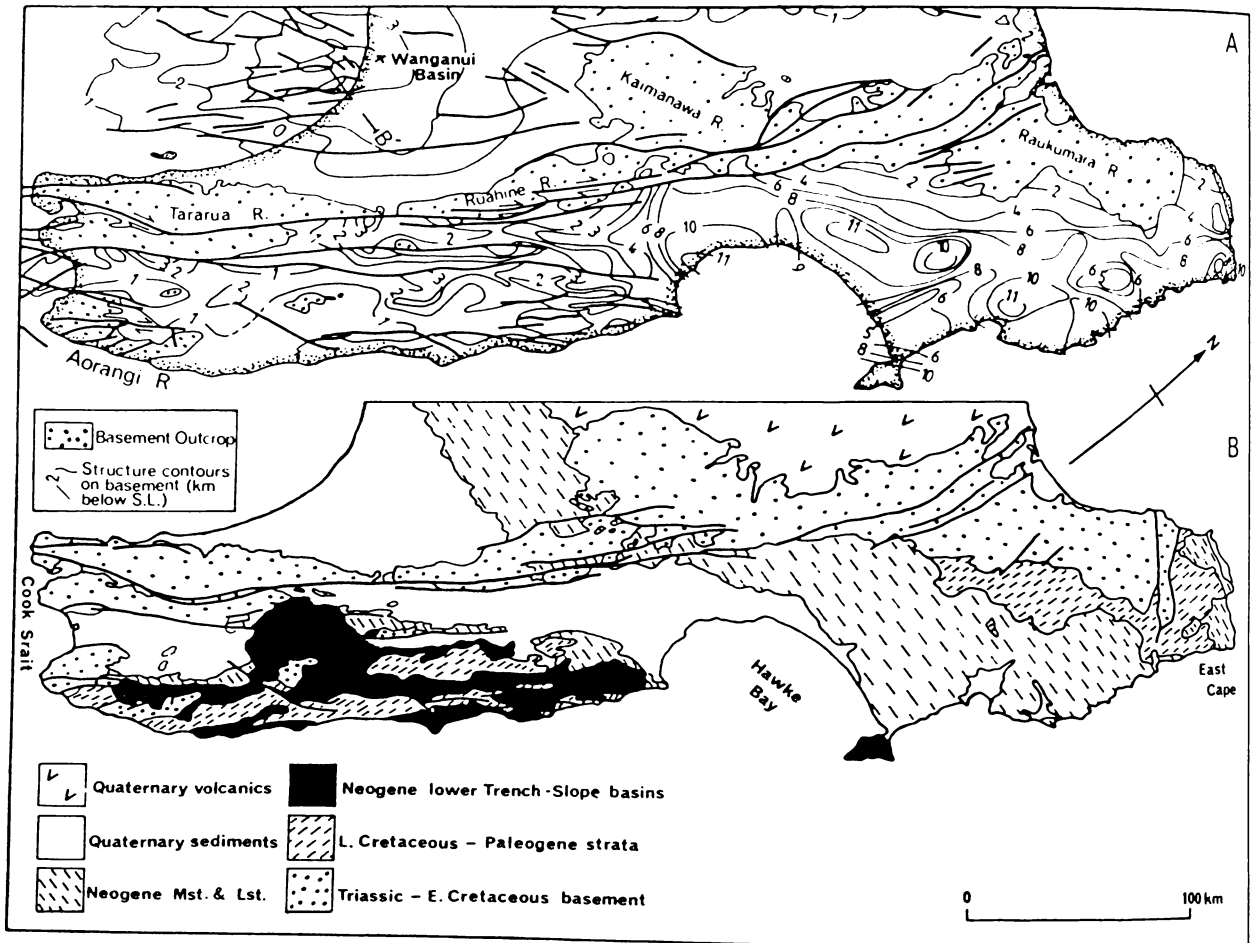


Fig.9 Two maps of eastern North Island showing in A, structure contours on basement at km intervals below sea level, and in B, the simplified geology. Data in A mainly from Hicks (1980), Hicks and Woodward (1978) and Anderton (1981), and in B from New Zealand Geological Survey (1972) and van der Lingen (1982).

the north. This is not just an artifact of the Quaternary pattern of deformation, but also characterises the Neogene as shown by the distribution and extent of intra-Tertiary unconformities (Suggate 1978, Fig. 7.43). Another manifestation of the greater compression in the south is the onshore occurrence at present of Neogene lower trench-slope flysch basins in southeastern North Island (Fig. 9B), whereas the equivalent basins are still mainly offshore further north in the Gisborne-East Cape region. In short, the structural-tectonic pattern is the inverse of that expected from the present rates and directions of relative plate motion.

2. From the structural and sedimentological analysis of the now onland structural high south of Cape Kidnappers (Fig. 9B), and from interpretations of offshore seismic profiles, Lewis (1980), van der Lingen and Pettinga (1980), Pettinga (1982) and van der Lingen (1982) have proposed that much of onshore and offshore eastern North Island comprises an accretionary prism. However, this is not a typical accretionary prism of the type described by Karig and Sharman (1975) and Seely (1979), as acknowledged by Pettinga (1982) and van der Lingen (1982). With perhaps the exception of the middle to lower slope regions immediately west of the Hikurangi Trench, this prism mostly comprises pre-existing (late Cretaceous-Paleogene) passive continental margin sediments (Stevens and Speden 1978) which have been tectonically imbricated, and not the typical abyssal plain, trench and slope basin sediments and ophiolite suites of accretionary prisms elsewhere. Consequently, this "accretionary prism" cannot have developed in the normal way and the more landward thrust zones cannot have formed by the progressive understuffing of pelagic and hemiterrigenous sediments at the trench. A subduction origin of the onshore thrust zones becomes even more problematical when one

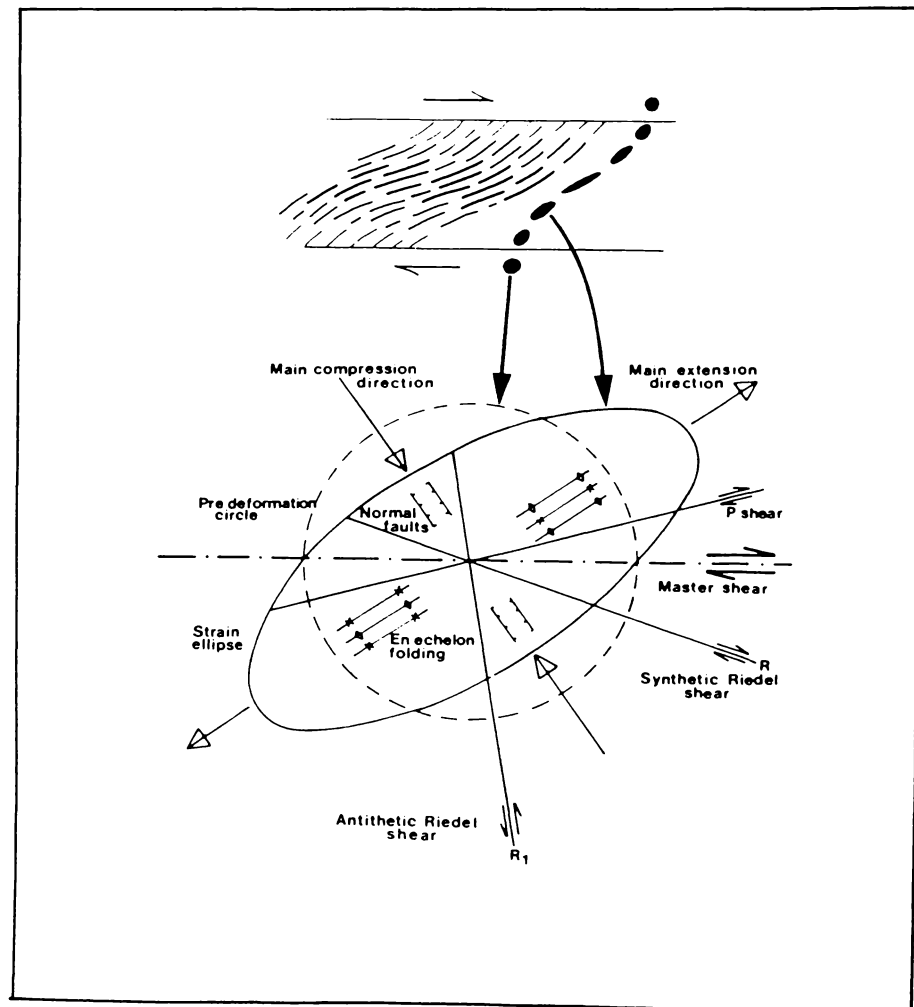


Fig.10 Diagram showing the fabric and strain variation in a ductile simple dextral shear zone. After Ramsay (1982) and Larter and Allison (1983).

considers the extent of thrust faulting to the west. Such faults extend across southeastern North Island to the Marton Anticline, a distance of 110km, and displace the Mesozoic basement with throws on individual faults of up to 1600m (Lillie 1953) (Fig.8). Even if the Coastal High is the inboard margin of a typical accretionary prism, the extent and degree of thrust deformation in southeastern North Island is atypical of the normal style of subduction interaction.

The degree of east-west shortening in southeastern North Island highlighted by these two points can however be partly attributed to the formation of the mega shear zone. The structural pattern anticipated in a simple right handed shear zone of limited strain and with conservation of rock volume is shown by the strain ellipses in Fig.10. In effect the rocks within the shear zone are stretched and concomitantly thickened normal to the direction of stretching. In addition, if the shear zone developed in an obliquely convergent regime with a volume reduction, Harland (1971) and Wilcox *et al.* (1973) have shown that the en echelon folds will tighten-up, develop more parallel to the trend of the shear zone, and become transformed into reverse faults; any extensional structures will be diminished in importance due to the loss in volume. The development of the Eastern Arc may well have followed this sequence from a simple dextral shear zone to an obliquely convergent one, as Walcott (1978a) and Stock and Molnar (1982) have shown that about 10 my B.P. the direction of Australia and Pacific plate motion, along the trend of the Alpine Fault, changed from nearly pure strike-slip motion to increasingly oblique convergence.

The pattern for structures in the more northern parts of eastern North Island to trend oblique to the margins of the shear zone (Kingma

1965), and for the structures in the southeastern parts to trend parallel to them (Fig.8), and for there to be much greater compression in the southeast, are all consistent with the predicted pattern (Fig.10). The Bideford Anticline, Tawhero Syncline and Whareama Syncline to the east of Castlepoint (Fig.8), which do trend oblique to the margins of the shear zone, are interpreted as early en echelon folds formed during the simple shear zone phase; the synclines contain middle to late Miocene strata (Johnston 1979).

Extensional structures oriented oblique to the shear zone are a manifestation of stretching and are less common in southeastern North Island than in the Gisborne-East Cape region. In the latter region, for example, the outcrop pattern of the late Miocene Tokomaru Formation is largely controlled by northeast to east trending normal faults (Blom 1984). In southeastern North Island evidence of extension may however be found in the pronounced sags within the axial ranges, namely, the Taruarau and Manuwatu saddles (Fig.8). Kingma (1957) identified the narrow east-west trending and normal fault bounded Kuripapango Graben, and from the marine strata it contains, inferred localised late Miocene-mid Pliocene extension before the graben widened to form the Taruarau Saddle. He evidently viewed this saddle as originating from profound stretching: "... the Ruahine Horst was torn off the Kaimanawa Range, leaving the Taruarau Saddle, or graben, behind as the movement progressed." (Kingma 1959,p.13). While a normal faulted graben is not evident in the Manuwatu Saddle (Lillie 1953), it may also have originated by stretching parallel to the shear zone. Similar structures with a comparable origin may also occur further east as the Woodville depression and Hawke Bay.

Although I have attempted to show that many of the structural features of eastern North Island owe their origin to formation of the mega shear zone, in addition to subduction accretion, a question remains of the age and origin of the strike-slip faults which border the axial ranges (Fig.8). These faults may be too far west to be considered as master faults within the shear zone. An earlier interpretation (Arabasz and Robinson 1976; Walcott 1978b; Spörli 1980) that they owe their origin to the transverse component (southwest) of the oblique plate convergence is possible. This implies that some of the east-west shortening in eastern North Island is due to repeated locking and unlocking of the subduction thrust. However, the strike-slip faults are probably no older than the Pliocene-Pleistocene boundary, judged from the age of strata involved in the overthrusting of basement along the eastern margin of the Ruahine Range (Lillie 1953) and the Taruarau Saddle (Kingma 1957). This conclusion is supported by the extent of the subducted Pacific Plate through the late Cenozoic (Kamp 1984). Not until the middle Pliocene had the subducted slab undertaken southeastern North Island by a sufficient amount and rate to act significantly upon the overriding shear zone.

#### **Late Cenozoic tectonic development of Marlborough in relation to the Eastern Arc**

Marlborough lies in the central part of the plate boundary zone, where, as a consequence of the stretching of the Rangitata Orogen around the rigid Northwest Nelson block of Tuhua rocks (Fig.3), the Mesozoic rocks have been narrowed to a band merely 75 km wide in northern Marlborough.

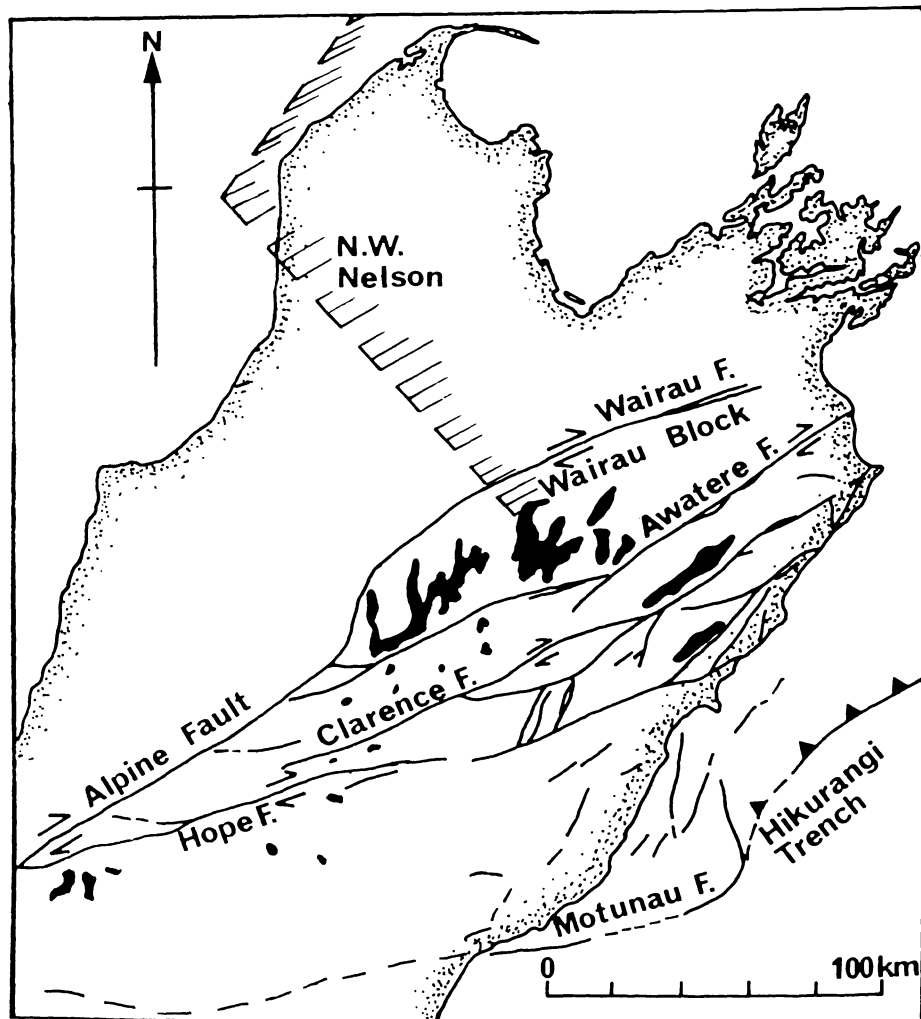


Fig.11 Map showing the distribution of the northern end of the Alpine Fault and the Marlborough fault system in northern South Island. The black regions represent areas above 1800m above sea level, and the dashed lines show the southwestern margin, projected to the surface, of the subducted Pacific Plate.

A system of subparallel northeast-southwest trending transcurrent to oblique-slip faults partially segment Marlborough into a series of basement blocks. Suggate (1979) emphasised the structural and geomorphic differences between the Wairau Fault/Block and the belt of faults and blocks further to the southeast (Fig.11).

1. The Wairau Fault is the continuation of the Alpine Fault northeast of its pronounced bend. Consequently, the Wairau Fault has an east-northeast trend, whereas the Awatere and Hope Faults trend northeast and branch as they approach the Alpine Fault.

2. The Wairau Fault is essentially a single trace, whereas there is frequent branching and cross faulting along the other faults which becomes more pronounced to the east (Fig.11).

3. The amount of lateral displacement increases towards the central portion on the Hope and Awatere faults (Suggate *et al.* 1961; Freund 1971). Transcurrent displacements in the central portions of the Clarence and Motunau faults do not even reach the Alpine Fault.

4. The Wairau Block on average has a higher elevation than the blocks to the southeast (Fig.11). The Inland and Seaward Kaikoura blocks rapidly lose their mountainous elevation towards the southeast. This corresponds with a 20° change in trend of the Hope and Clarence faults from 50°E to 70°E.

The Marlborough faults are generally viewed as transform faults which transform the relative plate motion between the Hikurangi Trench and the Alpine Fault (e.g. Christoffel 1971; Wellman 1971; Arabasz and Robinson 1976). The most explicit model of this concept is that of Scholz *et al.* (1973) and Ryan and Scholz (1978), who

suggested that the Awatere, Clarence and Hope faults sequentially developed in response to a changing plate motion vector, and, in turn, accommodated the bulk of the transform motion. Their model may be suspect simply because not all the transcurrent faults join the Alpine Fault and the Hikurangi Trench (point 2 above), and because the same amount of dextral displacement does not occur along the whole length of any one fault (point 3 above).

Following on from the conclusions reached by Bibby (1976,1981) and Walcott (1978a), too much emphasis has previously been placed on the importance of faults in transferring the plate motion through Marlborough. In the model developed here (Fig.6), the whole of the brittle-ductile shear zone in Marlborough transfers the plate motion; a comparison of geologic and geodetic data show that the rate of displacement on the major faults accounts for only  $\frac{1}{3}$  of the total shear strain rate (Lensen 1975; Bibby 1976). In this context it is not necessary, and indeed not expected, that the major faults should reach either or both the Alpine Fault and Hikurangi Trench. It is also consistent that the faults should show more transcurrent displacement along their central portions than at their ends (see the clay models of Wilcox *et al.* 1973).

In Figure 6 it is suggested that, initially, the Alpine Fault and Hikurangi Trench were aligned. As the amount of relative plate motion and shearing within the Eastern Arc increased, a trace of the Alpine Fault, the Wairau Fault, propagated northeastward to the Hikurangi Trench. With further shearing, the Wairau Fault became bent clockwise, and the Hikurangi Trench became offset to the east of the Alpine Fault and concomitantly migrated to the south. This meant that the brittle component of the shearing, which was probably starting to become significant in the late Miocene, could no longer be effectively

taken-up on the Wairau Fault. Consequently, the Awatere to Hope belt of faults and blocks, all of similar character (points 1-4 above), were incepted in close succession. Their more easterly position reflects their intermediate position within the widening zone between the offset ends of the Hikurangi Trench and the Alpine Fault. Another consequence of this increased offset was the creation of a zone of relative plate motion in central South Island. This zone presently incorporates the Southern Alps, where the plate motion is chiefly taken-up aseismically within the schists and greywackes (Walcott 1978a). The zone tapers southwestwards from the width of the Marlborough shear zone (100km) in northeastern South Island to several hundred metres in Fiordland where the Alpine Fault lies between Tuhua rocks. Thus the role of the Alpine Fault changed during the late Miocene-Pliocene from being the plane of displacement in the upper crust to being the western margin of a ductile-shear zone, essentially Walcott's Axial Tectonic Belt. Finally, the southward migration of the Hikurangi trench permitted the slab of subducted Pacific Plate to be emplaced beneath northern Marlborough during the last two million years (Arabasz and Robinson 1976; Kamp 1984), and thus caused the geomorphic changes referred to in point 4 above.

### Conclusions

I have attempted to show that there are two recurved arc structures within the late Paleozoic and Mesozoic basement of New Zealand. This is required of the two published sets of paleomagnetic data which record tectonic rotations within New Zealand. The older bend which involves the western basement terranes, named the Western Arc, formed mainly during the late Triassic phase of the Rangitata Orogeny, but it was accentuated during the late Eocene-Oligocene and

during the Plio-Pleistocene. The other arc, which chiefly involved the more eastern terranes and has been named the Eastern Arc, formed during the Kaikoura Orogeny. More specifically, the Western Arc originated by way of subduction accretion of the exotic Rakaia Terrane. This arc was tightened as a result of seafloor spreading in the south Tasman Sea during the late Eocene-Oligocene, and by drag on the Alpine Fault during the late Cenozoic. The Eastern Arc formed as a result of deformation accompanying the Neogene and Quaternary development of the Australia-Pacific plate boundary.

The model has important implications for the late Cenozoic structural and tectonic development of eastern North Island and Marlborough. It solves the longstanding conundrum of the nature and location north of the Alpine Fault of the relative plate motion evident as 480km of dextral displacement on the Alpine Fault. Northeast of the pronounced bend in the Alpine Fault, it was dissipated through Marlborough and eastern North Island as ductile shearing during the early and middle Miocene, and as brittle-ductile shearing during the late Miocene-Quaternary. This mechanism explains the paleomagnetic evidence for 62° of dextral rotation of eastern North Island and Marlborough during the late Cenozoic, the formation of the Marlborough Fault System, and, in part, the structural and stratigraphic evidence for stretching and crustal shortening in southeastern North Island. An additional factor in the late Cenozoic structural development of eastern North Island and Marlborough was the subduction emplacement of a slab of Pacific Ocean lithosphere beneath northern New Zealand. The effect of the subduction was to accentuate the crustal shortening normal to the coastline caused by the stretching along the shear zone; the oblique nature of the subduction also caused transcurrent faults to form during the Pleistocene along the axial ranges.

The contrast in competence between the soft accreted materials of the Rangitata Orogen, which have not been kratonised by granitic intrusions, and the rigid Tuhua Orogen, which has suffered multiple granite intrusions is considered the main reason for Alpine Fault movement in central and southern South Island, versus ductile to brittle-ductile shearing further to the northeast. In effect the Rangitata Orogen was stretched around the comparatively rigid Northwest Nelson-Westland block of Tuhua rocks, while the previously juxtaposed Fiordland-Campbell Plateau block was displaced to the southeast.

An implication of the new model for plate tectonic reconstructions of the southwest Pacific region, is that only approximately 500km of dextral displacement has occurred through New Zealand on the Australia-Pacific plate boundary. Most of the existing plate tectonic reconstructions describing the late Cretaceous-Cenozoic evolution of the southwest Pacific (e.g. Weissel *et al.* 1977; Crook and Belbin 1978) have assumed 1000km of displacement through New Zealand based on the previous model.

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Cross-referencing to thesis papers

- Kamp, P.J.J. 1980, is equivalent to Appendix II.
- Kamp, P.J.J. 1984, is equivalent to paper 6.
- Kamp, P.J.J. 1985a, is equivalent to paper 1.
- Kamp, P.J.J. 1985b, is equivalent to paper 5.

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## PAPER 5

Late Cretaceous-Cenozoic tectonic development of the southwest  
Pacific region

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## LATE CRETACEOUS-CENOZOIC TECTONIC DEVELOPMENT OF THE SOUTHWEST PACIFIC REGION

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## ABSTRACT

Kamp, P.J.J., Late Cretaceous-Cenozoic tectonic development of the southwest Pacific Region. *Tectonophysics*, in press.

A new model of the plate tectonic development of the southwest Pacific integrates the continental geology of New Zealand with the age structure of the surrounding oceanic crust revealed previously from magnetic anomaly lineations. The model differs from previous ones in that the onland geology of New Zealand is used to constrain the tectonic development in two important ways: (1) the modern Australia-Pacific plate boundary did not transect the New Zealand sector until 23 million years ago; (2) there has been a total of only c.500km of dextral displacement on the plate boundary through New Zealand.

The model is described with reference to a series of paleotectonic maps drawn to represent the setting at the times of Anomalies 32, 24, 7 and 5. Novel interpretations based on these reconstructions include

the following. During the late Cretaceous the Campbell Fault was a continental transform fault between the Tasman Sea spreading centre and the Bounty Rift, its 330km of dextral displacement accompanying 25° of counterclockwise rotation of a Campbell Plateau block. When the eastward-propagating Southeast Indian Ridge broke into the south Tasman Sea 57 million years ago, it continued to propagate directly into southern South Island, and generated late Eocene-Oligocene continental rifting through western New Zealand. At the same time, back-arc spreading in the Norfolk Basin caused continental rifting along a similar trend in western North Island. The Australia-Pacific plate boundary originated as a transform fault between the Southeast Indian Ridge and the pre-existing Kermadec Trench. It developed in response to the sudden cessation of spreading on the segment of the Southeast Indian Ridge east of a fracture zone here named Fracture Zone Z.

Two implications arise from this model regarding the integrity of Antarctica: (1) during the Cretaceous, Marie Byrd Land was probably no more than 200km northwest of its present position; (2) the proposition made in some earlier plate tectonic reconstructions, that if the Alpine Fault did not form until after the late Eocene there must be a late Cretaceous-early Tertiary plate boundary within Antarctica, is most probably valid.

## INTRODUCTION

The Australia, Antarctica and Pacific Plates interact in the southwest Pacific region (Fig.1). A southern mid-ocean ridge system lying to the south of New Zealand and between Australia and Antarctica comprises the Southeast Indian Ridge and the more easterly Pacific-Antarctic Ridge. The intersection of these two spreading centres is characterised by numerous and closely-spaced fracture zones. The Australia-Pacific plate boundary meets the southern ridge system within this highly fractured section (Fig.1). Northeast of this triple junction the Australia-Pacific plate boundary displays highly variable tectonic characteristics, with alternate short trench and transform sections which bisect the largely submerged New Zealand subcontinent (Fig.1). A reversal of subduction polarity between the opposite ends of the Alpine Fault is a notable feature of this plate boundary.

Several models have been published which attempt to describe the plate tectonic evolution of the southwest Pacific (Griffiths and Varne, 1972; Molnar et al., 1975; Weissel et al., 1977; Crook and Belbin, 1978; Barron and Harrison, 1979; Stock and Molnar, 1982). While these models are conceptually similar, they differ in their predictions of the age of inception of the Alpine Fault (Australia-Pacific plate boundary), an issue critical to the geology of New Zealand. For example, Molnar et al. (1975) predicted an early Oligocene age of Australia-Pacific plate boundary formation, while Weissel et al. (1977) proposed an evolution of this boundary from the early Paleocene. Stock and Molnar (1982) offered two possibilities,

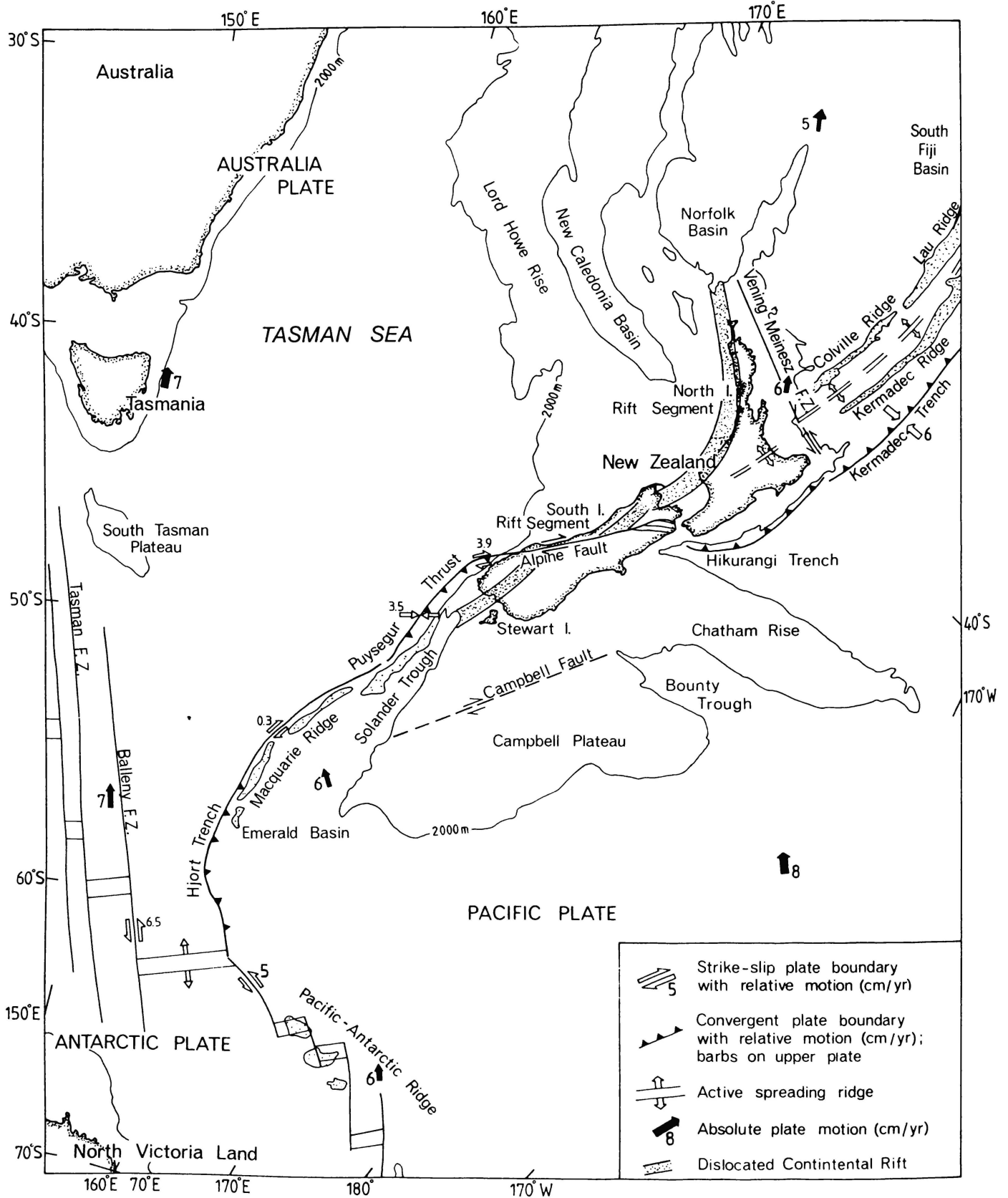


Figure 1 Map of the southwest Pacific region showing the tectonic character of the Australia-Pacific plate boundary, and directions and rates of plate motion taken from the Plate Tectonic Map of the Circum-Pacific Region - southwest quadrant (copyright: The American Association of Petroleum Geologists, Tulsa, U.S.A.).

one a late Eocene age of initial Alpine Fault movement, and another a late Cretaceous age. These differences are dependent upon assumptions about the late Cretaceous-Cenozoic integrity of Antarctica. The earlier ages (late Cretaceous-early Paleocene) are predicted if no significant displacement occurred within Antarctica; the late Eocene age is predicted if substantial late Cretaceous-Paleogene displacements occurred.

That Stock and Molnar (1982) were forced to present such widely different options for the inferred age of inception of the Australia-Pacific plate boundary results from the size of the uncertainty regions surrounding the best-fit poles which describe the finite rotations in the Australia-Antarctica-Pacific-Lord Howe Rise plates' circuit. By implication, it also indicates a wide degree of uncertainty surrounding the tectonic development of the southwest Pacific. They suggested, as others had done, that the onland geology of New Zealand might be able to constrain these options. Carter and Norris (1976) and Norris et al. (1978) have already compared the plate tectonic predictions of Molnar et al. (1975) with the Cenozoic geologic record of the South Island of New Zealand. They reported a close accord between their observations and the predictions, and consequently implied an early Oligocene age of plate boundary formation. However, their evidence rests critically upon an interpretation that the flysch depocentres, which rapidly developed in the early Oligocene in western South Island, originated within a continental transform boundary setting (see also Norris and Carter, 1982). I have proposed instead (Kamp 1985a) that these basins developed within a 100-200km wide Eocene-Oligocene continental rift

system which extended for 1200 km through western New Zealand (Fig.1). The trend and age of this rift in relation to the trend of the Alpine Fault, together with the age and pattern of the rift's subsequent disruption, indicate that movement on the Alpine Fault did not begin until near the Oligocene-Miocene boundary, about 23 My B.P. This age is about 13 million years later than that predicted by Molnar et al. (1975) and Stock and Molnar (1982).

I take this opportunity to present a new model of how the late Cretaceous-Cenozoic tectonic development of onshore and offshore New Zealand relates to the development of the southwest Pacific region. In particular, how the Paleogene rift system through western New Zealand related to contiguous seafloor spreading, and how the Neogene-Quaternary Australia-Pacific plate boundary was incepted and evolved.

The geomagnetic polarity time scale of La Brecque et al. (1977) is adopted in this paper.

#### NEW ZEALAND'S PRE-DRIFT CONFIGURATION AND POSITION WITHIN EASTERN GONDWANALAND

A knowledge of the New Zealand subcontinent's shape and position in eastern Gondwanaland is a pre-requisite to any model of the plate tectonic evolution of the southwest Pacific. Fig.2 depicts seven late Cretaceous pre-drift reconstructions published since 1975. It shows that although there are some differences in New Zealand's inferred position, there are greater differences in the inferred shape of the subcontinent, especially in the outline of the present landmass.

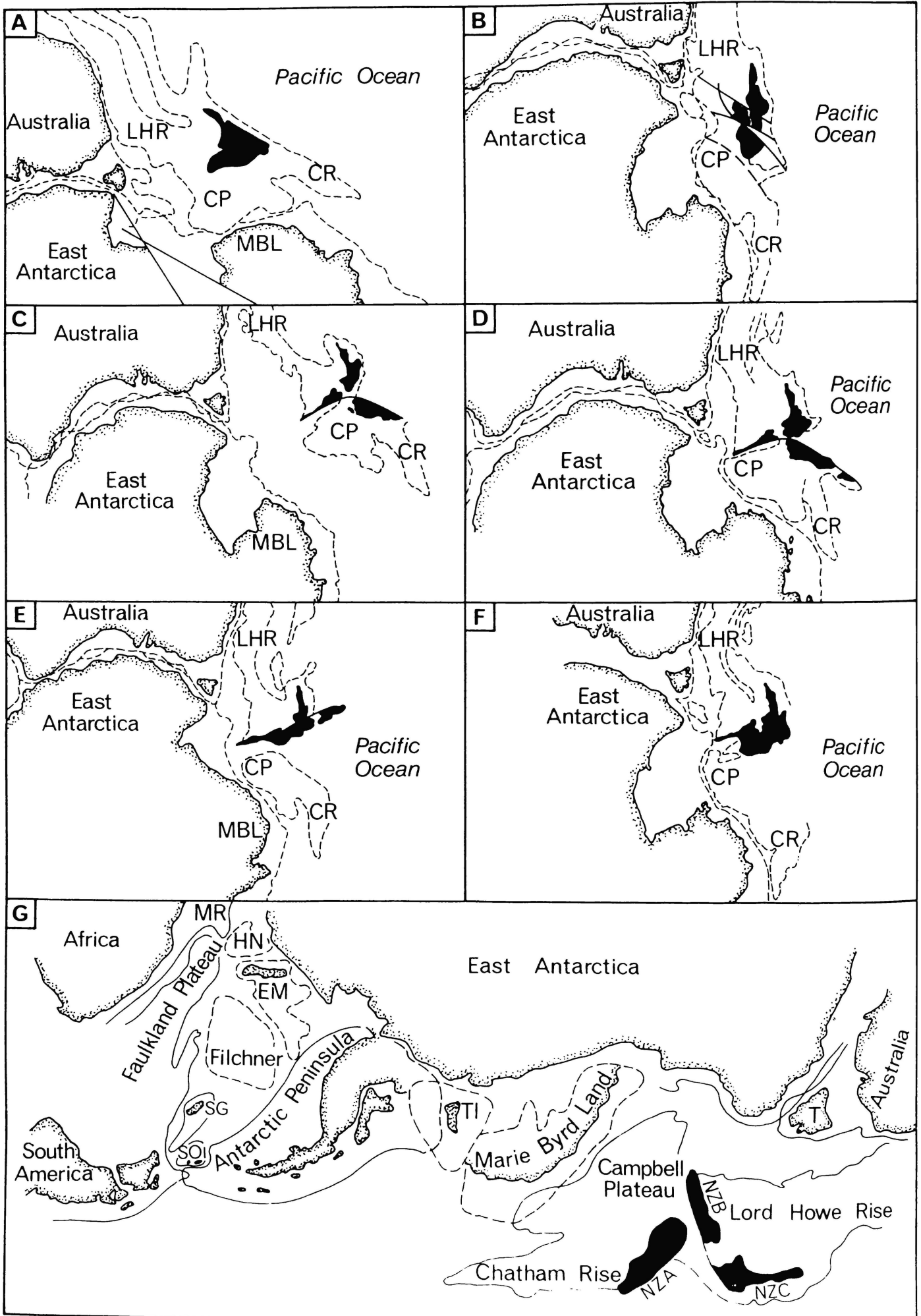


Figure 2 Late Cretaceous reconstructions of New Zealand, Australia and Antarctica by previous workers. A from Molnar et al. (1975); B, Cooper (1976); C, Weissel et al. (1977); D, Crook and Belbin (1978); E, Barron and Harrison (1979); F, Kamp (1980); G, Dalziel and Elliot (1982). Note that E is for 75 MyB.P. and after the start of seafloor spreading, and G was intended by Dalziel and Elliot as one possible reconstruction of part of the Pacific margin of Gondwanaland based on the results of the Reunite Gondwanaland Workshop. LHR stands for Lord Howe Rise; CP, Campbell Plateau; CR, Chatham Rise; EM, Ellsworth Mountains block; HN, Haag Nunataks; MR, Mozambique Ridge; SG, South Georgia; SOI, South Orkney Islands; TI, Thurston Island block. The black areas illustrate the present landmass of New Zealand.

The differences in position arise mainly because of different assumptions about the late Cretaceous integrity of Antarctica. The differences in shape originate for several reasons. Since the seafloor magnetic anomaly pattern has been established only for the northern limb of the Pacific-Antarctic Ridge, and no firm geologic lineations across the Marie Byrd Land coast and into the Campbell Plateau have been identified (Davey and Houtz, 1977; Grindley and Davey, 1982; Katz, 1982), the only basis for matching Marie Byrd Land to the Campbell Plateau is a morphological one. Griffiths (1971) showed that the 2000m contours of these two continental blocks are sympathetic to each other, and his fit is essentially that in Fig.2 B, D, E and F. On the other hand, because the pre-drift position of the Lord Howe Rise is very tightly constrained by the seafloor magnetic anomaly pattern in the Tasman Sea (Weissel and Hayes, 1977), the consequence of forcing Griffiths' Campbell Plateau-Marie Byrd Land fit is to internally distort New Zealand to an excessive degree.

Till now, this degree of distortion has generally been accepted because of the evidence for 480km of post-Permian dextral Alpine Fault displacement, and, in particular, because of the occurrence of a basement recurved arc. This arc or orocline has been interpreted by some New Zealand geologists (Wellman, 1973; Grindley, 1974; Hunt, 1978) as having formed in association with Alpine Fault displacement, and is considered by them to indicate at least a further 500km of dextral displacement. In this context, most pre-drift reconstructions which have originated within New Zealand (e.g. Fleming, 1970; Cooper et al., 1982) (Fig.2B) have distorted New Zealand to straighten the

orocline. Wood (1978) and Kamp (1980) (Fig.2F), however, adopted a different attitude and argued that the basement orocline was already recurved in the early Cretaceous, and therefore it was artificial to straighten it in a late Cretaceous reconstruction. An implication of this argument is that the total amount of displacement through New Zealand can only have been about 700km; later it is shown that there has probably been only 500km of dextral displacement since the early Cretaceous.

By contrast, pre-drift reconstructions which have originated outside New Zealand have generally not included the arguments relating to the age and origin of the recurved arc, and have distorted New Zealand in a different way. They showed all the "required" dextral displacement between the Lord Howe Rise and the Campbell Plateau (the 1000km figure) as having occurred solely on the Alpine Fault and its presumed extension through the North Island (Fig.2C and D). This assumption immensely complicates the geology of New Zealand. First, it implies several hundred kilometres of sinistral movement on an Alpine Fault between the Permian and the late Cretaceous despite no evidence for this having been documented. Second, it assumes the existence of a single linear fault extension of the Alpine Fault within Marlborough and eastern North Island. However, the late Cenozoic structure northeast of the Alpine Fault is actually characterised by a 70 to 100km wide zone of distributed faulting and aseismic strain (Walcott, 1978; Bibby, 1981). Moreover, the dislocation of eastern North Island (Fig.2E), or even only parts of it (Hawke's Bay and Wairarapa), as in Fig.2D, violates basement age and lithology trends (see Bradshaw et al., 1980; Mackinnon, 1983), and makes it difficult to identify any sensible outcrop patterns in either the Paleozoic, Mesozoic, or Cenozoic rocks.

In view of the recent appreciation that West Antarctica probably comprises an assemblage of discrete blocks (de Wit, 1977; Dalziel and Elliot, 1982), there is no longer an *a priori* reason for assuming that Marie Byrd Land had the same disposition to East Antarctica in the late Cretaceous as it has today. If Marie Byrd Land was formerly further north, much less deformation would be required through New Zealand to satisfy the fit of the Lord Howe Rise against Australia and the Campbell Plateau against Marie Byrd Land, than in most of the current models. Because the pre-drift position of the Lord Howe Rise is well constrained, it is important to establish the pre-drift shape of New Zealand as this will fix the position of the Campbell Plateau, and thus Marie Byrd Land. This approach is different from those previously adopted as it suggests that parts of eastern Gondwanaland should be fitted to New Zealand, rather than fitting New Zealand around the rest of Gondwanaland.

#### PRE-PLATE BOUNDARY SHAPE OF NEW ZEALAND

Most of the deformation of New Zealand after separation from Gondwanaland, was associated with the development of the Australia-Pacific plate boundary. To reconstruct the shape of New Zealand before this plate boundary formed, requires information about the nature, age and amount of this deformation. The following two issues are here discussed: the age of inception of the Alpine Fault, and the total amount of dextral displacement through New Zealand and the nature and location of that displacement northeast of the Alpine Fault.

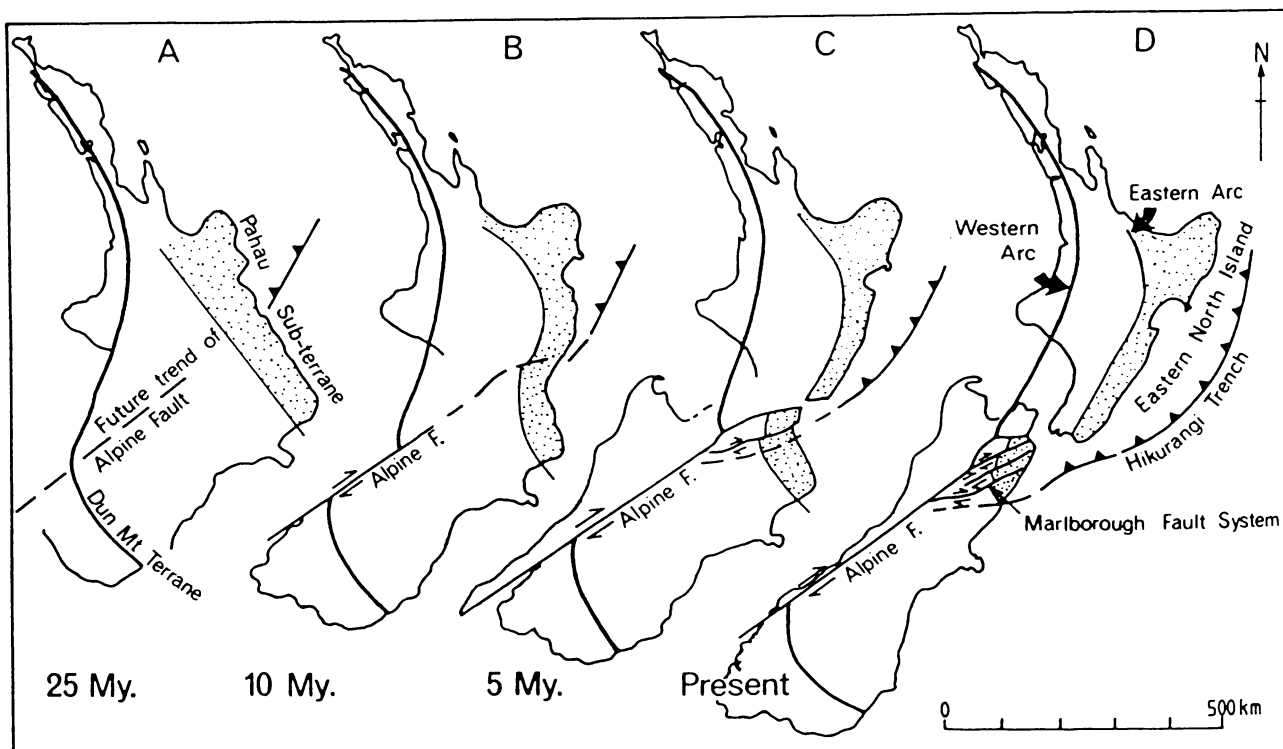


Figure 3 A model showing the late Cenozoic development of the basement recurred arcs (western vs eastern arcs of text) and the Alpine Fault in relation to the evolution of the plate boundary through New Zealand and the changing shape of the present landmass.

There are widely different views amongst New Zealand geologists as to the age of inception of the Alpine Fault, ranging from Cretaceous to late Miocene (see Suggate, 1963; Welman, 1964; Norris et al., 1978; Cutten, 1979). The difficulty in defining the age of initial displacement is due to the paucity of displaced marker beds. However, Kamp (1985a) recently postulated that with the restoration of 480km of Alpine Fault displacement, the continuity of an Eocene-Oligocene continental rift system through western New Zealand becomes evident. Both the age of this structure and the evidence for active crustal extension argue against any transcurrent displacement on the Alpine Fault until the end of the Oligocene. An earliest Miocene age for the start of dextral movement was suggested (Kamp, 1985a) on the basis of biostratigraphic ages of a major change in the sedimentation patterns in the former rift basins now adjacent to the plate boundary (Alpine Fault).

With regard to the total amount of dextral displacement and its nature and location northeast of the Alpine Fault, Kamp (1985b) proposed the model summarised in Fig.3. Within the context of an early Miocene age of plate boundary formation, this model proposes that the late Cenozoic plate boundary displacements were expressed differently along different parts of the boundary. In the South Island they were manifest mainly as Alpine Fault displacements, but in eastern North Island and Marlborough as the formation of a mega brittle-ductile shear zone. It is argued that there are in fact two recurved arcs (Fig.3): a western arc is represented by the outcrop and geophysically determined extent of the Dun Mountain ophiolite belt

(Hunt, 1978), and an eastern arc is defined by the relationship of the Pahau sub-terrane to the other terranes in the North Island (Bradshaw et al., 1980). The concept of two arcs is consistent with the two sets of paleomagnetic data which describe tectonic rotations within New Zealand. One set suggests that the basement rocks in western South Island, including the Dun Mountain terrane, were bent during the late Triassic-early Jurassic phase of the Rangitata Orogeny (Grindley et al., 1977, 1980; Grindley and Oliver, 1979; Oliver et al., 1979). The other set of data, from Tertiary cover rocks of eastern North Island and Marlborough, suggests that the recurved arc formed during the Neogene and Quaternary Kaikoura Orogeny (Walcott et al., 1981; Walcott and Mumme, 1982). In the context of a single recurved arc these data are contradictory, but are not so if the eastern arc developed during the Neogene-Quaternary, while the western arc, already recurved in the Mesozoic, was displaced on the Alpine Fault (Fig.3).

A principal conclusion of Kamp's (1985b) model is that only 500km of dextral displacement on the plate boundary is necessary to form both the eastern arc and cause the recorded 480km displacement on the Alpine Fault.

On the basis of an early Miocene age of Alpine Fault displacement, and the model just outlined for the age and origin of the recurved arc in relation to displacements northeast of the Alpine Fault, Fig.3A is accepted as the probably pre-plate boundary outline of New Zealand. This outline has been tested by consideration of the paleogeographic development of New Zealand through the Paleogene

(Kamp, 1985a). Although this test cannot be as definitive as, for example, the paleomagnetic method might be at its best, nonetheless very sensible patterns emerge in the disposition of source areas, sedimentary basins and paleo-shorelines.

#### LATE CRETACEOUS AND PALEOGENE MODIFICATION OF NEW ZEALAND'S SHAPE

In addition to the late Cenozoic development of the Australia-Pacific plate boundary, New Zealand sustained another two changes in its configuration which have implications for its shape. The first involved 330km of strike-slip displacement on the Campbell Fault; the other involved differential crustal extension mainly as a consequence of Eocene-Oligocene rifting within and seafloor spreading to the southwest of New Zealand.

Davey and Christoffel (1978) have proposed the existence of a NE-SW trending Campbell Fault (Fig.1). Their proposition is based upon 330km of dextral offset between the southeastern end of the onshore Stokes Magnetic Anomaly System (Hatherton, 1969; Hunt, 1978), and the linear belt of positive magnetic anomalies on the Campbell Plateau which they consider to be offshore correlatives. The Permian-Jurassic age of the magnetic source rocks in the South Island indicated to them a post-Jurassic age for the fault, but they were unable to geologically constrain the minimum age of displacement.

Grindley and Davey (1982) have suggested that 250km of the Campbell Fault offset is pre-late Cretaceous in age, and that the remaining 80km occurred during the late Cretaceous and was associated

with the opening of the Bounty Trough. Their pre-late Cretaceous age and amount of displacement is based on a correlation of the Campbell Fault with the Gambier-Sorell Fracture Zone (of Harrington et al., 1973), and the inferred dextral offset of the Dundas and Bowers Cambrian grabens across this fault. Two points suggest that it is not valid to apply this age and amount of displacement to the Campbell Fault. (1) The alignment of the Campbell Fault with the Gambier-Sorell fault is a function of Crook and Belbin's (1978) pre-drift reconstruction as adopted by Grindley and Davey (1982). I have pointed out earlier that this reconstruction (Fig.2D) is inconsistent with several well constrained aspects of New Zealand's Mesozoic and Cenozoic geology. In the new pre-drift reconstruction, which takes these aspects of New Zealand geology into account (Fig.4), the Campbell Fault is not collinear with the Gambier-Sorell Fracture Zone. (2) The more recent pre-drift reconstructions of Australia-Antarctica based on seafloor magnetic lineations and fracture zones (Griffiths, 1974; Norton and Sclater, 1979), and North Victoria Land - Tasmania - Victoria (Australia) geological ties (Laird et al., 1977; Burrett and Findlay, 1984), indicate that there has not been any pre-late Cretaceous dextral displacement between the Dundas and Bowers grabens. However, Grindley and Davey's (1982) suggestion that later movements of the Campbell Fault were related to opening of the Bounty Trough deserves closer examination.

Little is known about the origin of the Bounty Trough, and it has been treated differently in each of the pre-drift reconstructions illustrated in Fig.2. Seismic reflection profiles summarised by Davey (1977) suggest that it probably has a rift morphology. The early to

late Cretaceous (Albian-Cenomanian) age of sediments on Pitt Island adjacent to the trough (Grindley et al., 1977; Laird, 1980), and correlations with the lowest seismic sequence which abuts faulted basement (Davey, 1977), implies a mid-Cretaceous (~110 My B.P.) age of initial subsidence and sedimentation in the trough. As reversal of the 330km of Campbell Fault displacement nearly closes the Bounty Trough, it is proposed that these two structures are genetically related. This would suggest that the Campbell Fault did not move until the mid-Cretaceous. A minimum age of fault displacement and Bounty Trough development is suggested by the orientation of magnetic anomaly lineation number 32 (72 My B.P.), which trends across the end of the trough. The origin of the Campbell Fault-Bounty Trough and its relationship to Tasman Sea spreading are considered further in the following section.

The third factor which caused New Zealand's shape to change during the fragmentation of eastern Gondwanaland was differential extension and spreading accompanying the development of the middle Eocene and Oligocene Western Rift System. In the south Tasman Sea, north of the Solander Trough and south of the NW-SE oriented An33-An24 magnetic lineations of the central Tasman Sea, occur east-west oriented magnetic lineations aged An21-An7 which define an eastward thinning wedge of early Eocene-late Oligocene seafloor. In a pre-An21 reconstruction this wedge of seafloor must be removed; this can be achieved by sinistrally rotating 25° the Campbell Plateau-Chatham Rise block relative to the Lord Howe Rise about a map centre at 44°S 170°E. While this reconstruction closes the rift structures, it also removes 25° of the bend in the western recurved arc, as defined by the

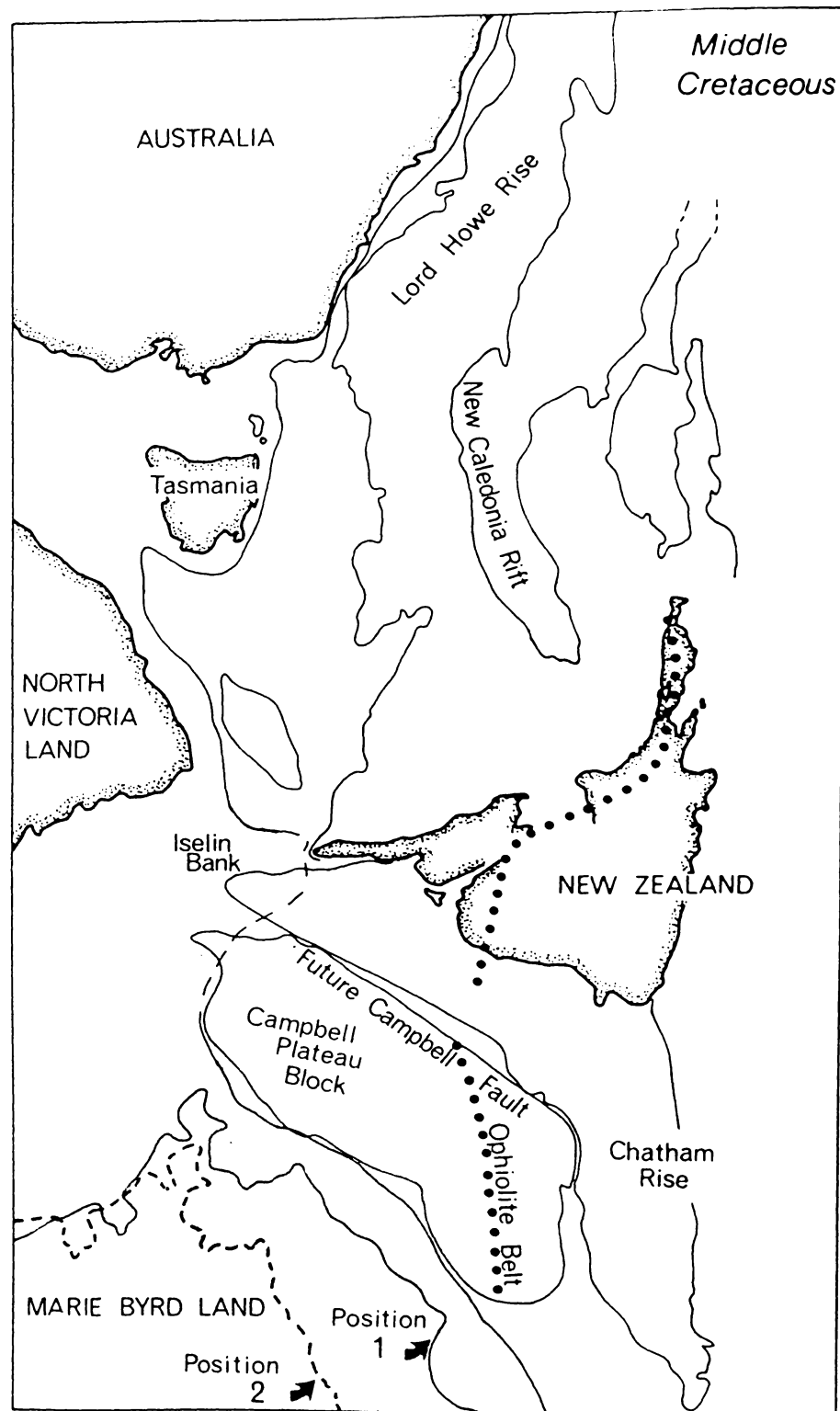


Figure 4 A new pre-drift reconstruction of part of eastern Gondwanaland. Position 1 is the proposed early Cretaceous position of Marie Byrd Land, and Position 2 is the present position. The outline of the New Zealand subcontinent is taken as the 2000m isobath.

ophiolite belt, and lengthens the East Coast-Marlborough region. New paleomagnetic data of Mumme and Walcott (manuscript in preparation) from western North Island supports this age and amount of rotation.

#### AN ALTERNATIVE PRE-DRIFT RECONSTRUCTION OF NEW ZEALAND WITHIN EASTERN GONDWANALAND

Following from the previous discussions, Fig.4 is proposed as an alternative mid-Cretaceous reconstruction of the New Zealand sector of eastern Gondwanaland. It is based upon the pre-drift positions of Australia and East Antarctica proposed by Griffiths (1974) and Laird et al., (1977), and the Weissel and Hayes (1977) pre-drift fit of the Lord Howe Rise against Australia. The shape and position of the rest of the New Zealand subcontinent results from the removal of the late Cretaceous and Cenozoic deformation as detailed earlier. Two positions of Marie Byrd Land are shown. The one labelled position 2 is the present position with respect to North Victoria Land; the other is the predicted position if it once lay adjacent to the Campbell Plateau. The New Caledonia basin is reconstructed in an open position as there is some evidence that it has mid-Cretaceous oceanic seafloor (Wilcox et al., 1980).

There are few problems with this reconstruction. The only overlap of the 2000m isobaths occurs with the corners of the Campbell Plateau and the Iselin Bank in the present-day Ross Sea region. It is not clear whether in fact this is a problem as little is known of the crustal type and structure of the Iselin Bank. Even if it is composed of continental crust, the overlap could be a function of convergence

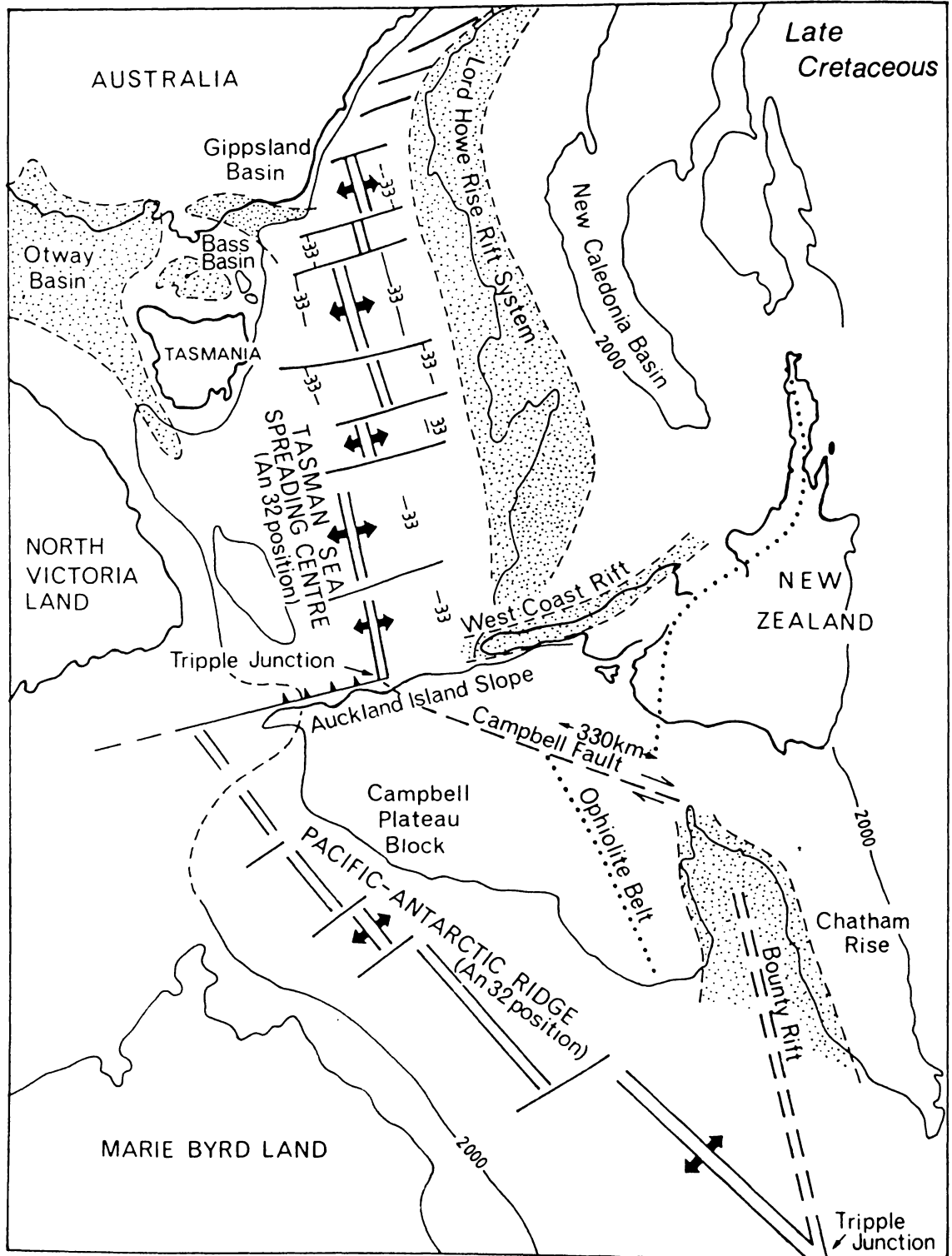


Figure 5 A plate tectonic map of the southwest Pacific for Anomaly 32 time (72 My B.P.).

with the Campbell Plateau Block in the early stages of breakup as detailed below. Alternatively, if the Iselin Bank is considered part of the Marie Byrd Land block, which it is not in Fig.4, then the more northern position of Marie Byrd Land (position 1) would remove the overlap of this bank with the Campbell Plateau.

Dalziel and Elliot (1982) have identified a 'space' problem in attempts to reconstruct the former disposition of the blocks along the Pacific margin of Gondwanaland. They suggested four general possibilities to account for this problem. The reconstruction presented here (Fig.4) argues against any wholesale (1000km or more) left-lateral transposition of the blocks (their option 1), but it does permit Marie Byrd Land to have formerly occupied a position one to two hundred km further north. This reconstruction does not constrain any of the other three options proposed (by Dalziel and Elliot, 1982) to reduce the space problem.

#### THE LATE CRETACEOUS BREAKUP PHASE

Fig.5 illustrates the tectonic pattern of the early break-up phase. It represents the setting at the time of anomaly 32 (72 My B.P.), a time when seafloor spreading was occurring on both the Tasman Sea spreading centre and the Pacific-Antarctic Ridge. Fig.5 was constructed by holding Australia stationary with respect to North Victoria Land and Marie Byrd Land, and rotating the whole of the New Zealand subcontinent as a single unit, excluding the Southern Campbell Plateau block, so that the Lord Howe Rise occupied the position relative to Australia described by Weissel and Hayes (1977) for anomaly 32 time.

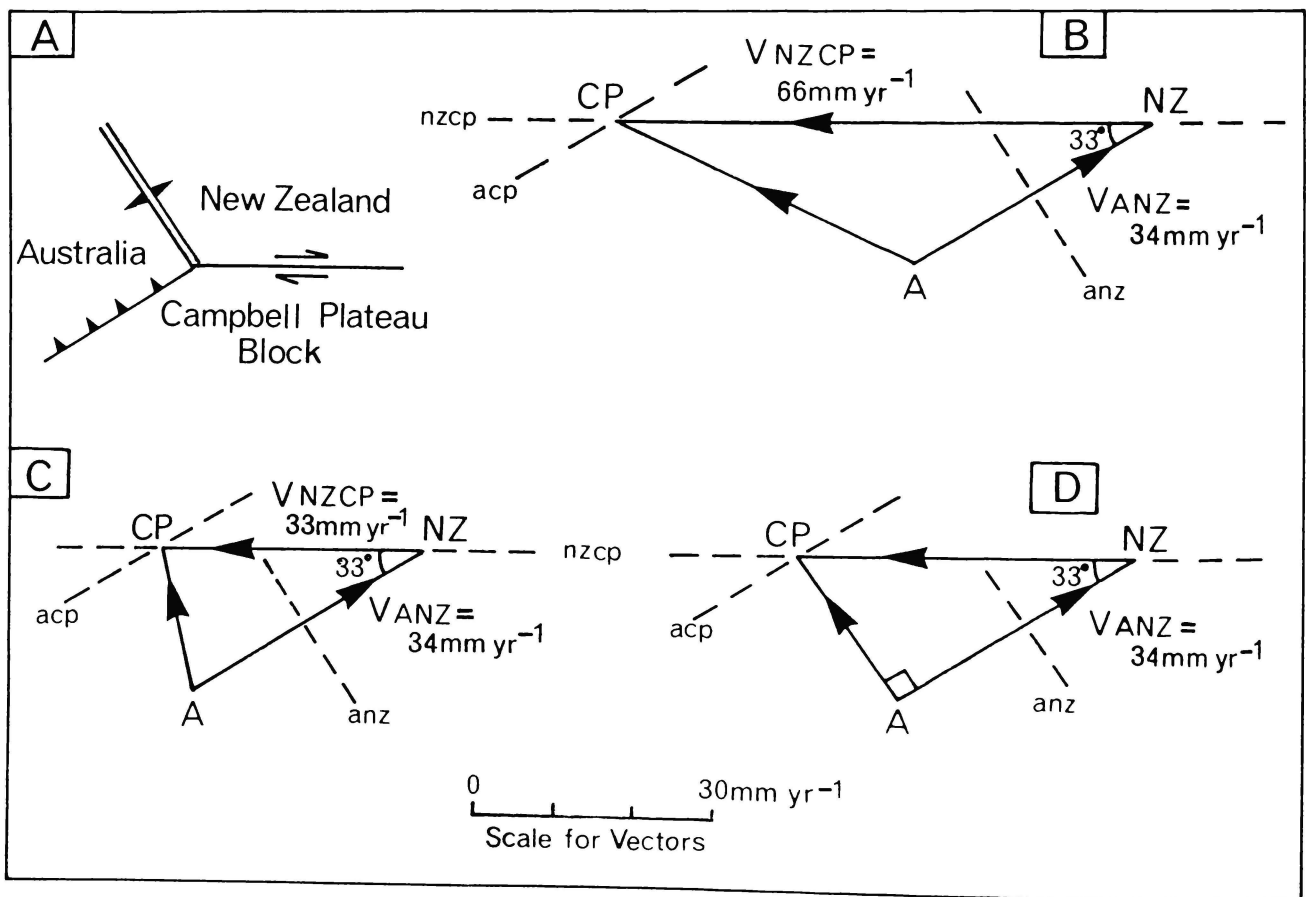


Figure 6 Velocity triangles in vector co-ordinates describing the development of the Australia-New Zealand-Campbell Plateau Ridge-Trench-Transform triple junction. See text for discussion.

Some 340km of seafloor formed at the southern end of the Tasman Sea spreading centre during the five million year interval between the times of An33 and An32 (Weissel and Hayes, 1977, Fig.2). However, a much lesser amount of spreading occurred at the northwestern end of the Pacific-Antarctic ridge. Thus a question arises as to how the relative displacement created by Tasman Sea spreading was accommodated through New Zealand south of the Lord Howe Rise? The Campbell Fault might well have acted as a ridge-ridge transform fault between the southern end of the Tasman Sea spreading centre and the Bounty Rift which formed during the middle and late Cretaceous. To obtain a solution to the problem of how much displacement is required across the Campbell Fault to satisfy the Tasman spreading, and to determine the nature of the relative motion between the Campbell Plateau Block and the Australia Plate, I have worked a three plate problem in vector coordinates (Fig.6).

Since the only reliable data available to construct a velocity triangle involving the Australia, New Zealand and Campbell Plateau plates are the rate and direction of Tasman Sea (Australia-New Zealand) spreading and the orientation of the Campbell Fault, one must initially assume the rate of Campbell Fault movement. In the extreme case 1 (Fig.6B) where the total dextral displacement (330km) occurred between the times of An33 and An32 (77-72 My B.P.), the Campbell Plateau would have converged obliquely (dextral) upon the Australia Plate at  $41.8 \text{ mm yr}^{-1}$ ; the Ridge-Trench-Transform tripple junction would have been highly unstable and would have migrated southwestward along the trench at  $21.5 \text{ mm yr}^{-1}$ . In case 2 (Fig.6c) where only half

of the total displacement (165km) occurred during the same interval, the rate of oblique (sinistral) convergence would be  $19 \text{ mm yr}^{-1}$ ; the triple junction would have been less unstable and would have migrated to the NE along the trench at  $6.1 \text{ mm yr}^{-1}$ . In case 3 where there is a different assumption that the triple junction was instantaneously stable, that is with convergence normal to the Campbell Plateau-Australia plate boundary (Fig.6D), it is now possible to calculate the rate of Campbell Fault displacement to satisfy this condition ( $40.5 \text{ mm yr}^{-1}$ ). In this case, 203km of dextral displacement would have occurred between An33 and An32 times. This rate and amount of displacement is similar to that on the Alpine Fault during the late Cenozoic.

A prediction in all three of the above cases is that the section of the Auckland Island Slope west of the Campbell Fault converged initially with the Iselin Bank and then with the seafloor west of the Tasman Sea spreading centre. This prediction remains to be geologically tested and requires the acquisition of deep seismic profiles. This part of the Auckland Island Slope should have an interesting geological history as it subsequently became a passive margin.

There is a minimum amount of data to constrain the nature and amount of spreading on the Pacific-Antarctic Ridge south of New Zealand during the early breakup phase. Magnetic anomaly lineation 32 is the oldest anomaly mapped and then only on the northeast side of the ridge. It notably converges towards the Campbell Plateau along the trend of the ridge. During the early breakup phase there was most

probably a RRR triple junction where the Bounty Rift meet the Pacific-Antarctic Ridge. This junction would have had a stable configuration (McKenzie and Morgan, 1969).

In comparing figures 4 and 5 it is evident that although the trend of the Bounty Trough roughly paralleled the Lord Howe Rise Rift System, their directions of maximum extension were different; the former trended NW-SE and the latter east-west. For the Bounty Rift, this originated because the Campbell Plateau Block moved NW relative to the Chatham Rise and the Chatham Rise moved NE relative to Marie Byrd Land. Thus to satisfy the condition that crust was neither created nor destroyed across the Campbell Fault, there must have been oblique rifting (transtension) in the Bounty Trough, with the direction of maximum extension oriented about 45° to its axis. This prediction needs to be tested by determination of the occurrence and orientation of transfer faults.

From the preceding discussion, it is possible to formulate a simple break up history. It started in the late-early Cretaceous, having been fission-track dated from volcanoclastic sediments in the Otway Basin as occurring between 126 and 103 million years ago (Neocomian-Albian) (Gleadow and Duddy, 1980), and biostratigraphically aged as intra-Albian (~100 My B.P.) in New Zealand (Laird, 1980). There was probably a very complex history of rifting in the Australia-New Zealand region. The Otway Basin may have formed a triple junction with the Lord Howe Rise rift system and Laird's (1980) West Coast Rift. Rifting probably also started at this time in the Bounty Rift. Because this rift's structures do not continue into New Zealand

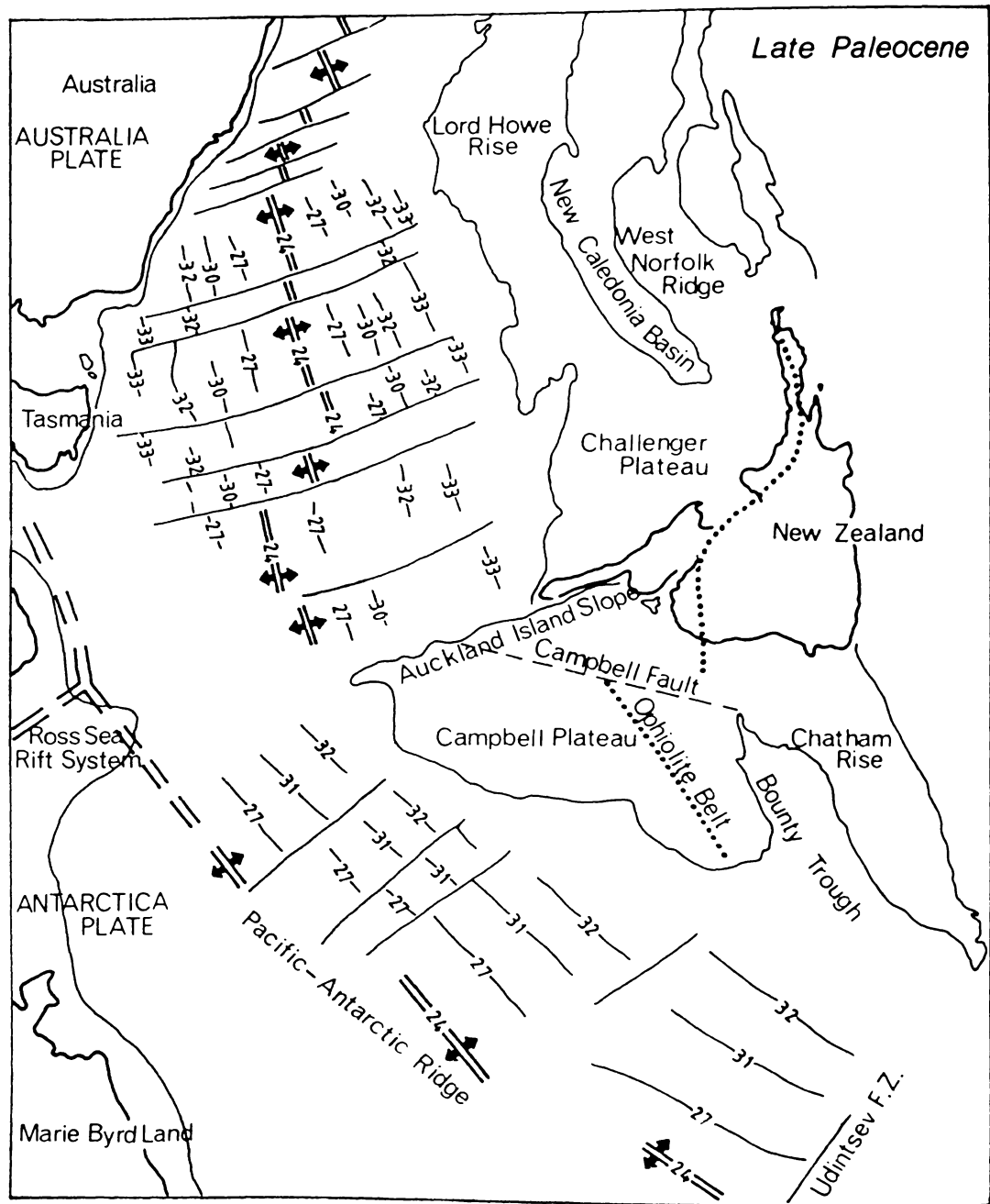


Figure 7 A plate tectonic map of the southwest Pacific for Anomaly 24 time (57 My B.P.).

(eastern South Island), the Campbell Fault may have also formed at this time. Following non-axial breaching of the Lord Howe Rise Rift System (Jongsma and Mutter, 1978), seafloor spreading started in the Tasman Sea in the early-late Cretaceous. Because spreading occurred at a much faster rate than on the adjacent end of the Pacific-Antarctic Ridge, dextral displacement occurred on the Campbell Fault. Between the times of An33 and An32 some 203 kilometers may have taken place at a rate of c.40 mm yr<sup>-1</sup>. The remainder of the fault displacement (127 km) probably occurred in the preceding 23 million years at a much slower rate. As a consequence of Tasman spreading and Campbell Fault movement, the Campbell Plateau block rotated anticlockwise by c.25° with respect to New Zealand (estimated from the offset of the ophiolite belt). Thus the present dispositions of the Campbell Plateau, Bounty Trough and Chatham Rise originated during the Late Cretaceous breakup phase.

#### LATEST CRETACEOUS-EARLY EOCENE (An32-An24) SEAFLOOR SPREADING

Fig.7 shows the southwest Pacific setting at An24 time (57My B.P.). The map was constructed by rotating New Zealand as a single unit from its position at An32 time (Fig.5) to the position the Lord Howe Rise occupied with respect to Australia at An24 time (Weissel and Hayes, 1977), which is also today's position. The Paleocene and early Eocene was a time of negligible tectonic activity in New Zealand and thus there is no basis to place a plate boundary through New Zealand at that time. However, the different trends of the Pacific-Antarctic and Tasman Sea spreading centres and their respective transform faults, suggests that there were two spreading systems at this time

with different poles of rotation. Because no plate boundary can be justified through New Zealand, one must have existed within Antarctica. Molnar et al. (1975) and Stock and Molnar (1982) earlier came to this conclusion. Because of the size of the uncertainty regions surrounding the best-fit poles, Stock and Molnar (1982) found that the method of finite rotations cannot establish the character of this boundary nor the amount of displacement across it with certainty. It is speculated that this may have been the time when the Ross Sea-Transantarctic rift (Davey, 1981) formed. Late Cretaceous to early Tertiary extension has been postulated in Antarctica by Jankowski, Drewry and Behrendt (1981) and Dalziel and Elliot (1982) to explain the formation of the continental mozaic of west Antarctica. If there was symmetrical spreading across the Pacific-Antarctic Ridge during this interval (An32-An24; 72-57 My B.P.), and no Australia-Pacific relative plate motion, Marie Byrd Land may have moved to the position shown in Fig.7. This would imply transtension along a Ross Sea-Transantarctic rift.

At An24 time spreading ceased in the Tasman Sea. At the same time the rate of spreading markedly reduced on the Pacific-Antarctic Ridge. It reduced by 70% at the westernmost end of this ridge, and by 60% at the Udintsev Fracture Zone. A 60% decrease also occurred further east adjacent to the Eltanin Fracture Zone, and probably also as far east as the Menard Fracture Zone.

## MIDDLE EOCENE-OLIGOCENE (An21-An7) SEAFLOOR SPREADING AND NEW ZEALAND TECTONICS

Structural and stratigraphic evidence for block-faulting and crustal extension is a major feature of the middle Eocene to Oligocene geology of New Zealand. Kamp (1985a) postulated that most of this extension was localised through western New Zealand and developed into a 1200 km long and 100-200km wide roughly north-south trending continental rift system. Along strike differences in the degree of rift development indicate that rifting propagated from both the north and the south into central-western New Zealand. Rift development ceased before the wholesale introduction of seafloor into its axis. However, geophysical evidence for the regularly spaced occurrences of large basaltic masses (Hatherton, 1967; Hatherton et al., 1979; Nathan, 1977) may indicate a transition to incipient seafloor spreading before extension stopped. From changes in the patterns of basin sedimentation in the South Island rift segment, the transition from crustal extension to crustal shortening has been aged as early-early Miocene (Kamp, 1985a). The initiation of compression is attributed to the inception of strike-slip movement on the Alpine Fault sector of the Australia-Pacific plate boundary. During the later part of the Miocene the plates became obliquely compressive across the Alpine Fault. The resulting crustal re-thickening has been spectacular. It formed the Southern Alps where basement has been uplifted over 3km above sea level, and it also everted many of the former rift basins such that basal sequences in Westland, buried to depths of 3km by the late Oligocene, now commonly lie at elevations of up to 1km a.s.l.



The North Island segment of the rift system was not so severely tectonically overprinted because it lies further from the continent-continent boundary of the Alpine Fault. However, the eastern rift shoulder was uplifted at least 1km. This uplift was primarily caused by late Cenozoic underthrusting of the subducted oceanic Pacific Plate (Kamp, 1984).

Fig.8 illustrates the plate tectonic setting at anomaly 7 time (26 My B.P.; late Oligocene) near the peak of rift system development and after the separation of Australia and Antarctica by spreading on the Southeast Indian Ridge. The map was constructed by rotating the Campbell Plateau-Chatham Rise block, and contiguous seafloor, counterclockwise to a position where the outline of the New Zealand landmass corresponded with the late Oligocene shape justified earlier on paleomagnetic and paleogeographic grounds. The calculations of Stock and Molnar (1982) predicted some counterclockwise rotation of the present Pacific Plate with respect to the Australia Plate between An18 and An13 (43 to 35 MyB.P.). The shape and position of the subcontinent in Fig.8 is very similar to that determined for 20 MyB.P. by Walcott (1984) by the method of finite rotations, having incorporated the revised pole positions and uncertainty regions of Stock and Molnar (1982). In addition to the counterclockwise rotation, seafloor produced on the Pacific-Antarctic Ridge and the Southeast Indian Ridge between An24 and An7 has also been included in Fig.8. The seafloor spreading centres either occupy the position and orientation of magnetic anomaly number 7, where it has been mapped, or a position and orientation determined by interpolation from the anomaly lineations which bracket number seven.

The two main features of the SW Pacific plate tectonic setting between An21 and An7 times are the propagation of the Southeast Indian Ridge into the South Island rift segment, and the propagation of the Norfolk Basin backarc spreading centre into the North Island rift segment.

#### *Southeast Indian Ridge and the South Island Rift Segment*

The magnetic unconformity defined by the 90° difference in the trends of An24 and An21 lineations is a major characteristic of the age structure of the south Tasman Sea (Weissel and Hayes, 1977) (Fig.8). This unconformity indicates a dramatic change in the orientation of seafloor spreading within the space of 5 million years. In this reconstruction (Fig.8) the magnetic lineations 12 and 13, now in the Emerald Basin (Weissel et al., 1977), lie opposite the lineations 18-12 south of the unconformity, and together indicate that a spreading centre must have lain between them. Although Weissel et al. (1977) were tentative about the identification of anomalies 12 and 13 in the Emerald Basin, their interpretations are in agreement with the earlier work of Hayes and Talwani (1972) and Christoffel and Falconer (1972), who also proposed that Oligocene aged ocean crust floored the more northern Solander Trough. The south Tasman Sea and Emerald Basin anomalies define an eastwards thinning wedge of Eocene and Oligocene crust which is aligned with the Southeast Indian Ridge and with the southern end of the continental rift system. Accordingly, it is proposed that when this ridge broke through between Australia and Antarctica, it rapidly propagated eastwards and directly into southern South Island. This is confirmed by the good correlation

between the seafloor ages adjacent to the rift and the biostratigraphic ages of rifting (Kamp, 1985a). In addition to developing the continental rift system, the propagation of the spreading ridge into New Zealand caused the reactivation of pre-existing faults in more distant parts of the subcontinent. A principal effect of this reactivation was late Eocene-early Oligocene submarine basaltic volcanism on the Challenger Plateau (Nelson et al., 1985) and Chatham Rise (Grindley et al., 1977).

The Southeast Indian Ridge appears to have been offset from its eastern extension by a fracture zone named here Fracture Zone Z (Fig,8). The differences in spreading rate on the Southeast Indian Ridge either side of Fracture Zone Z suggests that the fracture zone propagated southwards and linked with the western end of the Pacific-Antarctic Ridge. This probably occurred during the early Oligocene, at or soon after An13 time (37My B.P.). Thus, during most of the Oligocene, spreading on the eastern side of the fracture zone was distributed between two spreading centres, the Southeast Indian Ridge extension and the Pacific-Antarctic Ridge.

Near the Oligocene-Miocene boundary spreading ceased on the Southeast Indian Ridge extension. The cessation of spreading is aged latest Oligocene-early Miocene by biostratigraphic and paleomagnetic means (Quilty et al., 1973; Kennett et al., 1975; Williamson, 1974) on the Macquarie Ridge, considered here to be the paleo-spreading centre. This age is also indicated by the earliest Miocene age of the change in character of rifting in the South Island segment of the rift system. With the sudden stop to spreading on the Southeast Indian

Ridge extension, a sudden disparity in the spreading rates either side of Fracture Zone Z would have occurred, and consequently there would then have been the potential, and geometric need, for the Australia-Pacific plate boundary to propagate through New Zealand.

#### *Norfolk Basin and the North Island Rift Segment*

The North Island segment of the continental rift system lies at the southern end of the Western Pacific collage of island arcs, trenches, and marginal basins known collectively as the Melanesian borderlands (Coleman and Packham, 1976) (Fig.8). There is good evidence that at least the South Fiji Basin formed during the Oligocene by back-arc spreading marginal to the Tonga-Kermadec arc-trench system. Magnetic anomaly lineations 12 to 7A have been widely mapped (Watts et al., 1977; Davey, 1982; Malahoff et al., 1982), and locally anomaly 13 has been identified (Malahoff et al., 1982), indicating 36 to 25.5 MyB.P. seafloor spreading involving a triple junction.

A rift and seafloor spreading origin of the Norfolk basin has also been suggested (Coleman and Packham, 1976; Crook and Belbin, 1978). Davey (1977, 1982) has presented marine seismic reflection profiles showing the rifted basement morphology of both the western and eastern margins of this basin. Unfortunately, there is no direct data on the age of the Norfolk Basin seafloor as the subdued magnetic anomaly pattern (Malahoff et al., 1982) has not yet been analysed. In the absence of such information, the age of this basin has been inferred from tectonic models based on the age and structure of the South Fiji Basin.

Existing plate tectonic models of the evolution of the marginal basins to the north of New Zealand (Crook and Belbin, 1978; Davey, 1982) postulate that formation of the Norfolk Basin was contemporaneous with formation of the South Fiji Basin. The Norfolk Basin, according to Ballance et al. (1982) and Davey (1982), appears to have formed by back-arc spreading to a Three Kings Rise arc, itself related to subduction of the western plate of the South Fiji Basin spreading centre. If this origin is correct, it implies an Oligocene age of active rift subsidence and incipient seafloor spreading within the North Island segment of the continental rift system along strike to the south of the Norfolk Basin (Fig.8).

Fig.8 implies that a very complex tectonic environment existed adjacent to northern North Island in the Oligocene. The Northland Peninsula was flanked in the west by a well developed rift trough, in the north by complex marginal basin formation and island arc activity, and in the east by a transform fault. This fault, the Vening Meinesz Fracture Zone (VMFZ) (van der Lingen, 1967), appears to have accommodated the dextral transform displacement between the seafloor of the South Fiji Basin and the continental crust of the North Island. Together these elements may explain some aspects of Northland's correspondingly complex geology, and in particular, the emplacement of the ophiolite massifs.

Large fault-bounded and rootless igneous massifs, considered to be ophiolite seamounts, cover 1500km<sup>2</sup> of Northland (Brothers and Delayloye, 1982). Their origin has been attributed to Oligocene

shearing within the Vening Meinesz Fracture Zone of old MORB ocean crust, which was intruded and added to by alkaline igneous activity (Brothers, 1983). These seamount-like structures were evidently dismembered from their source and obducted to the west about 23My B.P., and in the space of only one or two million years (Brothers, 1983). The profound tectonic event which caused the obduction has been attributed by Brothers and Delayoye (1982) to an acceleration in Pacific Plate rotation at about that time. However, they did not detail the connection between the obduction and the change in Pacific Plate rotation.

The obduction of the ophiolites at 23 My B.P. corresponds very closely with the postulated age of inception of the Australia-Pacific Plate boundary through New Zealand (Kamp, 1985a). Although the rupturing of the continental crust to create the Alpine Fault would have caused a major and short-lived tectonic event, this fault is well to the south of Northland (Fig.8), and by itself is unlikely to have caused the ophiolite obduction. However, this tectonic disturbance could well have been transferred to the VMFZ via the subducted slab of the Pacific Plate. In the late Oligocene a shallow dipping slab, subducted at the Kermadec Trench, must have underlain the South Fiji Basin; its southwestern margin would have paralleled the VMFZ. With the formation of the Alpine Fault, the Pacific Plate started moving southwestward relative to the Australia Plate. One manifestation of this was dislocation of the western rift system; another was the commencement of southwestward lateral underthrusting of the subducted Pacific slab beneath the VMFZ and thus northeastern North Island (Kamp, 1984). The lateral movement of the already subducted slab was

in a direction oblique to the trend of the VMFZ. Any coupling of the subducted slab with the South Fiji Basin lithosphere would have caused in quick succession: compression across the VMFZ, dismemberment of the ophiolites from their source, and westward obduction. The emplacement of the ophiolites onto the adjacent continental crust was also promoted by the occurrence of the rift system along the west coast of Northland. With the Paleogene development of the rift, especially during the Oligocene, the eastern rift shoulder adjacent to the VMFZ would have isostatically subsided. That eastern Northland was completely submerged by the middle Oligocene is shown by the occurrence of autochthonous outliers of skeletal shelf limestones (Hay, 1960). By the late Oligocene the narrow rift shoulder may have lain at a similar level to the adjacent and high-standing oceanic crust and the developing ophiolite masses. Once the ophiolites were emplaced onto eastern Northland, they evidently slid gravitationally towards the rift axis.

#### MIOCENE-RECENT DEVELOPMENT OF THE NEW ZEALAND SECTOR OF THE AUSTRALIA-PACIFIC PLATE BOUNDARY

Near the Oligocene-Miocene boundary there was a major reorganisation of the plate tectonic setting in the southwest Pacific. Spreading on the Southeast Indian Ridge extension ceased, and the Alpine Fault sector of the Australia-Pacific plate boundary was initiated. This involved the creation of a fault, shown by the broken line in Fig.8 between the pre-existing Kermadec Trench and the eastern end of the Southeast Indian Ridge. This fault was broadly arcuate and cut obliquely across many of the pre-existing structures such as the

continental rift system and Fracture Zone Z. To test whether or not this sector of the plate boundary originated as a transform fault, small circles were visually fitted to it, and thus the instantaneous pole of relative motion between the two plates was established. This pole (Fig.8) lies within the overlap zone of the uncertainty regions for the Australia-Pacific finite plate poles (Stock and Molnar, 1982) at the times of anomaly 6 (19.5 MyB.P.) and anomaly 13 (36 MyB.P.). The coincidence of the pole positions strongly suggests that the New Zealand sector of the Australia-Pacific plate boundary indeed originated as a transform fault, in this case between a trench and a mid-ocean ridge.

The early Miocene position of this transform fault plate boundary determined which of the pre-existing structural elements became part of the Pacific Plate, and which became part of the Australia Plate. The Southeast Indian Ridge extension spreading centre was one major element captured by the Pacific Plate. It is proposed below that this ridge is represented today, at least in part, by the Macquarie Ridge.

That the Macquarie Ridge comprises oceanic lithosphere formed at a mid-ocean ridge is certain for Macquarie Island (Griffin and Varne 1980), and has also been suggested for the rest of the ridge on the basis of *in situ* dredged rock samples (Watkins and Gunn, 1971). That the ridge represents all or part of the fossil spreading ridge is more difficult to prove. To this end it is significant that Williamson (1974) inferred an anomaly 7 (26 My B.P.) age for Macquarie Island basalts, based on a correlation of a broad magnetic anomaly across the island with marine magnetic anomalies around the island.

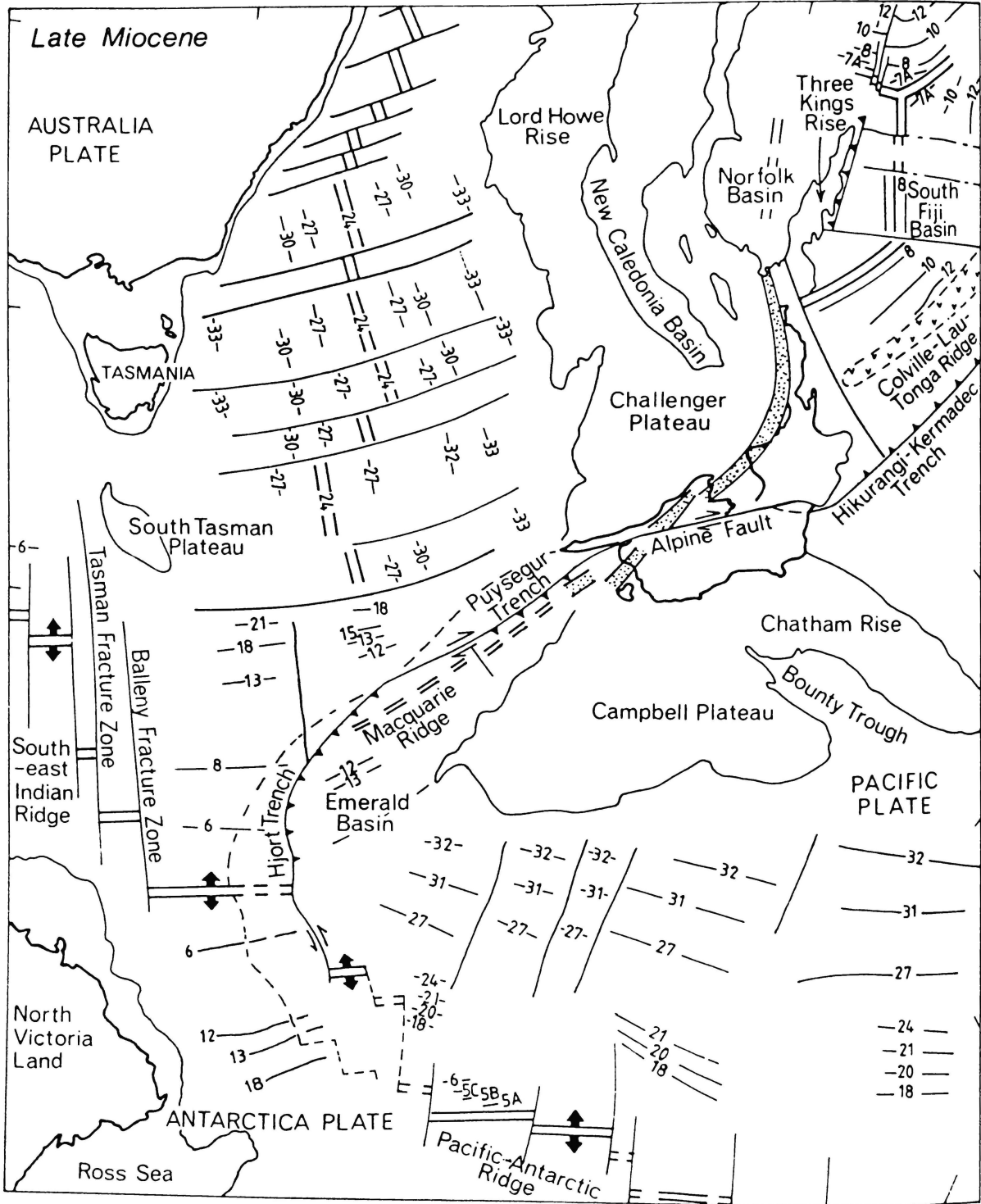


Figure 9 A plate tectonic map of the southwest Pacific for Anomaly 5 time (9.5 My B.P.). The broken line represents the present position of the Australia-Pacific plate boundary south of New Zealand relative to the Australia plate.

Fig.8 shows that when the Australia-Pacific transform fault plate boundary formed, it lay a short distance to the northwest of the recently extinct spreading centre. Perhaps this was coincidental, but as a result of the plate interactions, and especially the oblique compression, the ridge has attained its present elevation. This has involved about 3km of uplift which has occurred mainly during the Pliocene and Pleistocene (Hayes and Talwani, 1972).

In summary, the Macquarie Ridge is a fossil spreading centre, now dextrally displaced and underthrust by oceanic lithosphere which once formed its northwestern flank.

Since the early Miocene formation of the plate boundary, the transform fault has evolved into a more complicated structure with two short trench sections (Fig.1). Oceanic lithosphere of the Australia Plate is presently being subducted beneath the Pacific Plate at the Puysegur Trench and the Hjort Trench. The total amount of underthrusting has not been great, as evidenced by the absence of a well developed island arc; the only calc-alkaline volcano occurs as Solander Island (Harrington and Wood, 1958), aged about 1 My B.P. (Davey and Smith, 1983). Although some underthrusting had developed by 10 MyB.P. (Fig.9), most has occurred since then. The broken line in Fig.9 indicates the present position of the plate boundary south of New Zealand, and gives a measure of the amount of convergence of the two plates in the last 10 million years.

The evolution of the Puysegur Trench-Hjort Trench section of the plate boundary can be simply explained by the interaction of two

factors: (1) the initial shape in plan view of the transform fault; and (2) the changes in direction of relative plate motion since the early Miocene as monitored by changes in position of the Australia-Pacific finite pole of rotation.

When the transform fault formed it was not a perfect arc, but its central part was flattened with respect to the ends (Fig.8). With strike-slip displacement on such a fault, it is easy to see that parts of the fault will become transpressive, and other parts will sustain transtension. Superimposed on this effect is the migration of the finite pole of rotation. Stock and Molnar (1982) have shown that from before An 6 (19 My B.P.) (probably from 23 MyB.P., as argued earlier) until An 5 (9.5 My B.P.), the pole migrated SSE. This direction would have caused minimal compression across the plate boundary. However, after An 5, the finite pole migrated along a SW path. Importantly, this was oblique to the trend of the plate boundary, and caused an additional component of underthrusting to occur. This component of compression has not been so great, however, that the whole boundary has become one of subduction. There is still a central section which is essentially a transform margin (Fig.1).

#### SUMMARY AND CONCLUSIONS

(1) A new model of the tectonic evolution of the southwest Pacific region is presented which attempts to integrate the geology of New Zealand with the spreading history of the surrounding oceans.

(2) A new pre-drift reconstruction of New Zealand indicates that Marie Byrd Land cannot have occupied a very different position formerly from the one that it presently occupies.

(3) Because seafloor spreading in the Tasman Sea occurred at a much faster rate than spreading on the Pacific-Antarctic Ridge, it is predicted that the Campbell Fault originated and moved as a transform fault c.100-72 million years ago. Between the times of An33 and 32 it may have moved at a rate of c.40 mm yr<sup>-1</sup>. It is also predicted that the Bounty Trough rifted obliquely, and that a Campbell Plateau block rotated c.25° counterclockwise during the late Cretaceous breakup phase.

(4) The latest Cretaceous - early Eocene (An32 - An24) was a time of tectonic quiescence in New Zealand and there is no basis for a plate boundary at this time. At 57 MyB.P. spreading suddenly stopped in the Tasman Sea, and also reduced in rate by up to 70% on the Pacific-Antarctic Ridge.

(5) At the time of An21 (51 MyB.P.) the Southeast Indian Ridge propagated into the south Tasman Sea, and linked with a zone of active continental rifting through western South Island. During the late Eocene and Oligocene, spreading on the Southeast Indian Ridge proper was distributed, east of Fracture Zone Z, between the Southeast Indian Ridge extension and the Pacific Antarctic Ridge. Marginal basins also formed to the north of New Zealand during the Oligocene. The poorly dated Norfolk Basin was one of these, and appears to have been closely

related to continental rifting in the North Island segment of the rift system. This presents an unusual situation where a mid-ocean ridge is linked with a back-arc spreading centre via a continental rift.

(6) Spreading ceased on the Southeast Indian Ridge in the late Oligocene, about 26 MyB.P. (An 7). This resulted in a sudden disparity in the spreading rates on the two remaining ridges, causing propagation of the Australia-Pacific plate boundary through New Zealand as a dextral transform fault, thus accommodating the faster spreading rate on the Southeast Indian Ridge. In turn, this may have triggered obduction of the Northland ophiolites and the initiation of calc-alkaline subduction related volcanism in northern North Island. The fossil Southeast Indian Ridge extension was captured by the Pacific Plate and is now represented by the Macquarie Ridge.

(7) Since the early Miocene, the initial Australia-Pacific transform has evolved into alternating short trench and transform fault sections. This is due mainly to the plan shape of the original transform fault, and a change 10 million years ago in the migration direction of the Australia-Pacific finite pole.

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Cross-referencing to thesis papers

- Kamp, P.J.J., 1980, is equivalent to Appendix II.
- Kamp, P.J.J., 1984, is equivalent to paper 6.
- Kamp, P.J.J., 1985a, is equivalent to paper 1.
- Kamp, P.J.J., 1985b, is equivalent to paper 4.
- Nelson, C.S., Briggs, R.M. and Kamp, P.J.J., 1985. is equivalent to Appendix III.

## PAPER 6

Neogene and Quaternary extent and geometry of the subducted  
Pacific Plate beneath North Island, New Zealand: implications for  
Kaikoura tectonics

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## NEOGENE AND QUATERNARY EXTENT AND GEOMETRY OF THE SUBDUCTED PACIFIC PLATE BENEATH NORTH ISLAND, NEW ZEALAND: IMPLICATIONS FOR KAIKOURA TECTONICS

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### ABSTRACT

Kamp, P.J.J., 1984. Neogene and Quaternary extent and geometry of the subducted Pacific Plate beneath North Island, New Zealand: implications for Kaikoura tectonics. *Tectonophysics*, 108: 241–266.

The extent and geometry of the obliquely subducted oceanic Pacific Plate beneath North Island, New Zealand, for five million year intervals through the mid-Miocene to Quaternary, are presented in a series of maps and cross-sections. These show that the subducted plate progressively increased its extent from NE to SW beneath the North Island, and in the more northern regions where it was first emplaced, concomitantly increased its dip from 10° to 50°.

The changing extent and geometry of the subducted slab has been established from the age pattern of orogenic andesites and from the geochemical  $K_2O-h$  parameter of depth of magma generation. The radiometric dates show a migration of the volcanic front back towards the trench at an average rate of 20 km/My. The trenchward migration is explained by a model of increasing slab dip which is corroborated by the  $K_2O$  data calibrated against the presently active arc (Taupo Volcanic Zone). With the exception of northern Coromandel Peninsula, the andesitic magmas were generated at 85–100 km depth. The interpretation of the dates adopted here indicates that the subducted slab originated at the NE–SW trending Kermadec–Hikurangi Trench, and implies a different and much simpler evolution of the Australia–Pacific plate boundary in the vicinity of North Island than other recent models.

Subduction geometry has been found elsewhere to be a principal influence upon the state of stress and deformational style in an over-riding plate. The possibility is explored that the timing, nature and pattern of the Neogene to Quaternary Kaikoura Orogeny in North Island is due to this influence. Apart from the effect of oblique subduction in eastern North Island, there is an accord between the onset of deformation and the emplacement sequence of the shallow slab beneath North Island, and between the change in subduction geometry and a progressive north to south change in northern North Island from compression to extension.

### INTRODUCTION

The concept that subduction geometry is the principal influence upon the state of stress and deformational style within the leading edge of an overriding plate is now

well established (Kelleher and McCann, 1976; Barazangi and Isacks, 1976; Cross and Pilger, 1982). Low angle or flat plate subduction causes a high degree of compressional stress which is expressed as large earthquakes, basement involved foreland deformation, and magmatic nulls or increased arc-trench distances. With high angle subduction the plates are decoupled, lack comparable large interplate thrust earthquakes, and are associated with active volcanic arc segments and back-arc extension or spreading. These end-member relationships have been developed from consideration of subduction settings about the Pacific Ocean (Molnar and Atwater, 1978; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980), and generally explain the nature and occurrence of Andean and Cordilleran tectonics (Coney and Reynolds, 1977; Cross and Pilger, 1978; Jordan et al., 1983).

The North Island of New Zealand occupies the leading margin of the Australia Plate where it is obliquely underthrust by the oceanic Pacific Plate (Fig. 1) (Hather-ton, 1978). This plate boundary dates from the Oligocene–Miocene boundary, and throughout the Neogene–Quaternary, the North Island has been subjected to a complex pattern of arc volcanism, and regional compression, extension and transcurrent displacements, collectively referred to as the Kaikoura Orogeny (Suggate, 1978). That the pattern of Kaikoura tectonics might be related to the subduction geometry, as for Andean and Cordilleran tectonics, has not previously been considered. Subduction geometry is, however, unlikely to be the only influence, as the dextral rotations and transcurrent displacements in eastern North Island (Kingma, 1959; Walcott and Mumme, 1982) are considered a manifestation of oblique subduction (Walcott, 1978a), after a model by Fitch (1972). Given that the contribution to Kaikoura tectonics of oblique subduction can be identified, several lines of evidence and, specifically, the radiometric ages of orogenic andesites, show that through the Neogene–Quaternary there were progressive changes in the extent and geometry of the subducted Pacific Plate; the shallow dipping slab progressively increased its extent beneath North Island from the northeast (Northland–Coromandel) to the southwest (northernmost South Island), and for northern North Island, subsequently increased its dip. These changes in the configuration of subduction introduce a degree of spatial and temporal complexity which appears necessary to explain the observed deformational patterns.

The principal objective of this paper is to establish the extent and geometry of the subducted Pacific Plate beneath North Island through the Neogene and Quaternary. This forms their basis to subsequently evaluate the influence of the subduction geometry on the nature and pattern of Kaikoura tectonics of the North Island.

A traditional method of determining the extent of a subducted slab at particular times involves calculating the relative plate motions over given intervals of time from poles of instantaneous rotation. Davey and Smith (1983) successfully applied this method to establish the extent of the Australia Plate beneath southern South Island. Walcott (1979) similarly inferred the extent of the Pacific Plate beneath North Island for Anomaly 5 (10 My B.P.) and Anomaly 6 (21 My B.P.) times. Consideration,

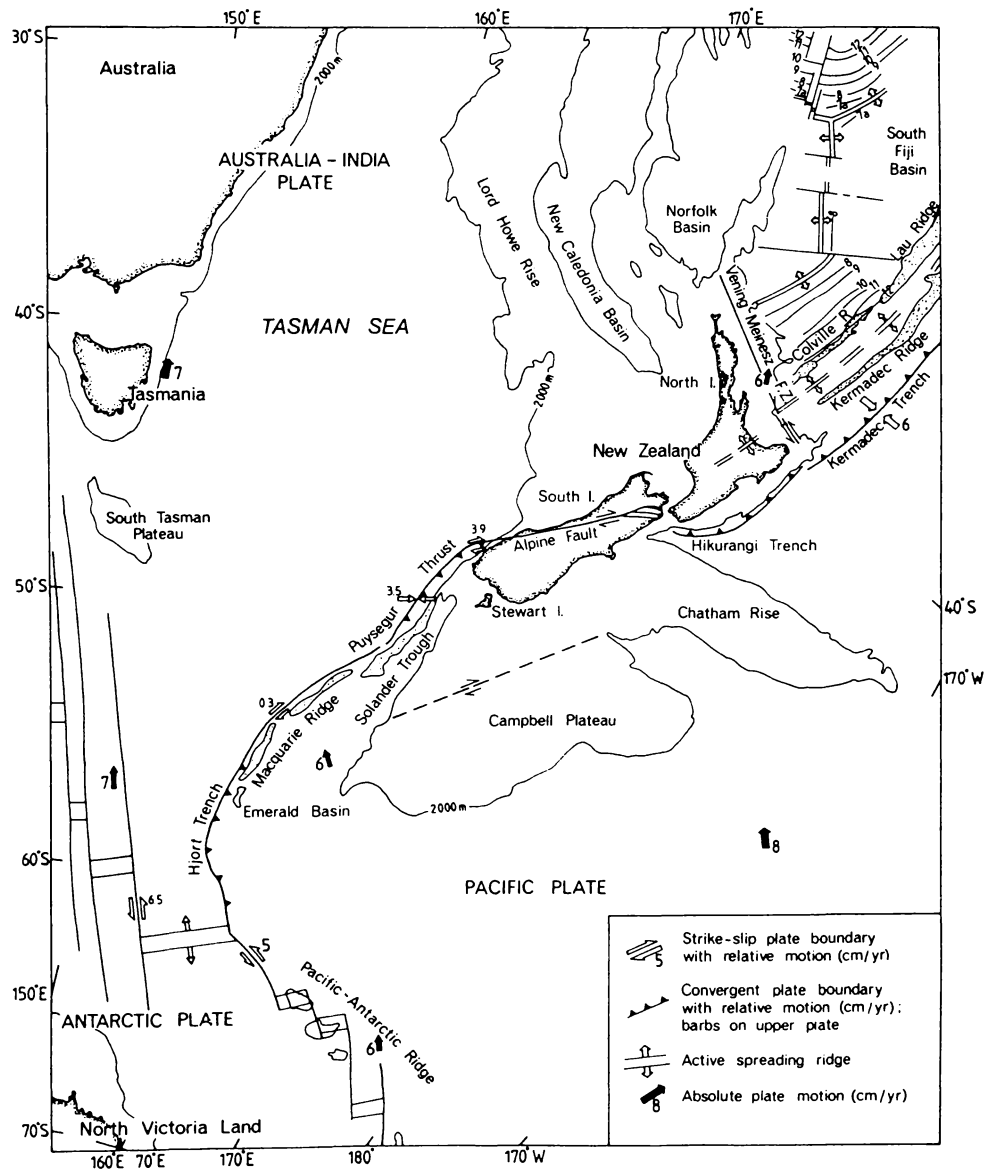


Fig. 1. Plate tectonic map of New Zealand and the southwest Pacific showing the surface location and character of the Australia-Pacific plate boundary. Reproduced from the Plate Tectonic Map of the Circum-Pacific Region—Southwest Quadrant (the American Association of Petroleum Geologists, Tulsa, U.S.A.). Sea floor magnetic anomalies 7a–12 in the South Fiji Basin have been added from Malahoff et al. (1982).

however, of the distribution of the older (early Miocene) orogenic andesites, many of which are located up to 350 km northwest of the presently active arc (Taupo Volcanic Zone), indicates that this method markedly under-estimates the extent of

the slab through the Neogene. Because eastern North Island has undergone large-scale rotations and translations over the last 20 My (Walcott et al., 1981; Walcott and Mumme, 1982), it has not afforded a fixed position which may be taken as a reference against which relative plate motions may be plotted. A surrogate means of establishing the extent of the subducted slab might be the distribution of orogenic andesites throughout northern North Island. This approach has the advantage that consideration of geochemical parameters of depth to the dipping seismic zone permits inferences to be made about the subduction geometry at particular times.

A complication in this approach is the recently favoured interpretation of the age pattern of the northern North Island subduction related volcanics. Ballance (1976) and others (Hayward, 1979; Cole, 1979; Cole and Lewis, 1981; Ballance et al., 1982) have interpreted the available radiometric ages as a series of NNW–SSE oriented Neogene arcs. I show here that the radiometric ages are better interpreted as younging to the southeast consistently parallel to the Taupo Volcanic Zone; this interpretation is corroborated by other considerations of the volcanic geology. This implies that the subducted plate has always originated at a NE–SW oriented Kermadec–Hikurangi Trench, and obviates the need for the controversial fractured slab model (cf. Ballance, 1976), or the need for any rotation of Northland (cf. Ballance et al., 1982).

The southwestern end of the volcanic front at any time delimits the southwestern margin of the subducted slab, whereas the northwestern margin of the slab is established from a model of increasing dip constrained by  $K_2O-h$  ratios calibrated against the presently active arc. These data permit estimates of the extent of the subducted slab projected to the surface to be made for 15, 10 and 5 My B.P. The Cretaceous Pacific Ocean lithosphere was evidently subducted at a shallow angle ( $10^\circ$ ) for 550 km before the slab dip progressively steepened to the  $50^\circ$  it is today. The initiation of andesitic volcanism (20–18 My B.P.) appears to have coincided with penetration at about 85 km of the asthenosphere by the subducted slab; this probably initiated crustal phase changes (gabbro–basalt to eclogite) which added to the gravitational instability and overcame the hydrodynamic forces and any residual thermal buoyancy, thus permitting the slab to decouple and sink to its present position.

#### SUMMARY OF NORTH ISLAND NEOGENE VOLCANICS

Submarine and subaerially erupted volcanics and associated intrusives of early Miocene–Pliocene age are widely distributed throughout Northland and the Hauraki Volcanic Region (Fig. 2). Most of these rocks can be geographically grouped into four igneous provinces: western Northland, eastern Northland, Coromandel Peninsula, and western Hauraki. Within each of these provinces there are broad similarities in the eruptive environments, compositional ranges and eruptive volumes of individual centres. The identification of broad regional differences in the volcanic

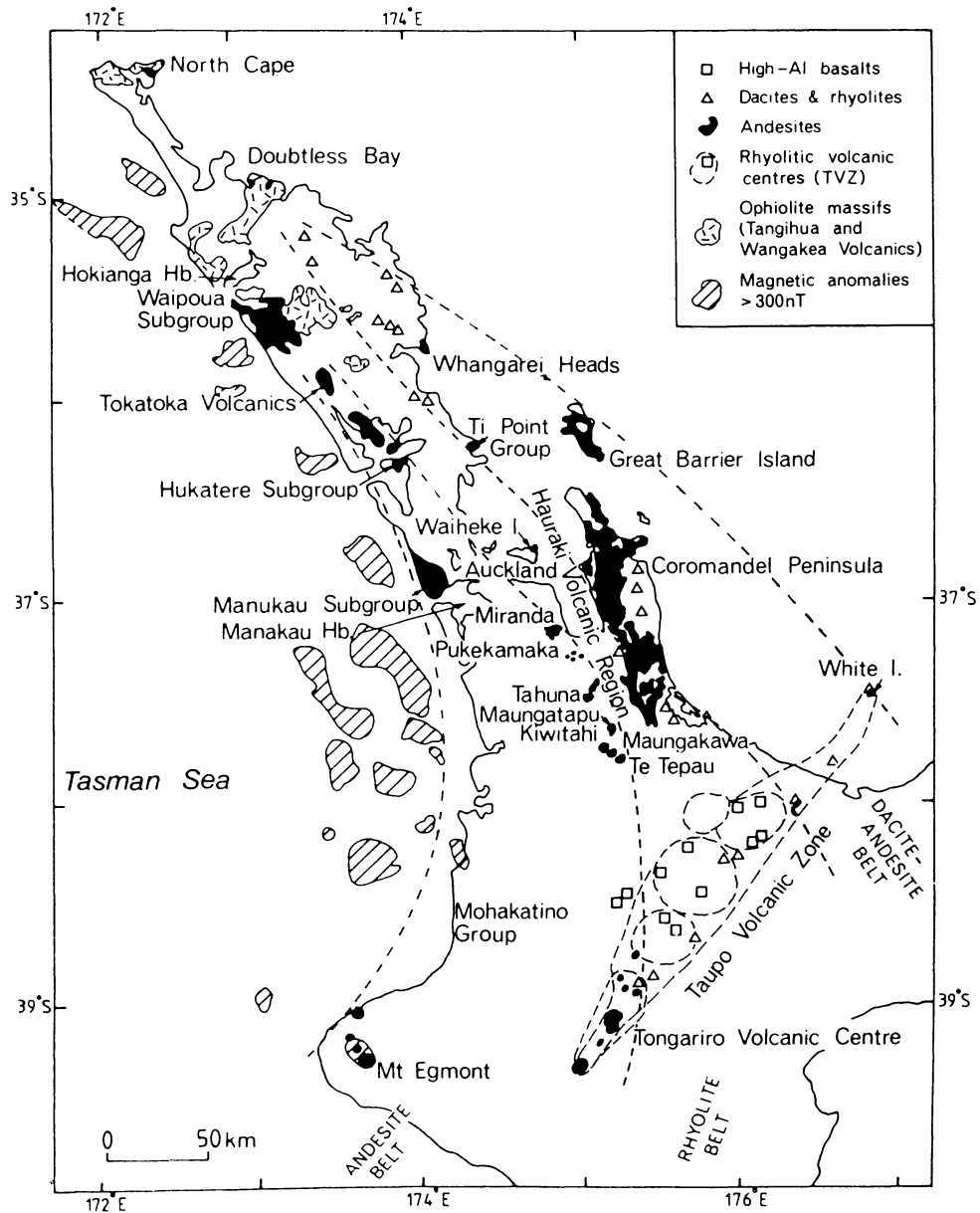


Fig. 2. Map principally showing the distribution of volcanic front andesites, dacites, rhyolites and high Al basalts in northern North Island. Map compiled from numerous sources. Note the western andesite belt, the central rhyolite belt which only extends to Coromandel Peninsula, and the northeastern dacite-andesite belt. The magnetic anomalies offshore from western North Island are from Hatherton et al. (1979). Most of these anomalies probably have a rift origin, unrelated to the subduction related volcanism discussed here, but the smaller ones close inshore to the south may be submerged calc-alkaline volcanoes and the source of the thick andesitic Purupuru Tuff in the onshore Mohakatino Group.

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geology helps to constrain the opposing interpretations of the radiometric age distribution of these volcanics and thus of the attitude of the subducted slab.

#### *Western Northland*

Early to mid-Miocene calc-alkaline and tholeiitic volcanics and associated volcanoclastic sediments, referred to the Waitakere Group (Ballance et al., 1977), crop out in four main areas between the Hokianga and Manukau Harbours (Fig. 2). Each region is considered to mark an original volcanic centre, for which the stratigraphy is now established (Black, 1967a; Hayward, 1979, 1983; Wright, 1980). The most abundant rock type is basalt to basaltic andesite with plagioclase and lesser augite and olivine phenocrysts (Wright and Black, 1981). The Hukatere Subgroup and lower parts of the Manukau Subgroup, with pillow lavas, lava flows and hyaloclastites, were submarine emplaced, whereas the more northern Waipoua Subgroup and higher levels of the Manukau pile comprise terrestrial basaltic to andesitic lava flows, tephra, dikes, and for the Manukau Subgroup, localised dacitic plugs (Hayward, 1979; Wright, 1980). One hundred and forty intrusive igneous bodies near Tokatoka, ranging in composition from olivine basalt to biotite dacite, are interpreted as the roots of a highly eroded volcanic field (Black, 1967a).

#### *Eastern Northland*

The igneous rocks of eastern Northland in contrast with those to the west are mainly of calc-alkaline intermediate and acidic composition, were emplaced in an entirely subaerial environment and comprise much lesser eruptive volumes. The Miocene Wairakau Andesites are mainly fragmental andesitic breccia but with dikes and lavas that all crop out east of Whangarei Harbour (Watters, 1978). Quartz diorite porphyry and hypersthene-bearing granodiorite have been described by Elliot (1968), and dioritic and granodioritic rocks have been described from scattered islands offshore from Whangarei Heads (Thompson and Wodzicki, 1967; Brothers and Hopkins, 1967). Miocene dacites with lesser rhyolite and porphyry, all included in the Parahaki Volcanic Group, crop out as clusters in four localities along eastern Northland (Fig. 2).

#### *Coromandel Peninsula*

Coromandel Peninsula contains the most extensive outpourings of intermediate composition volcanics in New Zealand; in part this is due to the longer-lived activity which extended from the early Miocene to early Pleistocene. The volcanics are predominantly hornblende—hypersthene andesite to dacite, with significant volumes of rhyolite and dacite, and both dacitic and rhyolitic ignimbrites (Skinner, 1976, 1979). In contrast to west Northland volcanics, basalt is minor, hornblende is common, biotite is moderately common and olivine is rare.

### *Western Hauraki Volcanics*

Individual late Miocene cones and flows, named the Kiwitahi Volcanics were subaerially erupted from discrete centres along a sublinear belt on the western margin of the Hauraki Volcanic Region (Fig. 2) (Cole, 1978a). From the meagre exposure of thin lava flows totalling a maximum of 90 m at any one centre, and the absence of associated volcanoclastic sediment, the eruptive volumes must have been invariably small. Labradorite–pyroxene and pyroxene andesites are the predominant lava rock types. Hornblende andesites occur near Miranda, and olivine andesites north of Kiwitahi (Cole, 1978a).

### PRESENT SUBDUCTION GEOMETRY AND TAUPO VOLCANIC ZONE VOLCANISM

The present extent and geometry of the subducted Pacific Plate is defined by a dipping seismic zone (Hatherton, 1970; Adams and Ware, 1977). The subducted slab originates at the Hikurangi Trench east of North Island, and dips initially at a shallow angle of  $12^{\circ}$ – $15^{\circ}$  for 250 km, before it abruptly steepens to a dip of  $50^{\circ}$  at a depth of 80 km; the plane of the slab strikes  $N45^{\circ}E$  and dips to the northwest. Recent microearthquake studies have confirmed that the seismic zone dips initially at a shallow angle of  $12^{\circ}$ – $15^{\circ}$  (Arabasz and Robinson, 1976; Smith, 1979; Arabasz and Lowry, 1980). There is a pronounced shallowing of the leading edge of the Waditi–Benioff Zone along its strike from a maximum depth of 300 km near Bay of Plenty to a depth of 150 km in northern Marlborough. This shallowing parallels a shallowing of the Hikurangi Trench from 4 km opposite East Cape to 1 km near Marlborough, where the subducted slab terminates and the oblique ocean–continent convergence is transformed into oblique continent–continent convergence on the Alpine Fault.

The line of marked change in dip of the subducted Pacific Plate corresponds at the surface with the trend of the Taupo Volcanic Zone, a calc-alkaline province of Quaternary volcanics. The zone comprises a graben structure 300 km long and up to 75 km wide where basement has been differentially tilted and down thrown as much as 4000 m (Modriniak and Studt, 1959). Lavas ranging in composition from high-Al basalts to rhyolites have been erupted, but rhyolites are far more voluminous ( $16,000 \text{ km}^3$ ) than andesite ( $260 \text{ km}^3$ ) or dacite ( $5 \text{ km}^3$ ) or high-Al basalt ( $2 \text{ km}^3$ ) (Cole, 1979).

There is an obvious spatial separation of andesites, low-Al basalts and to a lesser degree dacites, from the rhyolite centres (Fig. 2). Ninety-five percent by volume of andesites occur in the Tongariro Volcanic Centre (Cole, 1978b). Olivine-bearing andesite, low-silica andesite and low-Al basalt erupted in the last 50,000 yrs are considered by Cole (1978b) to derive from andesitic magma generated at a subduction thrust at a depth of 80–100 km, from the partial melting of amphibolite. Northeast of Tongariro, isolated acid andesite to dacite volcanoes form an arc along

the eastern margin of the Taupo Volcanic Zone. White Island of mainly dacitic composition has recently erupted an olivine bearing andesite (Clark et al., 1979).

#### AGE PATTERN OF NEOGENE SUBDUCTION DERIVED VOLCANICS

The radiometric ages of subduction derived volcanics (Richards et al., 1966; Stipp and Thompson, 1971; Adams et al., 1974) are summarised in Fig. 3. I interpret the spatial distribution of these ages in a similar fashion to that of Challis (1978), as indicating a younging in the direction of Neogene andesitic volcanism towards the southeast and into the Taupo Volcanic Zone at an average rate of 20 km/My. To some extent this direction of younging is masked by differences in the width of the volcanic front for different intervals through the Neogene (Fig. 4). Andesitic volcanism in the age range 18–15 My B.P. may have been erupted over a width of 250 km from Te Aroha to Tokatoka if the 16.2 My B.P. date on the hydrothermally altered andesites at Te Aroha is upheld by further dating. Subsequent volcanism was confined to a narrower volcanic front (Fig. 4). Hence the age pattern of the subduction derived volcanics shows a southwestward younging towards the Hikurangi Trench; it may also have been accompanied in the early and mid-Miocene by a decrease in the width of the volcanic front.

A model capable of reconciling both elements of this age pattern is one involving a persistent steepening in the dip of the subducted slab from an initial flat plate configuration to a dip of about 50°. Geometric reasoning shows that andesites derived from normal depths of magma generation (80–125 km; Gill, 1981) would, with a shallow slab dip, have a wide geographic spread, while a steepening of dip would both geographically confine the volcanism and shift it trenchward.

Northern Coromandel Peninsula is an exception to the regional eruptive age pattern as the eruption of orogenic andesites continued until the latest Miocene, thus lagging behind the volcanic front for at least 5 My (Fig. 4). Consistent with the model of increasing slab dip, geochemical parameters show that the successively younger volcanics indeed derived from deeper levels (Skinner, 1979).

The radiometric ages of the Northland–Hauraki volcanics and associated intrusives are however at present interpreted by many New Zealand geologists as a series of magmatic arcs that young in a fundamentally different direction: towards the east-northeast. Ballance (1976) developed an earlier notion (Hatherton, 1969; Brothers, 1974) of a series of geologically separate NNW trending arcs: the first three parallel to the coasts of Northland (Waitakere Arc, 18–15 My; Northland Arc, c. 15 My; Coromandel Arc, c. 10 My), followed by a shortlived north trending Tauranga Arc (c. 6 My), before the presently NE–SW trending Taupo Volcanic Zone became active. Each arc was viewed as having been at the time of its eruption continuous with the NNE trending Tonga–Kermadec Arc, a position from which each was subsequently rotated anti-clockwise to its present location. The older arcs appeared to have rotated up to 70° in the last 3 million years. Ballance recognised as

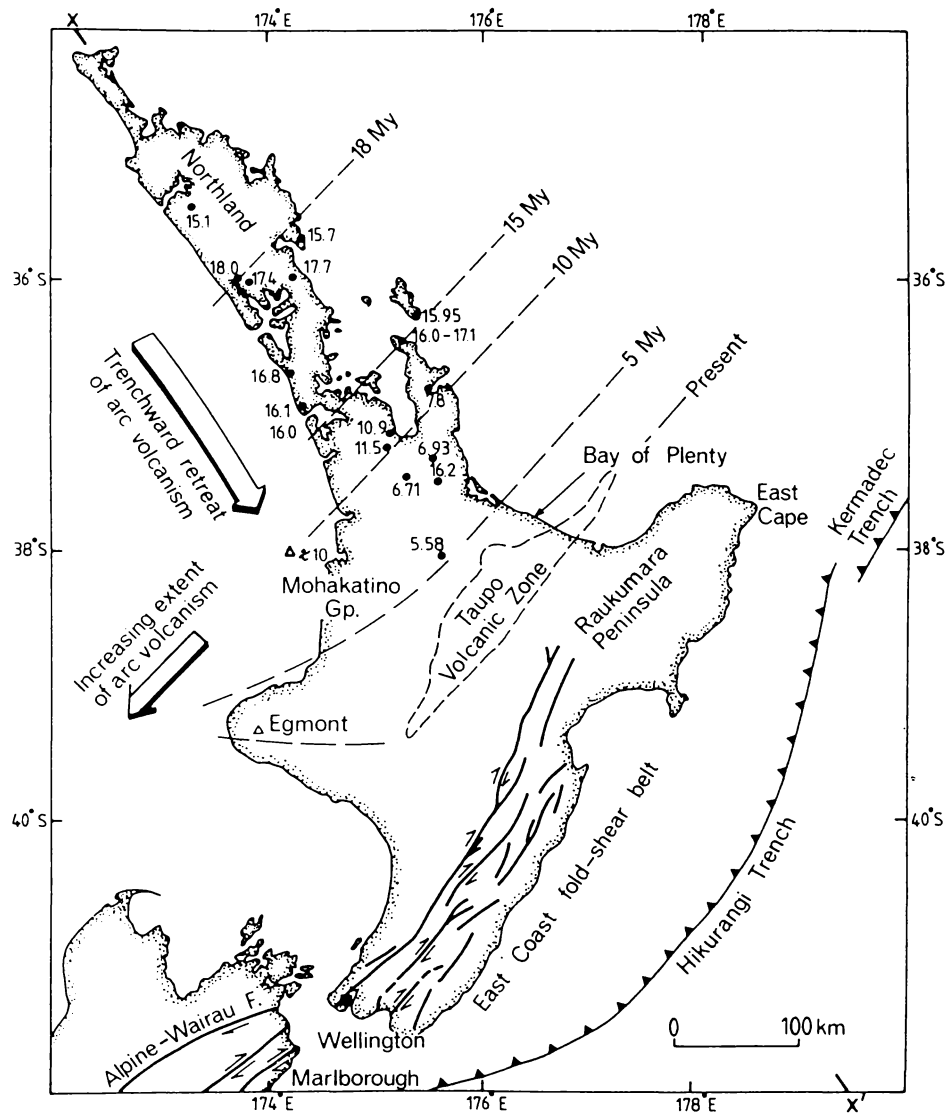


Fig. 3. Distribution of published (sources in text) radiometric ages of orogenic andesites with interpreted isolines showing both a trenchward retreat and an increasing southwestward extent of arc volcanism with time. While the 18.0 My B.P. age is the oldest published date, it should not be strictly regarded as the start of andesitic volcanism. Wright and Black (1981) and Brothers and Delaloye (1982) both refer to unpublished ages of andesites at Whangarei Heads that range back to 21 My B.P. Andesitic volcanoes in the Taupo Volcanic Zone (Fig. 2) and Mt. Egmont are presently active. The Mohakatino Group records offshore mid-Miocene andesitic volcanism biostratigraphically aged about 10 My B.P.

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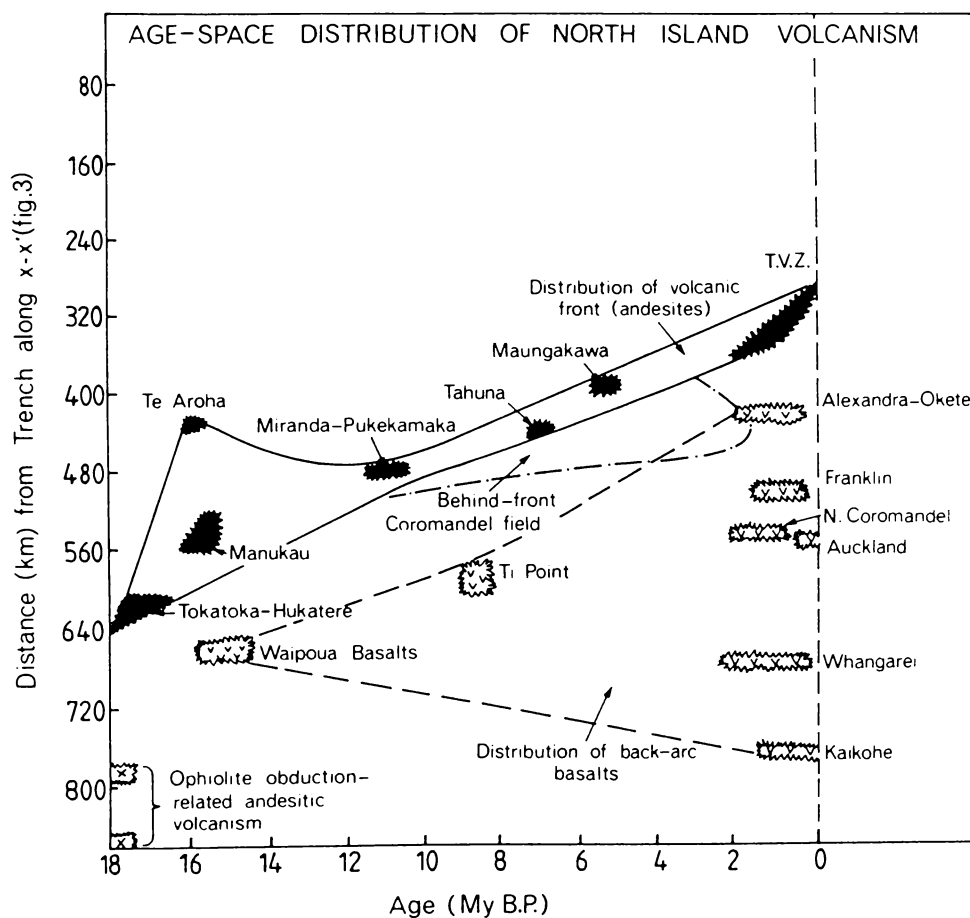


Fig. 4. A diagram showing the trenchward retreat on the andesitic volcanic front with time. The eruption of andesites and subsequently dacites and rhyolites in Coromandel lagged behind the volcanic front. Back-arc basalts (Heming, 1980a, b; Briggs, 1983) have always erupted at least 130 km behind the volcanic front, and show a trend of increasing their spatial distribution with time. Only the distribution of dated andesites of western Northland, Hauraki and the Taupo Volcanic Zone are plotted. The biostratigraphically dated (early Miocene) ophiolite related andesitic volcanism may be slightly older than 18 My B.P. If, as suspected, the 16.2 My B.P. date from Te Aroha is too old, the volcanic front will have been narrower and closer to the Tokatoka and Manukau regions during the early and mid-Miocene than shown in this diagram.

a difficulty with the model of migrating arcs, the fact that contemporaneous andesitic volcanism occurred on both the Waitakere and Northland Arcs. Geochemical data available to him for these arcs (Black, 1967b; Ferrar, 1925) suggested on the basis of the relationship between potassium contents and depths to the Wadati-Benioff Zone (Dickinson and Hatherton, 1967), that the depths of magma generation were comparable. This led to the unusual application of a fractured slab model to

account for continued subduction related volcanism after the arc had migrated.

Cole and Lewis (1981) recognised the improbability of  $70^\circ$  of rotation of the older arcs and proposed an alternative evolutionary model which involved Miocene subduction from a NW–SE oriented trench now identified as the Vening Meinesz Fracture Zone (Fig. 1). Ballance et al. (1982), with the benefit of new data of the mid-Miocene age of the Colville Ridge and the age structure of the South Fiji Basin (Malahoff et al., 1982), surrendered the notion of  $70^\circ$  of rotation of the older arcs and formulated another model quite similar to that of Cole and Lewis (1981) which now involved only  $20^\circ$ – $30^\circ$  of rotation. That the Neogene volcanism youngs to the east is still an integral element of both these models. The validity of the younging direction adopted here (Fig. 3) compared with that of Cole and Lewis and Ballance et al., can be argued in two ways: (1) by showing that their models and the implied subduction orientations violate the regional geology; and (2), by corroborating the radiometric age pattern identified here with other geologic considerations.

(1) The NE–SW trend of seafloor magnetic anomalies 8–12 in the South Fiji Basin adjacent to eastern North Island (Malahoff et al., 1982) (Fig. 1), together with the occurrence of Miocene age volcanics on the Colville and Kermadec Ridges, now clearly precludes any possibility of wholesale southwestward directed subduction at a trench parallel to but east of Northland (c.f. Cole and Lewis, 1981). Without such a trench it is difficult to sustain the notion of northeasterly migrating NW–SE trending arcs onland in Northland–Coromandel.

A common element in both the Cole and Lewis and Ballance et al. models is the idea that eastern North Island formerly lay in a forearc position adjacent to Northland. This appears to be an attractive solution to the apparent conundrum that Northland–Coromandel contains arc volcanics of Miocene–Pliocene age, but has no accretionary prism, yet eastern North Island has a Miocene–Quaternary accretionary prism but its adjacent arc, the Taupo Volcanic Zone, is only of Quaternary age. To achieve this amount of transposition of eastern North Island, the 480 km of displacement evident in the South Island on the Alpine Fault must also have passed through North Island on a narrow fault zone. Not only would this degree of displacement of eastern North Island complicate the pattern of basement terranes and violate basement age and lithology trends (Bradshaw et al., 1980; MacKinnon, 1983), but it is also inconsistent with the late Cenozoic pattern of deformation in eastern North Island. The fault displacements are in fact distributed across a 70 km wide zone named the Axial Tectonic Belt by Walcott (1978a), who also showed that about half of the present deformation in this belt is taken up as aseismic ductile flow (Walcott, 1978b). Furthermore, a conspicuous feature of the late Cenozoic structure of eastern North Island is the absence of any transcurrent faults in its northern parts (Fig. 3) about which the displacement is inferred to have occurred.

(2) I consider that broad compositional trends in the Neogene and Quaternary volcanics show a southeast to southwesterly trend corroborating the age pattern adopted here from the radiometric dates.

The Taupo Volcanic Zone shows a marked spatial separation of andesites at the southwest end, rhyolites in the centre, and dacites with andesites mainly to the northeast. With the qualification that widespread rhyolitic volcanism was delayed until the late Miocene, the Taupo Volcanic Zone compositional pattern persists as curved belts away from the active arc and through the provinces of Neogene volcanism (Fig. 2). The persistence of this composition–space pattern, apart from changes in the locus of volcanism which can be explained by a gradual steepening of the angle of subduction, is suggestive of a certain stability in the configuration of subduction. The pattern argues against any radical changes in either the trench position or the strike of the subducted plate through time. This pattern, combined with the southeastward younging of the radiometric dates, indicate that the subducted slab always originated at a NE–SW trending Kermadec–Hikurangi Trench. The widening of the compositional belts, particularly the western andesite belt, is considered to record the progressive increase in the southwest extent of subduction beneath North Island since the early Miocene (Fig. 3).

I view the models of Cole and Lewis (1981) and Ballance et al. (1982) as unnecessarily complicated. Not only do they need to infer a fractured slab model to explain coeval Waitakere Arc and Northland Arc volcanism, but also an unnecessary conundrum is perceived: the paradox of an early Miocene eastern North Island accretionary prism adjacent to a 2 million year old arc (T.V.Z.). The occurrence of an early Miocene accretionary prism in eastern North Island is entirely consistent with the dip direction of the subducted slab and the trend of the Hikurangi Trench inferred from the age and composition patterns outlined here.

Now that the age pattern of volcanism adopted here has been justified, I interpret from this the extent and geometry of the subducted Pacific Plate through the Neogene–Quaternary.

#### NEOGENE EXTENT AND GEOMETRY OF THE SUBDUCTED SLAB

Estimates of the extent of the subducted Pacific Plate beneath North Island for intervals through the Miocene–Pliocene are presented in Fig. 5. Comparison of the extent of the Taupo Volcanic Zone with the present extent and geometry of the subducted Pacific lithosphere (Fig. 5D) suggests that equivalent but older magmatic activity will record only a minimum extent of the subducted slab in directions both normal and parallel to the trench. With this in mind, the extents of the southwestern margins in Fig. 5A–C have been placed slightly southwest of the southwesternmost position of volcanism for each interval. The locations projected onto the overriding plate of the northwestern margin of the subducted slab through time are more difficult to establish. This depends on two factors, one being the location of the northwesternmost volcanics clearly directly related to the subducted Pacific Plate, and the other being the dip of the subducted slab at each interval under consideration.

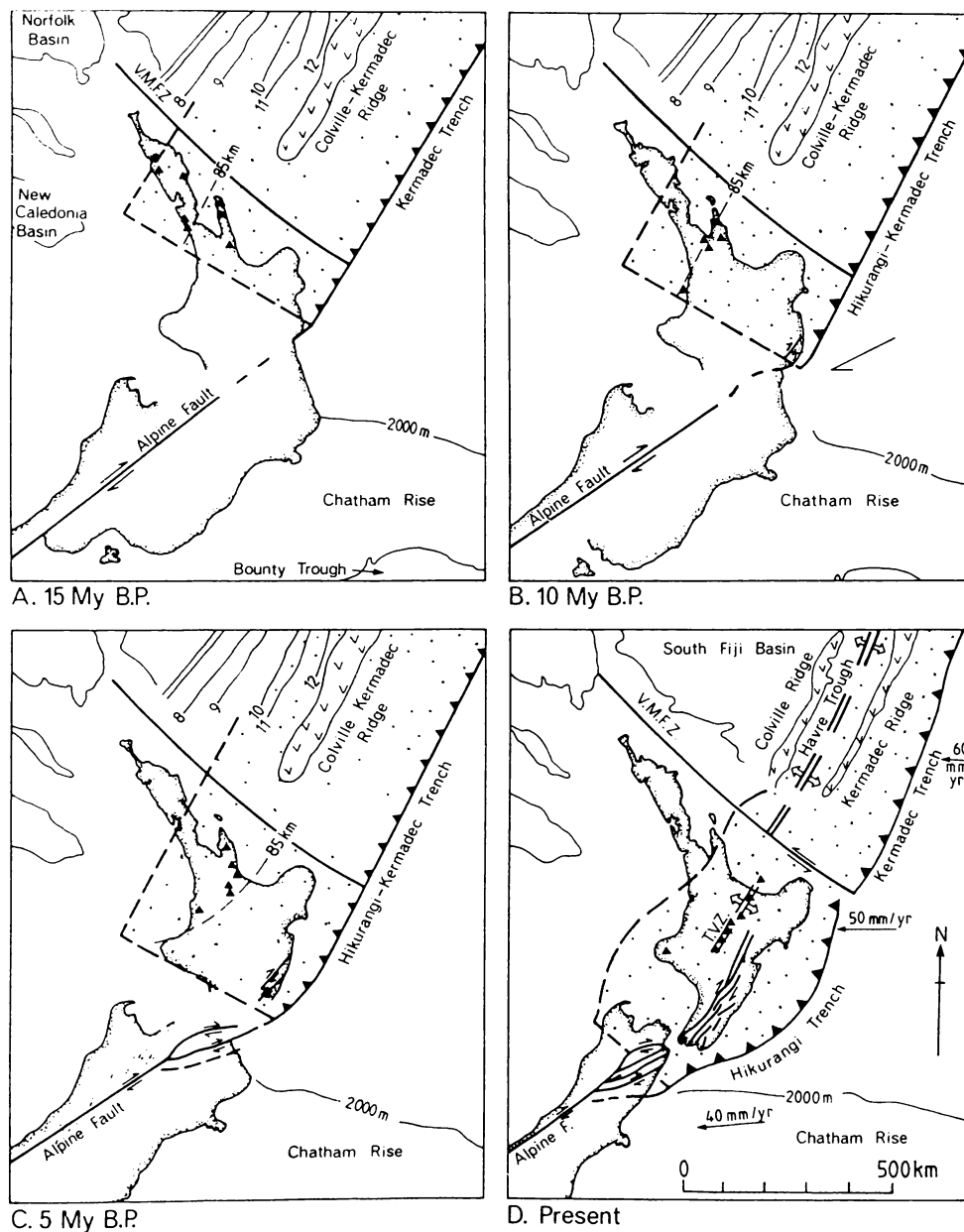


Fig. 5. Maps showing the extent (by dots) of the subducted Pacific Plate projected on to the overriding Australia Plate. Note how the southwestern extent of the subducted slab increases with time as the Pacific Plate is dextrally displaced on the plate boundary (Alpine Fault-Hikurangi-Kermadec Trench). The northwestern extent of the subducted slab retreats towards the trench as the dip steepens. Seafloor magnetic anomalies 8-12 in the south Fiji Basin are from Malahoff et al. (1982).

*Location of the northwesternmost subduction related volcanics*

At several localities in northern Northland, latest Oligocene and early Miocene calc-alkaline volcanics, intrusives and volcanoclastics outcrop in association with disrupted ophiolite sequences. The ophiolites were generated at the Vening Meinesz Fracture Zone and obductively emplaced about the Oligocene–Miocene boundary (Brothers and Delaloye, 1982). At North Cape the latest Oligocene–early Miocene Parengarenga Group which includes thick (1000 m) andesite conglomerates and augite diorite dikes, rests disconformably on an ophiolite massif (Leitch, 1970). At Doubtless Bay, early Miocene calc-alkaline andesites and diorite flows and dikes and a plutonic complex also intrude an ophiolite massif (Cooper and Searle, 1970; Hay, 1975). The very close stratigraphic and especially age association of these andesites with the ophiolites, together with their geographic separation 130 km to the north of the more voluminous and clearly subduction derived Waitakere Group (Fig. 2), suggested to Brothers and Delaloye (1982) that these andesites have a different origin closely related to the obductive event which emplaced the ophiolite massifs. They proposed that the calc-alkaline melts were locally generated beneath northeastern Northland at a steep westerly dipping surface resulting from the obductive modification of the Vening Meinesz Fracture Zone. In accord with this, the most northern volcanics accepted here as clearly having an origin related to the subducted Pacific Plate are those of the Waipoua Subgroup basalts (Fig. 2), although as discussed below, these volcanics have back-arc affinities to the andesites at Manukau (Fig. 4).

*Dip of the subducted slab*

The preferred explanation offered earlier of the radiometric ages involved a progressive trenchward retreat and concomitant increase in the angle of subduction throughout the last 18 million years. This model predicts that volcanics of the retreating volcanic front should consistently derive from similar and shallow depths of andesitic magma generation while volcanics lagging behind the volcanic front should derive from correspondingly deeper levels. A test of this might be afforded by the application of geochemical parameters of the depth of magma generation to these orogenic andesites.

*The  $K_2O$  depth parameter*

Potash contents differ more between andesite suites across arcs than any other oxide, and several attempts have been made to relate  $K_2O$  content at specified  $SiO_2$  wt.% values to absolute depths to the Wadati–Benioff Zone (Dickinson and Hather-ton, 1967; Ninkovitch and Hays, 1972; Dickinson, 1975). Empirical correlations of  $K_2O-h$  have been applied in many arc settings, and especially to Cretaceous–Cenozoic volcanics of western North America, to infer the dips of paleosubduction slabs

(Lipman et al., 1971; Coney and Reynolds, 1977). However, there has been some criticism of the  $K_2O-h$  correlations arising from significant variations in  $K_2O$  content along western Pacific arcs where there is no change in the depth to the dipping seismic zone (Whitford and Jezek, 1979; Meijer and Reagan, 1983). Nevertheless these criticisms do not necessarily deny the existence of some fundamental  $K_2O$ -depth causal relationship. Meijer and Reagan (1983) have shown that  $K_2O-SiO_2$  variations in the Mariana Arc which can not be attributed to differences in depth of magma generation, can be related to different degrees of partial melting of parental melts. The  $K_2O-h$  parameter is applied here to constrain the slab dip through time, and it is used relative to the presently active arc for which there is good seismic evidence of the depth to the top of the subducted slab.

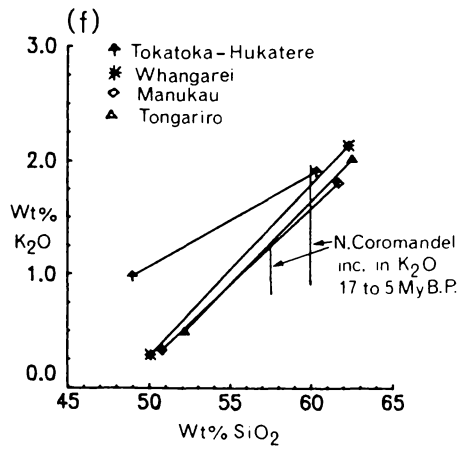
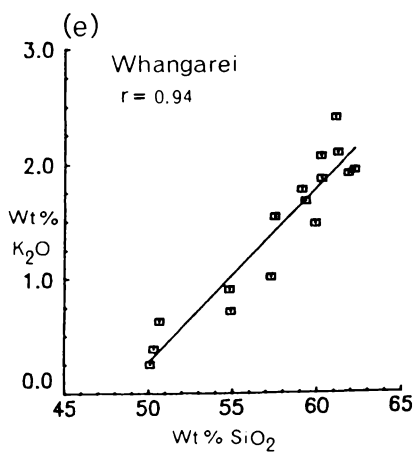
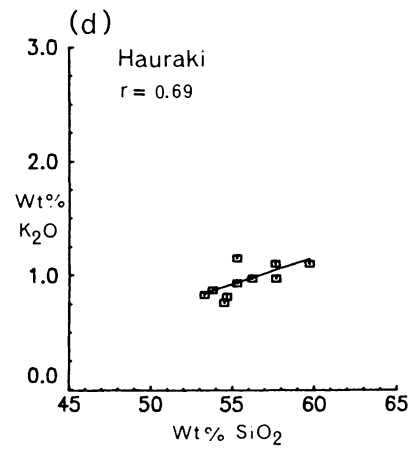
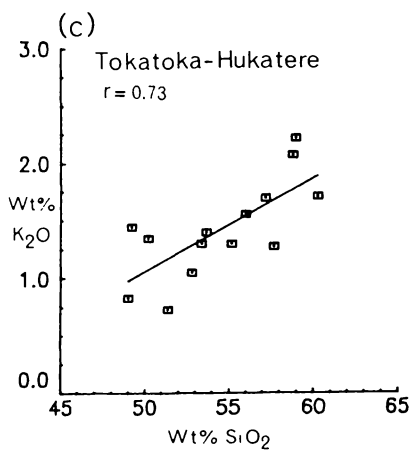
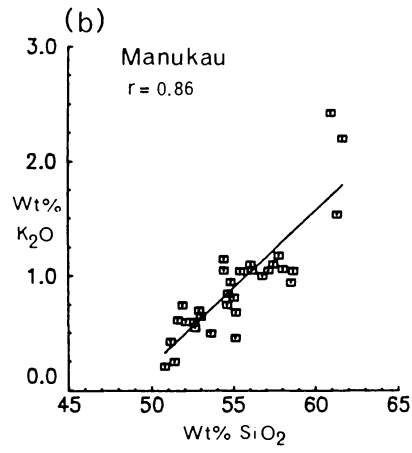
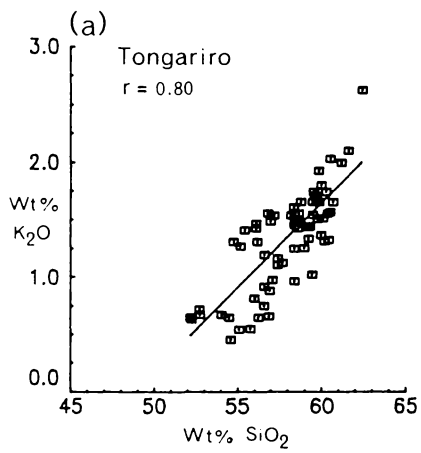
*Application of the  $K_2O-h$  parameter to North Island*

Much  $K_2O-SiO_2$  data are available for North Island volcanics to compare the depths of magma generation (Ferrar, 1925; Cole, 1978a, b; Skinner, 1979; Wright and Black, 1981). Figure 6 displays for the Tongariro lavas (6a), Manukau Subgroup (6b), Hukatere Subgroup (6c) and Whangarei lavas (6e), the spread of  $K_2O-SiO_2$  contents, with computer plotted best fit regression lines and correlation coefficients, each of which is highly significant. Figure 6d gives the plot for Hauraki volcanics, and Fig. 6f facilitates a visual comparison of the correlation lines of Fig. 6a-c, e.

Because the correlation lines of the Manukau, Whangarei and Tongariro lavas are not significantly different in either their intercepts or slope (Fig. 6f), there is no reason to suggest that the parental melts of these basalts and andesites derived from significantly different depths. The Tongariro Volcanic Centre lies 85 km above the top of the dipping seismic zone (Adams and Ware, 1977) and this depth is adopted for the generation of the Manukau and Whangarei magmas, presumably at the subducted slab-mantle wedge interface.

The Hukatere-Tokatoka regression line is markedly offset from the others at all  $SiO_2$  values by up to 60% (Fig. 6c). This may indicate a deeper level of magma generation; taking the Hatherton (1969)  $K_2O-h$  depth relationship at face value, corrected for the shallower earthquake hypocentres beneath Tongariro (Adams and Ware, 1977), indicates that at  $K_{55}$  the Tokatoka/Hukatere volcanics derived from 20 km deeper than the neighbouring Manukau and Whangarei lavas. Alternatively, the magma may have been generated at similar depths, the offset in the regression line indicating that the parental liquids sustained a lesser degree of partial melting; this option is supported by the lesser volumes of Tokatoka-Hukatere eruptives. A third possibility of variations in source compositions cannot be discounted because of the unavailability of isotopic data. The different slope of the regression line can be explained by a different crystal fractionation pathway, an idea supported by the mineralogical and geochemical distinctiveness of volcanics in the Tokatoka district (Black, 1967b). Because of the alternative explanations of the  $K_2O-SiO_2$  character of the Tokatoka/Hukatere lavas, one cannot state unequivocally that they derived

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from deeper levels, but it is possible to say that they did not derive from levels shallower than the neighbouring volcanics of Whangarei Heads and the Manukau Subgroup.

It is not valid to compare the regression line of the Hauraki volcanics (Fig. 6d) with the others considered here because the analyses come from different eruptive centres up to 100 km apart (Figs. 2 and 4). Therefore the regression line does not represent a crystal fractionation trend as for the other data sets. The few analyses limit the statistical certainty of any interpretations of inferred depths to the dipping seismic zone, but the values of Waiheke Island and Mangatapu–Kiwitahi (Cole, 1978b) at either end of the Hauraki Volcanic region, are very similar to the Tongariro K55 values.

The  $K_2O$ – $SiO_2$  data as interpreted above indicates, with perhaps the exception of the Tokatoka–Hukatere suite, that the volcanics interpreted from the radiometric age pattern to have been erupted within the volcanic front, did indeed derive from depths similar to the presently active andesitic arc of the Taupo Volcanic Zone. That trenchward retreat of the frontal arc was accompanied (and caused) by a steepening in the dip of the subducted slab is more difficult to demonstrate because andesitic volcanism was mostly restricted to the volcanic front, as it is at present. An exception is northern Coromandel Peninsula where andesitic volcanism erupted intermittantly from before 17 My B.P. until the end of the Miocene (Skinner, 1976), at least 5 My after the volcanic front had passed to the southeast (Figs. 3 and 4). Geochemical data for these andesites is sparse but  $K_{57.5}$  and  $K_{60}$  values for each of 13 of the andesite formations (Skinner, 1979) show a strong correlation of increasing  $K_2O$  content with time between the lower Miocene and uppermost Miocene lavas (Fig. 6f). Skinner concluded of the trends in his data: “As the locus of volcanism changed little with time, the data suggest that the depth of magma generation progressively increased, and the dips of any related paleo-Benioff zone and subducting plate steepened with time” (Skinner, 1979, p.16). Applying the end member  $K_{60}$  values to the  $K_2O$ – $h$  relationship (Dickinson and Hatherton, 1967) gives a 60 km increase in the depth of the subducted slab at northern Coromandel between 15 and 5 My B.P.

From the preceding discussion, the geochemical estimates of the depth of magma generation are consistent with the conceptual model of subduction geometry inferred earlier from the radiometric age pattern. The inferred depths of magma generation

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Fig. 6. Plots of  $K_2O$  against  $SiO_2$  with computer plotted best fit regression lines and correlation coefficients. Data from Cole (1978a) (Tongariro), Wright and Black (1981) (Manukau, Tokatoka–Hukatere), Cole (1978b) (Hauraki) and Ferrar (1925) (Whangarei). Graph f compares the regression lines of a, b, c and e and shows that the composition of the parental melts of the Tongariro, Manukau and Whangarei lavas was similar, and that their fractionation trends are also very similar. The lavas erupted at north Coromandel increased their contents at  $K_{57.5}$  and  $K_{60}$  with time (17–5 My B.P.) which indicates a 60 km steepening of the depth of the subducted plate at that locality.

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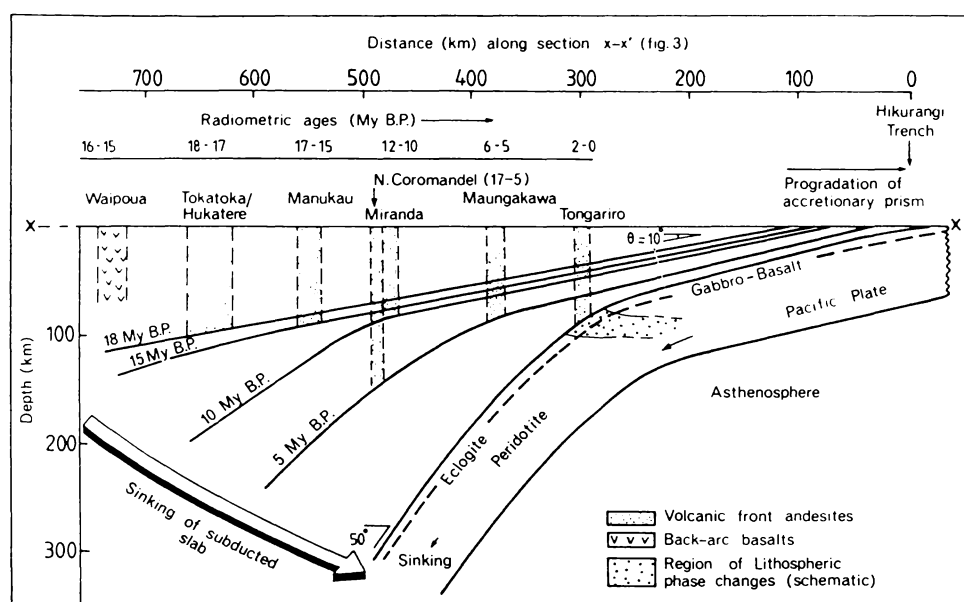


Fig. 7. A series of cross-sections representing the profile of the subducted Pacific Plate at intervals corresponding to each of the maps in Fig. 5. The cross-section is aligned NW-SE ( $X-X'$ , Fig. 3). The depths of the subducted plate at particular points through time have been established by comparison with the depth and  $K_2O$  content of the presently active arc. Once the subducted plate penetrated the asthenosphere beneath Northland (about 85 km), the available heat dehydrated the subducted crust and promoted density related phase changes (gabbro-basalt to eclogite, which reduced the flexural rigidity of the slab and gave it sufficient negative buoyancy to overcome the hydrodynamic forces. Consequently it was able to bend and decouple from the overriding plate. With time and the transformation of a substantial section of the subducted crust to eclogite, the slab would have had sufficient gravitational instability to sink to its present location. This model of subduction evolution is consistent with that proposed by Uyeda and Kanomori (1979).

are combined with the age data to reconstruct in two dimensions the geometry of the subducted slab at 18, 15, 10 and 5 My B.P. (Fig. 7) for the section  $X-X'$  on Fig. 3.

#### *Depth calibration of the steepening slab model*

The present geometry of the subducted slab is constrained by the top of the dipping seismic zone (Adams and Ware, 1977, section B). The slab dip at 5 My B.P. is constrained at two points: one by the position of the volcanic front (Maungakawa/Kiwitahi) and the corresponding depth of magma generation (85 km), and the other by the "behind front" uppermost Miocene andesites in Northern Coromandel, and their inferred origin 60 km deeper than the neighbouring 15 My B.P. lavas. The slab dip at 10 My B.P. is constrained by only one point (Miranda-Pukekamaka), and the  $K_2O$  values indicate that the dip to this point is a maximum estimate. While the dips at 15 and 18 My B.P. are also constrained by one point (Manukau, Tokatoka-Hukatere), they are distant from the trench and indicate

flat plate subduction for 450 km and 550 km at  $10^{\circ}$ – $12^{\circ}$  from the paleo-trench.  $K_2O$  analyses for the least hydrothermally altered andesite at Te Aroha (Weissberg and Wodzicki, 1970), aged 16.2 My B.P. (Adams et al., 1974, Fig. 3), range from 0.25 to 1.05 ( $\bar{x} = 0.7$ ) at 57%  $SiO_2$ , and calibrated against the  $K_2O-h$  of coeval Manukau lavas, suggests an anomalously shallow depth of magma generation of 52 km, compared with a predicted but still anomalously shallow depth of 64 km from the 15 My profile in the model (Fig. 7). This suggests that the 16.2 My B.P. date may be geochemically suspect. Since the early Miocene, subduction accretion has developed a large accretionary prism (Lewis, 1980; Pettinga, 1982) which in association with plate boundary evolution has loaded the subducting Pacific Plate and caused the Hikurangi Trench to migrate southeastward (Fig. 7).

*The Waipoua basalts: an anomaly in the model*

The Waipoua basalts are an anomaly in the steepening slab model because of their slightly younger age but more northern occurrence (Fig. 4). It is suggested here that they may represent basalts erupted in a back-arc environment 150 km behind the coeval Manukau volcanic front. There are numerous differences between the Waipoua Subgroup and the rest of the Waitakere Group (Wright and Black, 1981):  $SiO_2$  enrichment is weakest and it comprises only basalts, the behaviour of FeO and  $TiO_2$  shows enrichment trends opposite to the rest of the group, it has lower Rb/Sr ratios, and the rocks are olivine (not quartz) normative. Arguments suggestive of back-arc affinities include the partial overlap of Waipoua basalts with the field of younger (late Miocene–Quaternary) back-arc basalts on a total alkali– $SiO_2$  plot (Heming, 1980a, b). Furthermore, the Waipoua basalts are more enriched in  $P_2O_5$ ,  $TiO_2$  and most of the incompatible elements than the rest of the Waitakere Group (Wright and Black, 1981). These rocks have sustained little fractional crystallisation, the implication being that there were no crustal magma chambers, an interpretation consistent with the Waipoua basalts occupying a tensional back-arc environment. These rocks are therefore probably older and more northern tectonic equivalents of the previously oldest back-arc basalts identified: the 8.44 My B.P. Ti Point Group (Fig. 3) (Stipp and Thompson, 1971; Heming, 1980b). Provided that this interpretation is correct, the age–space distribution of the back-arc basalts is clarified. These volcanics also younged to the southeast, consistently 130–150 km behind the andesitic volcanic front. Superimposed upon this trend, however, is one of increasing spatial distribution with time (Fig. 4). This pattern is one manifestation of the Neogene–Quaternary transition from compression to extension which accompanied and was achieved by the increasing subduction angle and decreased coupling of the Australia and underthrust Pacific Plate.

*Position of the northwest margin of the subducted slab*

From the geometry of the subducted slab through time (Fig. 7) one can simply establish the surface projection of the northwestern margin of the underthrust plate.

This margin together with the southwestern margin defines the progressive extent through the Neogene–Quaternary of the subducted Pacific Ocean lithosphere beneath North Island–northernmost South Island (Fig. 5). The southwesterly propagation of the subducted plate is entirely consistent with the direction of relative convergence for North Island latitudes determined from instantaneous poles of Pacific Plate rotation (Walcott, 1978a, 1979; Stock and Molnar, 1982). When the extent of the subducted slab is considered in the broader context of relative plate boundary displacements, it appears that the rate of southwesterly propagation is comparable with the rate of relative displacement across the plate boundary (Stock and Molnar, 1982). Indeed, the progressive subduction beneath northern New Zealand was largely contingent upon the southwest displacement of eastern South Island on the Alpine Fault; this progressively exposed a greater area of eastern North Island to converging Pacific Ocean lithosphere.

One concern of the early Miocene extent of the subducted slab might be that the rate of subduction was insufficient to emplace a slab beneath Northland by 18 My B.P. If subduction adjacent to New Zealand at the Kermadec Trench commenced 32 My ago, a slab could be emplaced by 20 My B.P. by averaging 5 cm/yr. The occurrence of Eocene volcanics on the Tonga–Kermadec Ridge (Coleman and Packham, 1976), and the occurrence of back-arc spreading in the South Fiji Basin from 32 to 25 My B.P. indicates that subduction adjacent to New Zealand was active by 32 My B.P. That 5 cm/yr is not an unreasonable rate is suggested by the half spreading rate of 2.2 cm/yr for the South Fiji Basin (Malahoff et al., 1982). It is possible, however, that the slab from which Tokatoka–Hukatere volcanics derived, travelled a shorter path and was subducted earlier than 32 My B.P. The directions of relative plate motion (Walcott, 1979) imply oblique subduction at the Kermadec Trench in the Neogene, and therefore it is likely that the slab at first beneath Northland was subducted further to the northeast along the Kermadec Trench; it followed a southwest path that took it obliquely beneath the Vening Meinesz Fracture Zone. This is an attractive option as the shallow subduction and attendant coupling in the vicinity of the Vening Meinesz Fracture Zone may have caused the inferred (Brothers and Delaloye, 1982) obductive modification of this structure. This mechanism would then explain the striking temporal but not spatial coincidence of arc volcanism with the emplacement of ophiolites (Fig. 4).

#### IMPLICATIONS

The principal objective of this paper, to establish the extent and geometry of the subducted Pacific Plate beneath North Island, is illustrated in Figs. 5 and 7. This has been achieved by appealing to the volcanic geology of northern North Island, and has required reinterpretation of the radiometric age pattern. Given that the geometry of the subducted slab is a principal influence upon the state of stress and deformational style within the overriding plate (Cross and Pilger, 1982; Jordan et al., 1983),

the opportunity now exists to test whether the timing, nature and broad pattern of Kaikoura tectonics of North Island can be explained by this concept.

From Fig. 5 it is clear that the southern parts of the North Island did not become influenced by the subducted slab until the early Pliocene. The slab is still dipping beneath this region at a comparably shallow angle of  $15^\circ$  (Smith, 1979). Significantly, vigorous subsidence, amounting to 4000 m in the Wanganui Basin (Ander-ton, 1981), affected most of this region from the early Pliocene. It is also noticeable that the Taupo Volcanic Zone has not extended into this region of shallow subduction. Both the absence of volcanism and the strong subsidence are attributed to exclusion of the mantle wedge by the low angle subduction, as confirmed by moderately high  $Q$  values (Mooney, 1970). Exclusion of the mantle wedge permitted the thickness of the less dense lithosphere beneath the Wanganui Basin to effectively double and as a consequence the lithosphere subsided by isostatic adjustment. Barazangi and Isacks (1976), Cross and Pilger (1978) and Sachs (1983) have previously explained the absence of volcanism and the occurrence of regional subsidence in flat plate subduction settings in terms of exclusion of hot asthenosphere. The late Pliocene–Pleistocene uplift of southeastern North Island, now within the plate-boundary zone, is attributed to the effects of oblique subduction and consequent compression and transcurrent displacements (Walcott, 1978a; Kamp, 1982).

Northern North Island was first influenced by shallow subduction in the early Miocene, and by the Pliocene there had been a significant steepening of the subducted slab beneath this region. By analogy with the shallower segments of subduction beneath South America, the expected early Miocene geotectonic features would include: basement involved foreland deformation, sporadic volcanism distant from the trench, and thrusting adjacent to the trench. With slab steepening, one would expect more vigorous arc volcanism, a transition to extension behind the volcanic front with the eruption of back-arc basalts, and vertical crustal movements.

These features fit very well with the Neogene–Quaternary tectonic pattern of northern North Island. In the foreland region of Northland–Auckland, mesoscopic low angle thrust faults in the basal Waitemata sequence (Late Oligocene–early Miocene), but also involving the underlying Mesozoic basement, give NW–SE compression directions (Spörli, 1982) consistent with the inferred direction of slab subduction (Fig. 5). Extension axes from conjugate normal faults also in the Waitemata sequence, dike trends in the Miocene volcanics, and vent alignments in the Quaternary back-arc basalts, all indicate a change to NW–SE extension from the mid-Miocene to the present (Spörli, 1982). The transition to extension appears to have accompanied the development of a vigorous andesitic arc. The late-early Miocene initiation of slab steepening permitted a wedge of asthenosphere to be inserted beneath northern Northland, thus partially melting the subducted crust and giving rise to the orogenic volcanism. A secondary and delayed effect of the intrusion of a hot wedge of asthenosphere, and the crustal intrusion of the generated

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magmas, was the thermal expansion and isostatic uplift of western Northland. This explains the mid-Miocene regional uplift and regression of western Northland–Auckland (Hayward, 1979). During the mid and late Miocene and Quaternary, back-arc basalts were erupted above the mantle wedge (Heming, 1980a, b).

Between Auckland and the Taupo Volcanic Zone, there is no documented evidence of pre-volcanic crustal shortening, but a well established pattern of north and northeast trending normal faults (Kear, 1960; Schofield, 1967) defines a basin-and-range topography which together with the back-arc basalts (Briggs, 1983) indicates substantial crustal extension. The vertical displacements of mid-Miocene strata in the South Auckland region, and the Plio-Pleistocene age of terrestrial sequences infilling the down-thrown basins (Todd, 1982), together suggest that crustal extension accompanied and followed the migration through this region of the volcanic front. This extension is consistent with the intrusion of a hot mantle wedge and with thermal expansion followed by gravitational collapse.

Between the Taupo Volcanic Zone and the Hikurangi Trench there is extensive evidence of early-mid Miocene thrusting; decollement and obductive emplacement of ophiolites (Stonley, 1968; Brothers and Delaloye, 1982). These events corresponded with the initial interval of flat plate subduction. In the Quaternary the Raukumara Peninsula has undergone rapid uplift and normal faulting, consistent with a steeper slab dip and the presence of a thin upper mantle high-frequency attenuating zone (Haines, 1979).

In conclusion, there appears to be a close relationship between the nature and pattern of Kaikoura tectonics, and the extent and geometry of the subducted Pacific Plate beneath North Island. This applies especially to northern and western parts of the island, as southeastern North Island has responded to the additional influence of oblique subduction. Both the trend for the shallowly subducted slab to increase its extent beneath North Island with time, and for the dip to increase with time where the slab was first emplaced, need to be considered in relating the geometry of the slab to the nature and pattern of Kaikoura tectonics.

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Cross-referencing to thesis papers

Kamp, P.J.J. 1982, is equivalent to paper 2.

## PAPER 7

A proposed seafloor spreading and subduction origin for the  
geophysical anomalies and igneous bodies off the west coast, North  
Island

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A PROPOSED SEAFLOOR SPREADING AND SUBDUCTION ORIGIN FOR THE GEOPHYSICAL ANOMALIES AND IGNEOUS BODIES OFF THE WEST COAST, NORTH ISLAND.

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ABSTRACT

Possible origins of the igneous bodies off the West Coast of the North Island revealed previously by geophysical surveys, are considered in the context of the wider Cenozoic geotectonic development of New Zealand. First it is shown that the NW-SE trending anomaly sources north of Manukau Harbour cannot be genetically related to the Miocene andesites and basalts onshore in western Northland, as earlier proposed, chiefly because the onshore subduction related frontal arcs were oriented NE-SW. An alternative rift origin is developed which shows that the offshore igneous bodies are of the correct age and position to be incipient seafloor spreading volcanics within the axial trough of a mid-Cenozoic western rift system.

The geophysical character together with limited geologic data of the anomaly sources in the southern field indicate that they may have a dual origin. At least some of these anomaly sources probably originated as

frontal arc andesites as the subducted Pacific Plate progressively extended to the southwest beneath northern New Zealand and concomitantly increased its dip; substantial intra-basement magnetic sources indicate that others have a rift or incipient seafloor spreading origin.

KEY WORDS

geophysical anomalies; West Coast; Cenozoic Volcanism; Northland; mid-Cenozoic rift system; Pacific Plate; Waitakere Group; ophiolites.

## INTRODUCTION

Aeromagnetic, gravity, and seismic surveys across the continental shelf west of North Island have shown large positive magnetic and gravity anomalies which are considered to represent igneous bodies of assumed Tertiary age (Davey, 1974; Hatherton *et al.* 1979) (Fig.1). The anomalies appear to be 10 times larger than those associated with onland volcanic centres. The offshore anomalies thus represent an immense but little known magmatic province. Since this province lies immediately north of the hydrocarbon productive Taranaki Basin, its detailed nature and age is of considerable importance to petroleum potential and exploration. It is also a major geologic element to be considered in any synthesis of the geotectonic evolution of northern New Zealand.

The origin and relationship of the igneous bodies to the adjacent onland geology has been considered by several workers. Hatherton *et al.* (1979) proposed a rift origin with no direct relationship to the onshore volcanics, whereas others (Ballance, 1976; Hayward, 1979) have proposed a subduction origin associated with the onshore orogenic andesites in western Northland. More recently Schofield (1983) considered the anomalies to be the roots of the allochthonous ophiolitic massifs of the Tangihua and Whangakea Volcanics. This notion conflicts with Brothers and Delaloye's (1982) evidence that these ophiolites were derived from the South Fiji Basin to the east of Northland.

Clearly, the relationship of the geophysical anomalies to the geology of the North Island is controversial, a situation due largely to the paucity of compositional data. The objective of this paper is to re-evaluate the relationship of the offshore magmatic province to the onshore geology in view of the identification of a mid-Cenozoic continental rift system through

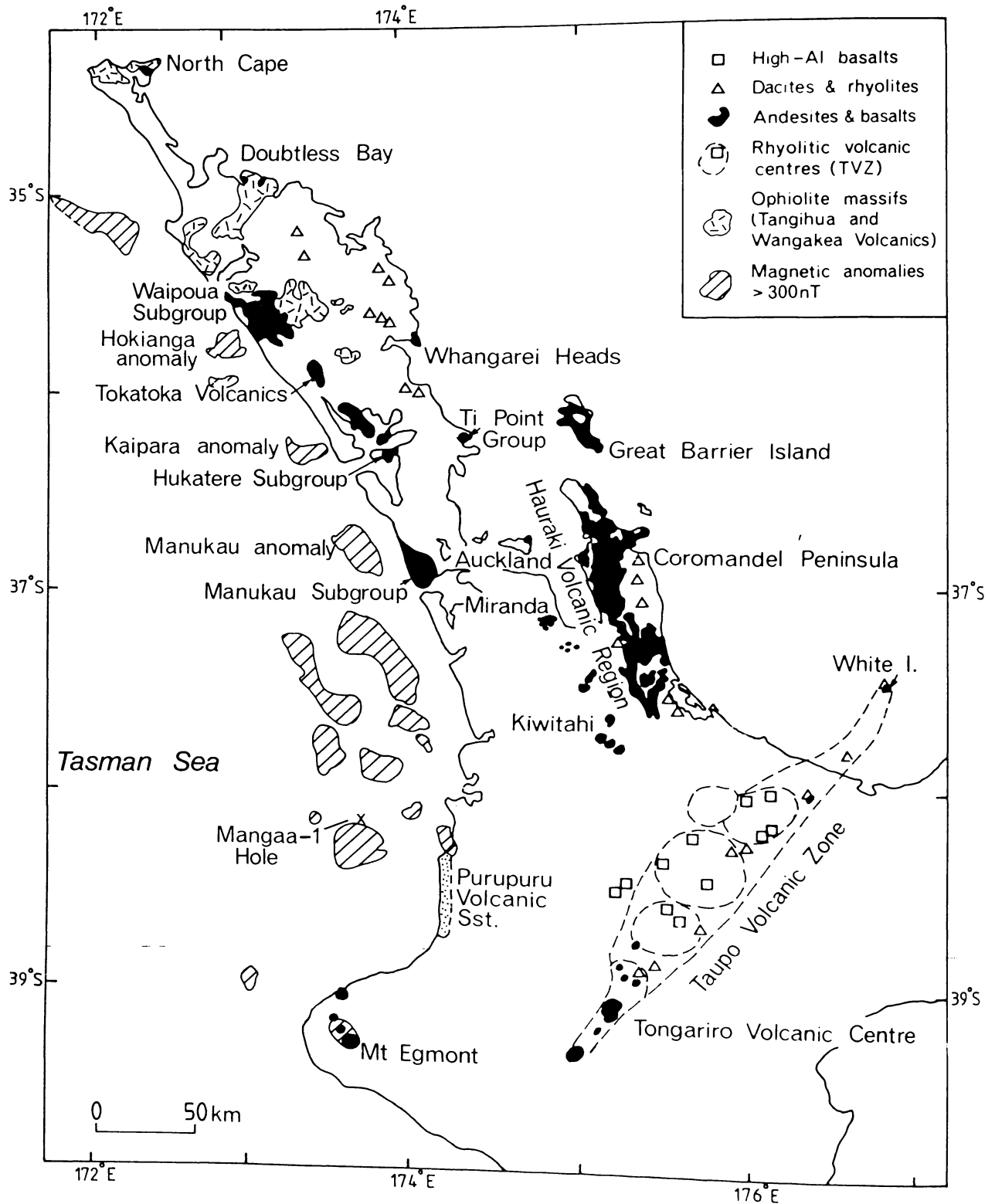


FIG.1. Map showing the position of the offshore geophysical anomalies in relation to the distribution and composition of some onland volcanics. Distribution of geophysical anomalies after Hatherton *et al.* (1979).

western New Zealand (Kamp 1984a), and in view of the recently established late Cenozoic extent and geometry of the subducted Pacific Plate beneath the North Island (Kamp, 1984b). It is suggested that the northern anomalies originated by incipient seafloor spreading, and that the southern anomalies originated by the interaction of subduction related volcanism with continental rifting.

#### DISTRIBUTION, COMPOSITION AND AGE OF THE OFFSHORE IGNEOUS BODIES

Apart from one offshore drill-hole (Mangaa-1 hole; Fig.1) which encountered late Miocene andesite, the only direct information available about these igneous bodies is provided by their geophysical character expressed by gravity, magnetic and seismic profiles (Davey, 1974; Hatherton *et al.*, 1979).

There appear to be distinctions between the anomalies to the north and to the south of Manukau Harbour. The northern anomalies are discrete and regularly spaced about 55km apart whereas the southern anomalies form a more dense pattern with a wider east-west distribution (Fig.1). The northern magnetic anomalies have associated gravity anomalies, while the southern ones do not. Hatherton *et al.* (1979) considered that the northern anomaly sources are almost flat-topped, of radius 10-15km, with steep flanks analogous to seamounts; the bodies are 5-6km thick with volumes in the range 1500-4000km<sup>3</sup>. All these features are suggestive of a basaltic composition. By comparison, the southern igneous bodies are deeper, having been buried 1-3km, and they probably have a more complex structure consisting of a very large body of intrusive material within the basement, as well as extrusive flows and volcanoclastics interbedded with sediments. Whereas the northern igneous bodies are up to 10 times the size of the onshore andesite volcano at Mt Egmont, individual bodies within the southern

anomaly field are of comparable mass to Mt Egmont.

The northern and southern anomaly sources also appear to have different ages. Davey (1974) inferred that the northern anomalies might be of early Miocene age because of their proximity to flows and volcanics in western Northland which have an early Miocene age obtained by radiometric and biostratigraphic means (Stipp and Thompson, 1971). More recently, Hatherton *et al.* (1979) have favoured a late Eocene age of inception of offshore volcanism. As evidence they cite the  $31.1 \pm 0.4$  My (middle Oligocene) age of the dolerite still encountered at 2.7km depth in the onshore Waimamaku-2 drillhole (Hornibrook *et al.*, 1976). Other evidence suggests that the large volcanic edifices had been constructed by the late Oligocene. Seismic profiles show highly folded sediments burying the landward side of the Hokianga and Kaipara anomalies. Onshore, these deformed beds are referred to the Northland Allochthon (Ballance and Spörli, 1979; Spörli, 1982), believed to have been emplaced during the late Oligocene (Waitakian Oppelezone).

Seismic reflection profiles and drillhole data suggest that the source materials of the southern anomalies were emplaced in the late Oligocene-Miocene. A seismic section across the Mangaa anomaly shows a prominent lower reflector of early Oligocene age to be broken and displaced, although a late Miocene-Pliocene reflector is only slightly distorted (Hatherton *et al.*, 1979). Knox (1982) shows a seismic section from the same vicinity and infers a latest-middle Miocene to late Miocene age of intrusion. This interpretation accords with the late Miocene age of an andesite lava at the base of the Mangaa-1 hole. That there was at least some middle Miocene andesite volcanism within the southern field has long been inferred from the andesitic composition of the Purupuru Volcanic Sandstone (Clifdenian - Waiauan Oppelezones) of the Mohakatino Group (Fleming, 1962; Hatherton, 1968).

CRITIQUE OF EXISTING IDEAS ON THE ORIGIN OF THE NORTHERN OFFSHORE IGNEOUS BODIES AND THEIR RELATIONSHIP TO ONSHORE VOLCANISM

Two contrasting hypotheses of the relationship of the offshore igneous bodies to the wider geotectonic evolution of North Island have thus far been proposed. The first considers that the igneous bodies are frontal arc and back-arc andesites derived from a slab subducted to the east of North Island (Ballance, 1976; Hayward, 1979); the second proposes a rift origin related to the formation of marginal basins to the north of New Zealand (Hatherton *et al.*, 1979).

Davey (1974) first identified the northern magnetic anomalies and drew attention to their proximity to onland exposures of the early Miocene Manukau Breccia and their probable similar composition. Based upon Hatherton's (1969) suggestion that the calc-alkaline andesites of western Northland derived from a Benioff Zone, Davey (1974) suggested that the offshore igneous bodies also had a subduction related origin. Subsequently, Ballance (1976) accepted the onshore - offshore correlation and developed a plate tectonic framework which had the onshore and offshore volcanics as a Waitakere Magmatic Arc, the first of a series of Neogene migratory arcs preceding the present active NE-SW trending Taupo Volcanic Zone. Hayward (1979) examined more closely the eruptive history of the Waitakere Group (of Ballance *et al.*, 1977). He presented data which aimed to show that the offshore igneous bodies were the buried products of the main eruptive centres of a Waitakere Volcanic Arc. The importance of Hayward's (1979) contribution is that by apparently relating the onshore volcanics to the larger offshore igneous bodies the credibility of a NW-SE oriented volcanic arc was strengthened to the extent that it came to be regarded as a constraint on the position and orientation of the Australia - Pacific Plate boundary. Consistent with the orientation of the Waitakere Arc, Hayward

(1979) suggested that the trench lay east of Northland and parallel to the coastline. In determining the broader plate tectonic setting, Cole and Lewis (1981) accepted and extended the notion of a trench east of Northland, and in a revised model Ballance *et al.* (1982) maintained the notion of a NW-SE oriented Waitakere Arc.

The proposition that the northern igneous bodies form part of a Waitakere Arc has been challenged by Hatherton *et al.* (1979). They reasoned that the anomaly sources are not suggestive of arc volcanics, and that they are probably older than the onshore volcanics.

That the offshore northern igneous bodies were not part of a NW-SE oriented Waitakere Arc is also evident from a re-interpretation of the pattern of Neogene volcanism in northern North Island. Kamp (1984b) demonstrates that the published radiometric dates of the northern North Island orogenic andesites indicate a NE-SW orientation of the volcanic front and a trenchward migration parallel to the presently active Taupo Volcanic Zone. This is corroborated by broad compositional trends and  $K_2O-h$  data of the depth of magma generation. This pattern is explained by a model involving a progressive increase in the southwestern extent of the Pacific Plate which underthrusts the North Island, and by a concomitant increase in the subduction angle.

The NE-SW orientation of the frontal arcs in northern North Island conflicts with the NW-SE orientation of a Waitakere Arc. Moreover, the offshore igneous bodies cannot all relate to a single onshore volcanic arc. Since the northernmost frontal arc trended through Tokatoka and Whangarei Heads, there is a possibility that the southern anomalies of the northern field still originated as subduction related volcanics. However, the geophysical arguments summarised earlier argue against this option.

The Waipoua Subgroup is the only onshore volcanic centre for which a direct connection can be claimed with an offshore geophysical anomaly (Davey, 1974), and deserves closer examination. The Waipoua Basalts are an exception in the steepening slab model (Kamp, 1984b) because of their slightly younger age but more northern occurrence. Wright and Black (1981) drew attention to the many petrologic differences between the Waipoua Basalts and the rest of the Waitakere Group. Kamp (1984b) briefly discussed the petrologic similarities with the late Miocene and Quaternary back-arc basalts (Heming 1980 a, b), and suggested that these are older (16-15 my B.P.) and more northern tectonic equivalents of the previously oldest back-arc basalts identified: the 8.44 my B.P. Ti Point Group (Stipp and Thompson, 1971). Hence the Waipoua Basalts are not arc volcanics, but were erupted 150km behind the coeval Manukau Arc. That the offshore Hokianga anomaly source may also have a back-arc origin would not be consistent with its older age as discussed earlier. Moreover, Wright (1980) considered on the basis of her field mapping that there was only a spatial coincidence between the two volcanic centres.

Hatherton *et al.* (1979) considered on balance that the northern anomalies represented rift volcanics. Some supporting evidence was noted by them but not discussed in detail. The concept that the northern anomalies originated by incipient seafloor spreading is now explored with wider consideration of New Zealand's Cenozoic geology.

#### THE NORTHERN ANOMALY SOURCES: INCIPIENT SEAFLOOR SPREADING VOLCANICS

An analysis of the structure and sedimentary geology of onshore and offshore western New Zealand has recently identified the middle Eocene to Miocene occurrence, and development, of a 1200km long and 100-200km wide continental rift system (Kamp, 1984a) (Fig.2). The evidence for this rift

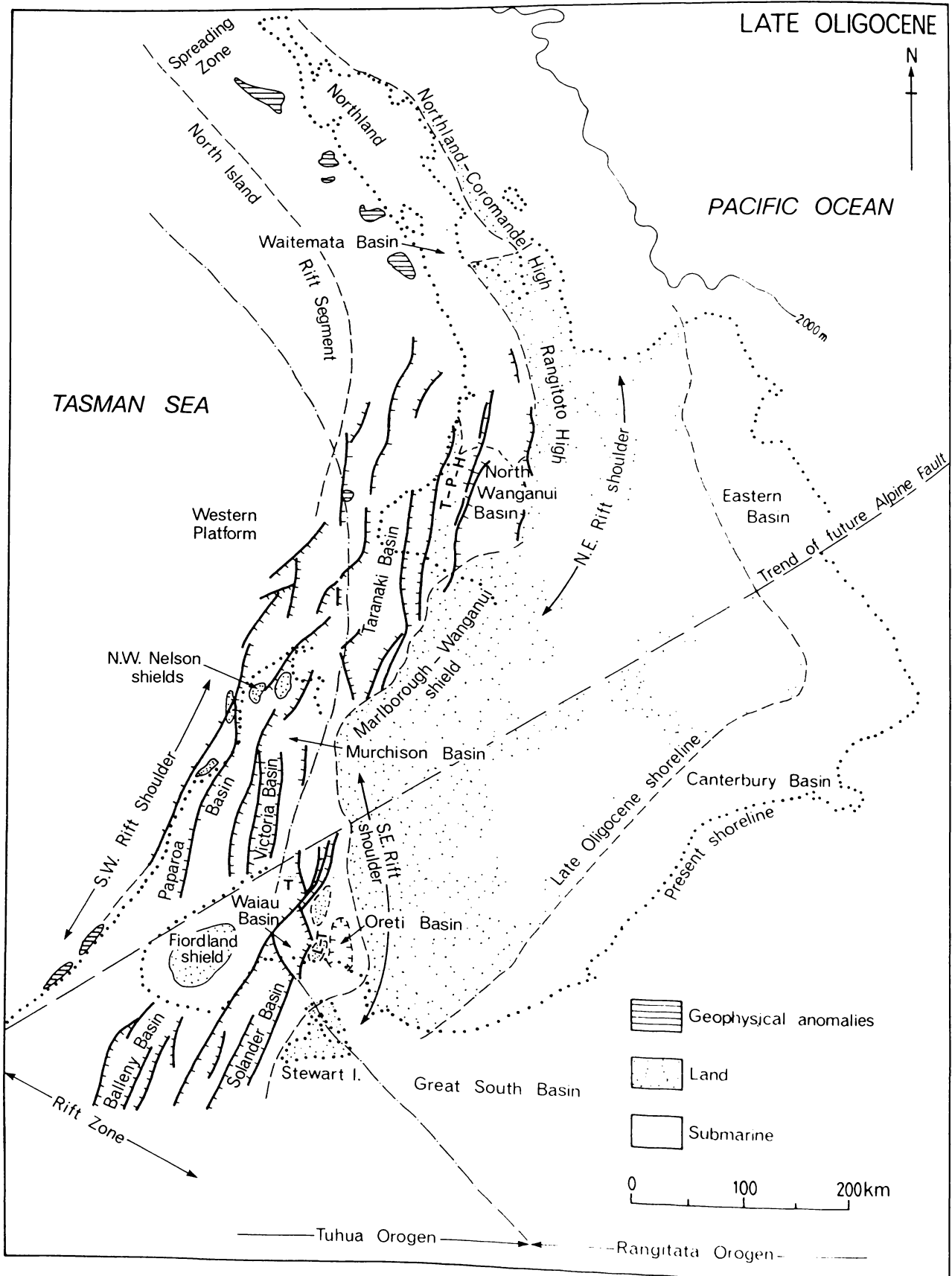


FIG.2. Map of the late Oligocene distribution of basins and structural highs comprising the rift system through western New Zealand. Note the position of the geophysical anomalies collinear with the rift. Apart from the identification of the rift shoulder in eastern Northland - the Northland - Coromandel High - it is not possible yet to identify the rift structures in Northland because of the pervasively deformed Cretaceous - Paleogene sequence. Perhaps the rift trough was the hole into which the allochthon was emplaced. Abbreviations; T, Te Anau Basin; L-T, Longwood - Takatimu High; T-P-H, Tongaporutu - Patea - Herangi High. Figure after Kamp (1984a).

system is based on the occurrence of a zone of interconnected normal fault-bounded troughs and half grabens in which accumulated 2-4km of sediments consistent with the development of modern rifts and continental margins in the early stages of passive margin development. From the extent, dimensions, and stratigraphy of these basins, and by comparison with models of rift propagation, it can be shown that the rift system comprised a northern and a southern segment, and that rifting propagated from both the north and south towards NW Nelson. Near the Oligocene-Miocene boundary the Alpine Fault was incepted and the South Island segment of the rift system became dislocated and subsequently overprinted by compressional tectonics. In the North Island rift segment, further from the plate boundary (i.e., the Alpine Fault), rifting persisted into the middle Miocene until it became influenced by the penetration beneath this region of the subducted slab of Pacific Ocean crust. It is argued below that the location and late Eocene-Oligocene age of the northern anomaly sources fit very naturally into the concept of a mid-Cenozoic continental rift system through western New Zealand.

In normal continental rift settings, seafloor spreading follows the extended rift phase of rifting (eg. Boillot, 1978; Curray, 1980). At any one time this temporal sequence can be observed along the trend of a developing plate boundary as a spatial sequence from seafloor spreading to incipient rifting (Vink, 1982). The development of the section of the North Island rift segment between Port Waikato and Nelson has been referred to the three phases of continental rifting which usually precede seafloor spreading (Kamp, 1984a).

A 15my interval of intra-rift subsidence and sedimentation (phase 1) in a broad zone east of the Taranaki Fault occurred between the late Paleocene and late-early Oligocene. In the early-middle Oligocene south of Awakino, but probably during the Eocene to the north, the Taranaki

Basin began to rapidly subside between its boundary faults, marking the transition to phase 2 in which an axial trough was clearly defined. Because of the creation of an unsupported margin at the Taranaki Fault and its northern extension, the eastern shoulder of the rift collapsed into an extended zone of half grabens and tilt blocks (phase 3). There was clearly a southward migration of the collapse of the eastern rift shoulder; it occurred during the late Eocene and Oligocene between Port Waikato and Awakino, and during the early and middle Miocene between Awakino and Ohakune where the North Wanganui Basin formed.

The identification of the extended phase of rift development during the Oligocene south of Port Waikato is important in so far as it predicts, by comparison with models of rift propagation (Vink, 1982), the introduction of oceanic crust within the rift axis in the region to the north. Not surprisingly, the northern magnetic anomaly sources are of the right age (late Eocene-Oligocene) and position to have been derived by seafloor spreading in the section of the rift north of the extended-rift section. The isolated and regular spacing of the anomalies suggests that they represent the incipient introduction of oceanic crust, and that the rift system did not develop into a full spreading centre.

In support of this origin of the northern anomaly sources is the inferred Oligocene age of active seafloor spreading in the back-arc Norfolk Basin immediately north of the rift system.

#### RELATIONSHIP OF THE NORTHERN ANOMALY SOURCES TO NORFOLK BASIN SPREADING

A rift and seafloor spreading origin of the Norfolk Basin has been consistently favoured by many workers (Coleman and Packham, 1976; Crook and Belbin, 1978). Davey (1977; 1982) has presented marine seismic

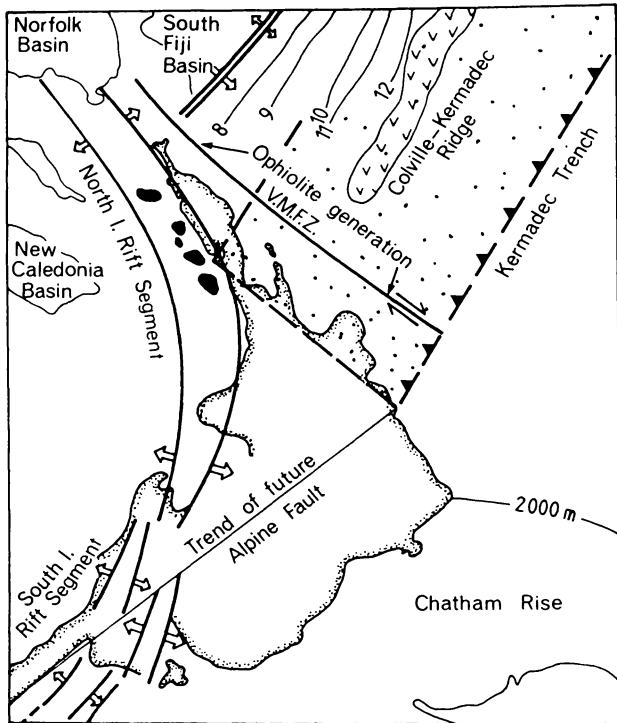
reflection profiles showing the rifted basement morphology of both the western and eastern margins of this basin. Unfortunately, there is no direct data on the age of Norfolk Basin seafloor spreading as the subdued magnetic anomaly pattern (Malahoff *et al.*, 1982) has not yet been analysed. In the absence of such information, the age of this basin has been inferred from tectonic models based on the age and structure of the South Fiji Basin for which the magnetic anomaly pattern is well established (Watts *et al.*, 1977; Malahoff *et al.*, 1982).

Existing plate tectonic models of the evolution of the marginal basins to the north of New Zealand (Crook and Belbin, 1978; Davey, 1982) postulate that formation of the Norfolk Basin was contemporaneous with formation of the South Fiji Basin. The Norfolk Basin appears to have formed by back-arc spreading to a Three Kings Rise Arc, itself related to subduction of the eastern plate of the South Fiji Basin spreading centre (Ballance *et al.*, 1982; Davey, 1982). If this origin is correct, it implies an Oligocene age of Norfolk Basin spreading from the An13 to An7 magnetic lineations in the South Fiji Basin. Davey (1982) has presented two possible models of the relationship between the development of the South Fiji Basin - Norfolk Basin and northern New Zealand. In his model 'b' the Norfolk Ridge is displaced westwards relative to New Zealand along the Vening Meinesz Fracture Zone, and minor rifting is proposed in the eastern south New Caledonia Basin. This model also requires extensional movements through western New Zealand during the Oligocene. His model 'c' assumed displacement of the Norfolk Ridge before the Oligocene, and thus implies a pre-Oligocene age of the Norfolk Basin. On balance Davey (1982) favoured model 'c' because of the "...requirement ...for subduction in the Lord Howe Rise - Norfolk Ridge section or large scale extension through New Zealand in the Oligocene, for which there is little evidence ..." In view of the recent documentation of evidence for active late Eocene - Oligocene

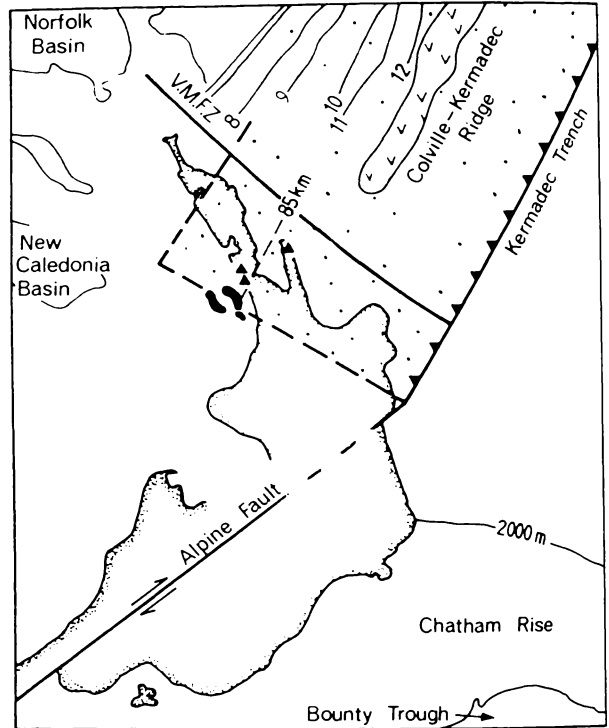
rifting through western New Zealand (Kamp, 1984a), model 'b' is now considered to offer a better relationship between the tectonic evolution of northern New Zealand and the Melanesian borderlands. This model would have Norfolk Basin spreading at the same time as active rifting in western New Zealand. The northern anomalies lie between the sections of active seafloor spreading and active rifting, a position utterly consistent with an origin as incipient seafloor spreading volcanics.

#### THE SOUTHERN ANOMALY SOURCES: A POSSIBLE DUAL ORIGIN INCLUDING FRONTAL ARC ANDESITES

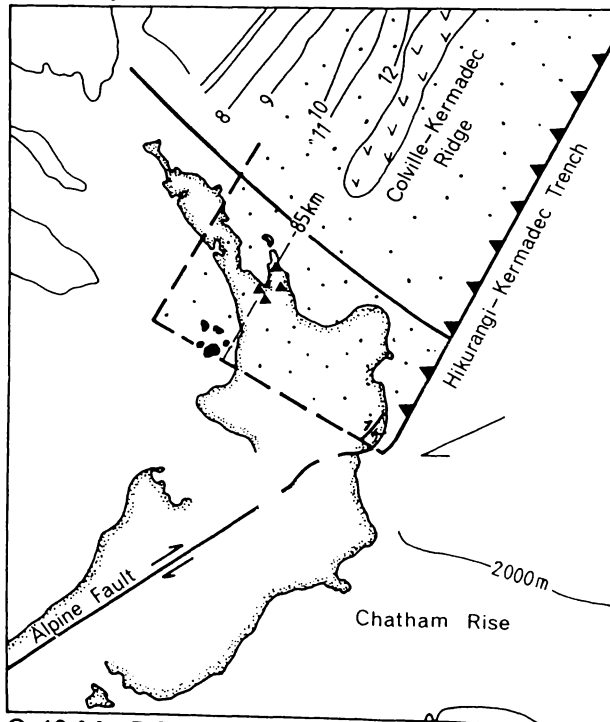
The southern anomaly sources also occupy an axial location within the rift system. However, their different geophysical expression and the evidence that at least some of them are andesitic and of late Miocene age, suggests that not all have the same origin as the northern anomalies. Ballance (1976) classified these offshore volcanics characterised by the andesitic detritus in the Mohakatino Group as behind-arc andesites derived from deeper levels of the subducted slab involved in the Northland and Coromandel frontal arcs. As an alternative to this origin, and in the context of the NE-SW oriented Neogene arcs in the North Island of Kamp (1984b), it is proposed that some of the anomaly sources are frontal arc andesites derived from the leading edge of the subducted slab as it progressively extended southwestwards beneath northern New Zealand. Fig.3 summarises the extent of the subducted slab through the late Cenozoic. With the exception of the Mangaa-1 occurrence of late Miocene andesite (Fig. 3C), the estimated extents of the slab at the respective times are based on the distribution and age of the onshore andesites. Fig.3A shows that during the late-early Miocene the subducted plate started to penetrate beneath the rift system. By 15 my B.P. the frontal arc had migrated to the Manukau centre; the more northern of the southern anomaly sources



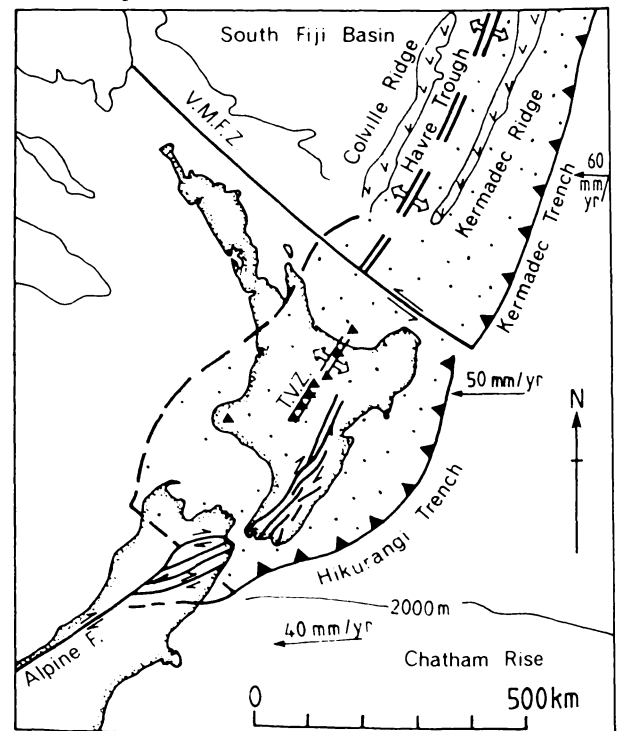
A. 23 My B.P.



B. 15 My B.P.



C. 10 My B.P.



D. Present

FIG.3. A series of four maps showing the extent (by dots) of the subducted Pacific Plate projected on to the overriding Australia Plate in relation to the position and inferred age of the offshore igneous bodies. The base maps in B, C, and D, giving the extent of the subducted plate and the 85km depth contour to the Benioff Zone, are after Kamp (1984b). Note how the southwestern extent of the subducted slab increases with time as the Pacific Plate is dextrally displaced on the plate boundary. Seafloor magnetic anomalies 8 through 12 in the South Fiji Basin are from Malahoff *et al.* (1982).

may have been emplaced at this time having derived from a similar depth (85km) but along strike to the southwest (Fig.3B). By 10 my B.P. the dip of the subducted slab had further steepened and the frontal arc had migrated trenchward and concomitantly extended further to the SW; the more southern anomaly sources may have been emplaced at this time and derived from 85km depth also. Although it is not clear what part the subducted crust plays in the source of andesitic melts, it is widely acknowledged that the subducted slab contributes in some way to the generation of these melts (Gill, 1981). In the offshore West Coast setting the generation of andesitic melts might be expected to have been promoted by the dynamic instabilities created as the southwestern plate edge laterally penetrated the mantle. Perhaps the greater degree of instability created at this plate edge explains the greater size of the offshore igneous bodies compared with the frontal arc andesites onshore (Hatherton *et al.*, 1979).

At present there is little evidence available to support the hypothesis that the southern anomaly sources contain frontal arc products which young to the south. The model is constrained by the late Miocene andesite flow in the Mangaa-1 hole referred to earlier. That some andesites as early as 15 my B.P. erupted offshore is shown onland by the mid-Miocene Purupuru Volcanic Sandstone. The facies distribution of the andesitic component of this formation indicates a more northern source than their present outcrop, but they cannot have derived from as far north as the Manukau centre, the nearest active onshore source at the time of this formation's deposition.

There is a possibility that the southern anomalies have a mixed origin - that the component of the magnetic anomalies indicative of intra-basement intrusives, referred to by Hatherton *et al.* (1979), have a different composition and origin to the andesitic flows and volcanoclastic detritus

within the Tertiary succession. The early and middle Miocene persistence of extension and subsidence within the central-western North Island section of the rift system suggests that some late Oligocene - early Miocene incipient seafloor spreading was possible within the Taranaki Basin. The frontal arc volcanism may subsequently have dominated in the middle and late Miocene. A dual origin of the southern anomaly sources is perhaps important to consider and test in future investigations.

The eruption of andesites through a continental rift is an unusual occurrence and these rocks should have a distinctive petrologic character. One effect of a frontal arc migrating into a rift system is that this is a region where the crust has been considerably thinned by crustal stretching. Cochran (1983) estimated for the Red Sea rift that 130% of crustal extension preceded the introduction of oceanic crust. The thinning and fracturing of the crust will undoubtedly facilitate the upward passage and eruption of subduction related volcanics, just as these crustal structures permit the intrusion of dikes and ultimately ocean floor basalts in simple rift settings. This factor may also partly explain the greater volume of the igneous bodies offshore compared with the tectonically equivalent andesites onshore.

#### IMPLICATIONS FOR NORTHLAND'S PALEOGENE VOLCANIC GEOLOGY

The preceding sections have indicated there is a juxtaposition of seafloor spreading volcanics with younger onshore frontal arc and back-arc volcanics. Since the rift system encompassed western Northland, one might expect to find there some related late Eocene - Oligocene igneous bodies.

Nepheline bearing basaltic dikes and flows with K-Ar dates between 39

and 11 my B.P. have been reported from 7 localities in Northland (Black and Brothers, 1968; Taylor, 1980). The small volumes of these undersaturated and saturated basaltic rocks have been interpreted by Heming (1980a) as the remnants of formerly more extensive volcanic fields of similar petrographic character to Northland's Quaternary back-arc volcanics. While the implied back-arc setting may well have been the case for the youngest of these dikes (11-12 my B.P. Todds Quarry and Hukutere localities; Black and Brothers, 1968; Stipp and Thompson, 1971), it does not explain those of Paleogene age which predate the early Miocene age of the earliest calc-alkaline volcanism (Wright and Black, 1981). Nevertheless, Taylor (1980) considered that by comparison with the tectonic regimes and petrogenetic histories of other global occurrences of nephelinites, the late Eocene and Oligocene dikes and flows in Northland were emplaced within an extensional tectonic setting. Accordingly, it is proposed that the Northland nephelinites and the 31 my B.P. dolerite dike in the Waimamaku-2 drillhole (Hornibrook *et al.*, 1976) are remnants of rift-associated magmatic activity marginal to the more voluminous extrusions in the axial part of the rift system a little further to the west.

In a recent attempt to reunify Northland's geology, Schofield (1983) proposed a novel relationship between the offshore igneous bodies and the Tangihua and Whangakea Volcanics. Based on his evidence of the eastwards translation of the serpentinites in central Northland, he suggested that the ophiolite massifs were derived from the offshore igneous bodies and transported eastwards. In his model the offshore igneous bodies and the onshore ophiolites are considered to have a subduction origin, the volcanic activity spanning the Cretaceous to Miocene. Schofield did not show or even discuss from where an oceanic plate was subducted to generate the arc volcanics. The idea of such a long-lived arc is difficult to accept in view of the major plate reorganisations in the SW Pacific during this

interval, including the separation of the New Zealand subcontinent from eastern Gondwanaland; a constant subduction orientation and geometry could not have been maintained throughout this time. Schofield's (1983) association of the offshore geophysical anomalies and the ophiolite massifs is here considered unlikely.

Brothers and Delaloye's (1982) transform fault origin of the ophiolites at the Vening Meinesz Fracture Zone and their westwards translation and disruption is preferred. In Fig.3A I show that these ophiolites were generated at the same time as the eruption of the northern seafloor spreading volcanics. However, and importantly, both of these igneous provinces were generated in association with marginal basin spreading, the Northland ophiolites with the South Fiji Basin and the northern seafloor spreading volcanics with the Norfolk Basin. Perhaps the rift trough involving western Northland provided the relief necessary to gravitationally slide and dismember the seamounts. In many ways the complexity of Northland's Paleogene geology can be explained by the intermediate position of this narrow peninsula between a fully developed rift system to the west and a major fracture zone to the east.

#### CONCLUSIONS

Little is known about the offshore igneous bodies other than their geophysical character. Nevertheless, a consideration of their ages and positions in the context of new ideas on the geotectonic development of onshore and offshore North Island enables one to evaluate existing hypotheses of their origin and to formulate new ones.

It is concluded that there is no genetic relationship between the

calc-alkaline volcanics onland in Northland and the offshore igneous bodies; a small but significant gap is considered to separate two magmatic provinces of different age and origin. A rift origin proposed by Hatherton *et al.*, (1979) is supported on the basis of the identification of a mid-Cenozoic continental rift system through western New Zealand which encompasses the northern anomalies, although they are specifically identified here as incipient seafloor spreading volcanics. This interpretation is consistent with Davey's (1982) model 'b' of the relationship of northern New Zealand to the Norfolk and South Fiji Basin. Correlatives of the offshore igneous bodies onland in Northland are to be found in the late Eocene and Oligocene small volume nephelinitic dikes and flows and the middle Oligocene dolerite dike at Waimamaku.

Although the southern anomaly sources erupted within the axial trough of the rift system, the occurrence of at least one late Miocene andesite flow offshore and the occurrence of middle Miocene andesitic detritus onshore are indicative of a different origin. The locations of these anomalies are consistent with their derivation as frontal arc volcanics produced by the progressive southwestward increase in the extent of the subducted plate and its concomitant steepening of dip. This origin applies to the flows and volcanoclastic detritus within the Tertiary succession, but it is possible that the intra-basement magnetic anomaly sources have a different origin akin to that of the northern anomalies.

#### ACKNOWLEDGEMENTS

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Cross-referencing to thesis papers

Kamp, P.J.J., 1984a, is equivalent to paper 1.

Kamp, P.J.J., 1984b, is equivalent to Paper 6.

## PAPER 8

Subduction geometry and its control on the Quaternary structure,  
volcanism and tectonics of northern New Zealand

To be submitted to: Tectonics

SUBDUCTION GEOMETRY AND ITS CONTROL ON THE QUATERNARY STRUCTURE,  
VOLCANISM AND TECTONICS OF NORTHERN NEW ZEALAND

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ABSTRACT The dipping seismic zone in the Mantle beneath northern New Zealand has previously been described as having a planar configuration. In part 1 of this paper this configuration is re-examined in view of the published results of microearthquake surveys of shallow subduction depths (< 50km) and some deep marine seismic reflection and refraction studies. It is proposed that the subducting slab is actually buckled in the general plane of subduction; the folds have a wavelength of 430km, and  $1\frac{1}{2}$  wavelengths occur beneath northern New Zealand. This interpretation is corroborated by spatial trends in (1) the boundary between the upper Mantle high frequency transmitting and absorbing areas, (2) the regional gravity anomaly contours, and (3), the heat flow patterns.

In part 2 of this paper I show how the variable dip of the subducting Pacific Plate coupled with evidence for the persistent retreat of the slab, have controlled the Quaternary volcanic, structural and tectonic development of the overriding crust. Two main

associations occur in the North Island: the region over the shallower dipping lithosphere is characterised by large magnitude ( $> 7$ ) earthquakes, a broad zone (300 km from the trench) of low heat flow values, basement-cored thrust deformation, and discontinuous andesitic volcanism 380km from the trench; the region of steeper dipping subduction involves an active andesite-dacite arc, bimodal back-arc volcanism, a normal heat flow pattern, and a foreland basin-and-range topography. It is proposed that the persistent retreat of the buckled slab causes upper Mantle flow towards the trench, and this in turn causes the crustal extension behind and in front of the frontal arc by way of drag on the base of the crust.

## INTRODUCTION

Geophysical and geological considerations indicate that the oceanic Pacific Plate is being actively subducted beneath the continental crust of northern New Zealand (Figure 1). This was first documented by Hatherton (1970a, b), who based it upon the occurrence of a dipping seismic zone and its North Island spatial associations with a structural trench (Hikurangi), an active calc-alkaline volcanic arc (Taupo Volcanic Zone - Mt Egmont), large gravity anomalies, heat flow anomalies and recent tectonism. More recently, this interpretation has been supported by geodetic data from the forearc region (Walcott, 1978a, b), and marine seismic reflection profiles of the trench slope off eastern North Island which show evidence for active subduction accretion (Lewis, 1980).

Adams and Ware (1977) have developed a laterally inhomogeneous velocity model to locate the hypocentres of subcrustal earthquakes recorded by the New Zealand seismograph network. From this study they have described the Wadati-Benioff Zone as having a planar configuration. This configuration is problematical in that certain geophysical and geological phenomena which normally parallel the strike of the dipping seismic zone appear to trend oblique to it as detailed below:

- (1) Between the latitudes of 39°S - 41°S a belt of large negative isostatic gravity anomalies (-50 to -160 mgals) diverges 30° west from the SW trend of the Hikurangi Trench and the strike of the inferred planar Wadati-Benioff Zone. Between 41°S and 43°S the same belt of gravity anomalies then trends southeastward across this planar zone towards the trench.

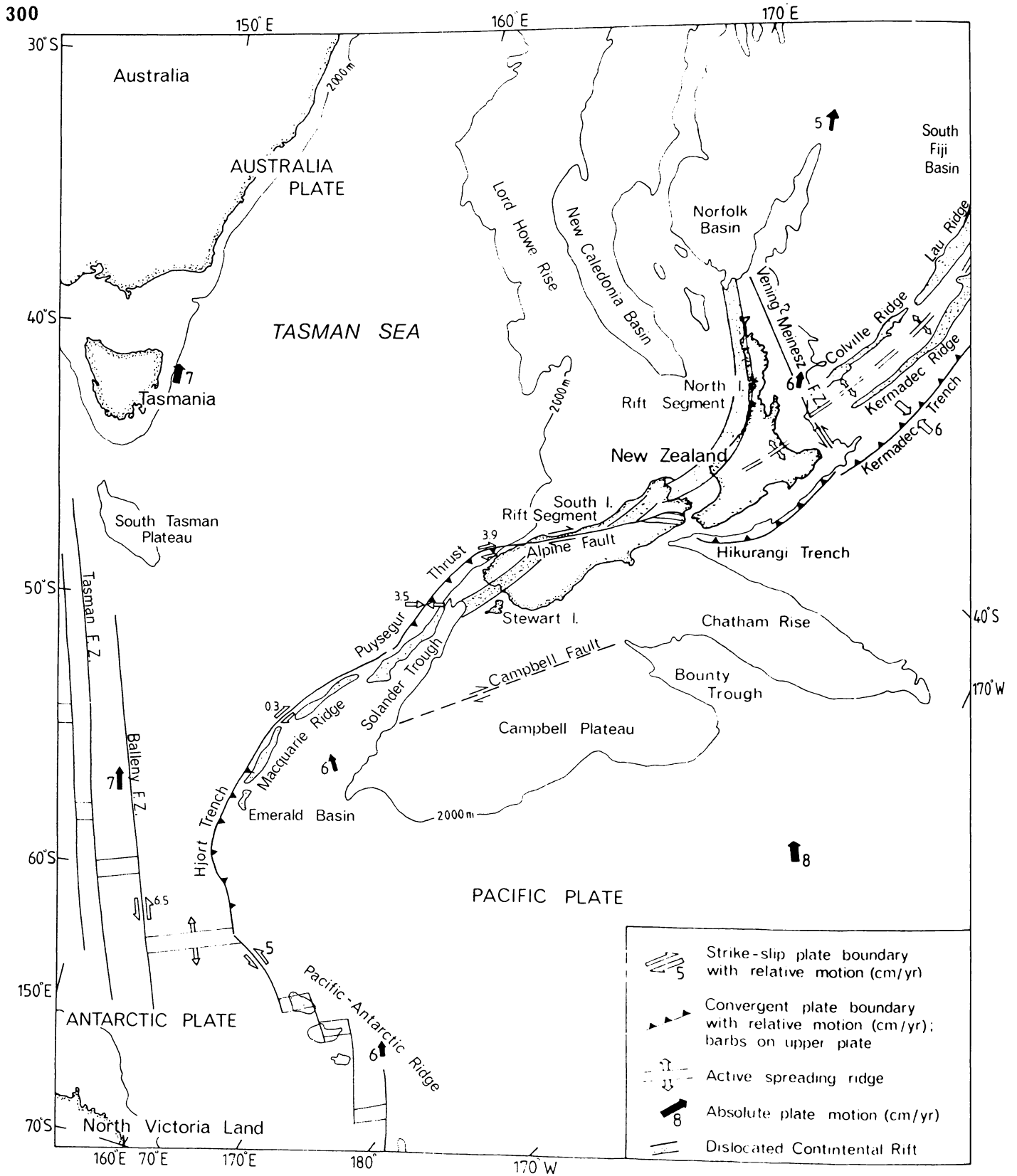


Figure 1 Plate tectonic map of New Zealand in the southwest Pacific region showing the location and character of the Australia-Pacific obliquely convergent plate boundary. Reproduced from the Plate Tectonic Map of the Circum Pacific Region - Southwest Quadrant (The American Association of Petroleum Geologists, Tulsa, U.S.A.).

(2) At 39°25'S the active frontal arc suddenly stops, despite the continuation of the dipping seismic zone for 350km and 3° of latitude further to the southwest. In addition, Mt Egmont, an active andesite volcano, occurs due west of the southern end of the frontal arc and at an anomalous distance of about 200km above the Wadati-Benioff Zone according to Adams and Ware's isobaths.

(3) The boundary between the upper Mantle high frequency absorption area (an intensified low velocity zone) and the high frequency transmitting area (Mooney, 1970) also diverges by 45°S from the trend of the dipping seismic zone and at a similar latitude to the other phenomena (1 and 2 above).

(4) Large variations in terrestrial heat flow over the North Island suggest that the isotherms trend obliquely to the strike of the planar Wadati-Benioff zone of Adams and Ware (1977) by a similar amount and in a similar direction to the other geophysical and geological observations.

From these discrepancies the question arises as to how these phenomena can be reconciled with the configuration of the subducting slab? A re-examination of the seismic data of Adams and Ware (1977) in the context of the more recently published microearthquake data, indicates that the dipping seismic zone most probably has a buckled morphology with a wavelength of 430km. One and a half wavelengths occur over the length of the Hikurangi Margin between the northern end of the Alpine Fault and the transition to the Tonga-Kermadec Margin. The changes in strike of the subducting slab inferred from the buckled morphology of the seismic zone correspond very closely to the changes in trend noted in 1-4 above.

From the buckled morphology of the subducting slab the Hikurangi Margin may be broadly partitioned into a northern section with a higher subduction angle, and a southern section with a lower angle. Regional differences in the short term stress patterns of the overriding crust, as determined by composite earthquake focal mechanism solutions and geodetic data, show that the zone of compression is broader over the shallower dipping southern section. These regional differences are also clearly expressed in the longer term (Quaternary) structural and volcanic patterns of northern New Zealand. The crust above the steeper dipping section is characterised by an active andesite-dacite arc, bimodal volcanism behind the frontal arc, a normal trench-foreland heat flow pattern, and the development of a foreland basin-and-range topography. In contrast, the shallower dipping southern section has a discontinuous andesite arc displaced 83 km further from the trench than the neighbouring arc segment, has low heat flow values up to 300km normal to the trench, and is characterised by a broad zone of basement-cored thrust deformation. Northern New Zealand appears to be a compact field example of the control of subduction geometry upon the structural and volcanic development of overriding continental crust.

This paper comprises two parts. First, a case is made for a buckled morphology of the subducting Pacific Plate. Second, I explore the effects the variable dip subduction coupled with retreat of the subducted slab have had upon the Quaternary structure and volcanism of northern New Zealand.

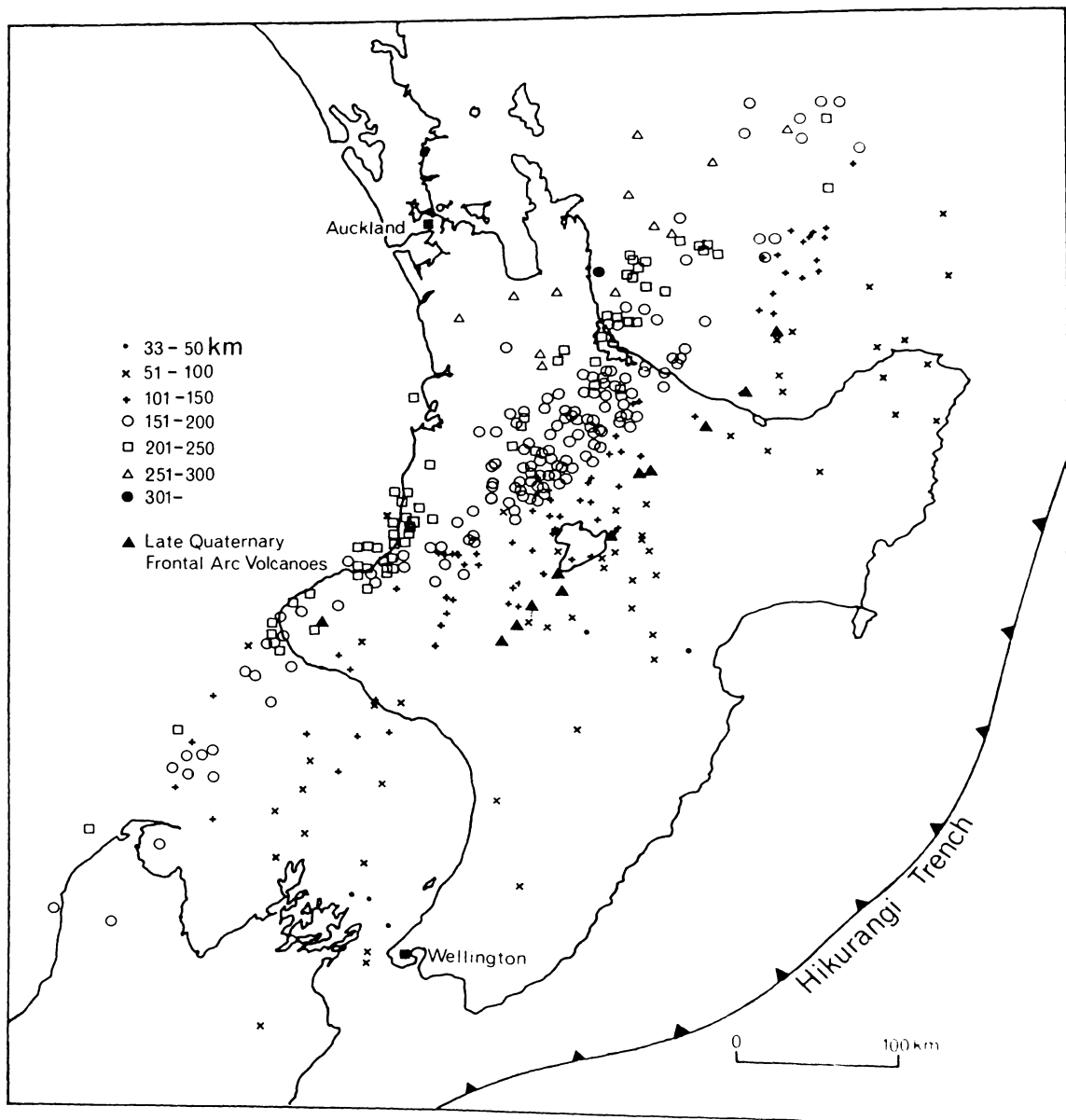


Figure 2 Intermediate focus earthquakes in northern New Zealand. Replotted from data in Adams and Ware (1977). Good quality earthquake epicentres only included (see text).

## THE DIPPING SEISMIC ZONE

### Location and distribution of earthquakes

The hypocentres of subcrustal earthquakes in New Zealand are routinely located using a laterally homogeneous velocity model from P and S phases received by a well spaced seismograph network. Because inconsistencies have become apparent in the locations allocated to the subcrustal earthquakes by this model (Robinson, 1976), Adams and Ware (1977) devised a laterally inhomogeneous velocity model in which velocities are increased (by 11%) along ray paths considered to lie entirely in the subducting plate. By comparison with the standard velocity model, solutions determined by the new model show a greater number of high-quality solutions with standard errors of 0.5s or less, but there is also an increase in the number of solutions with standard errors greater than 2s. Figure 2 shows the distribution of subcrustal earthquake foci determined by the new model by Adams and Ware (1977); only the more reliable locations based on readings at 5 stations, or more, with standard errors of 1.5s, or less, have been plotted in Figure 2.

The principal features of this distribution have changed little from earlier studies (e.g. Hamilton and Gale, 1968; Hatherton, 1970b). It shows a northeast-southwest trending zone of mantle seismicity that dips to the northwest and shoals to the southwest. The trend for intermediate depth earthquakes to be more frequent north of Lake Taupo (Figure 2) is also evident in pre-1970 seismic records (Dickinson and Adams, 1967; Hamilton and Gale, 1968). The main

effect of relocating the hypocentres by the new model is to shallow their depth and thus displace them to the northwest. From isobaths of seismic activity Adams and Ware (1977) considered that this produced an essentially planar Wadati-Benioff Zone, with a strike of  $N45^{\circ}E$  and dip of  $50^{\circ}NW$ . It is not clear how their isobaths, drawn at 50km intervals between 100-250km, were constructed and what they represent. That is, whether they are the depth to the middle or top of the seismic zone. The critical parameter for a study of subduction geometry is clearly the depth to the top of the subducting slab. How to identify this surface, or zone, and where it lies with respect to the dipping seismic zone is a universal problem.

#### A PLATE INTERFACE IN RELATION TO THE WADATI-BENIOFF ZONE

Soon after the concept of lithospheric subduction was proposed (Oliver and Isacks, 1967), Isacks and Molnar (1969, 1971) showed clearly from seismic focal mechanisms that earthquakes deeper than 70-100km originated from large stresses within the subducting plate, and that they could not be the result of shear displacement at the interface between the mantle and the subducting slab. This has subsequently been confirmed by numerous other studies where there has been tight control on hypocentre determinations, and, in particular, where there has been independent data of the seismic velocity structure. For example, using a seismic ray tracing method, Engdahl (1973) relocated the hypocentres of intermediate depth earthquakes caused by the Amchitka network in the Central Aleutians, and showed that the seismicity originated 13 to 23 km from the top of the slab, its position having been independently derived from travel-time

residuals and amplitudes originating from nearby nuclear explosions. Stefani et al. (1982) were able to make a direct measurement of the distance from an intermediate depth hypocentre in the Wadati-Benioff Zone of the southern Kuriles to the interface between the subducting slab and the overlying asthenosphere ( $38 \pm 5$  km) by identifying a low amplitude P wave reflection off the interface. The earthquake studied occurred in the lower layer of a double seismic zone. From this data and the distance between the two seismic zones they estimated that the upper layer of seismicity is within 15 km of the slab-asthenosphere contact. Shimamuro (1973, in Seno and Pongsawat, 1981) relocated earthquakes below the Kuril Arc by interpreting the secondary phase between P and S arrivals observed at a station in Hokkaido. In the 20-50 km depth range of the subducting plate, he located the hypocentres 10km below the plate interface. On the other hand, Hasegawa et al. (1981), using ScSp waves converted from ScS waves at the boundary of a sharp velocity contrast at the plate interface, located the thin upper plane of the double-planned seismic zone under northern Japan immediately below the plate interface in the depth range greater than 60km. Seno and Pongsawat (1981) have reconciled these two observations (Shimamura's (1973) and Hasegawa et al's (1981)) by showing that beneath northern Honshu at depths shallower than 60km, the upper plane of the double seismic zone occurs 10km below the plate interface, as detected by interplate thrust earthquakes, but that below 60km, the upper plane lies immediately below the plate interface.

From these Northern Hemisphere studies, one may conclude that, with the exception of interplate earthquakes of shallow depths, the dipping seismic zone lies predominantly within the oceanic crust of the subducting lithosphere at subduction depths greater than about 60km, but probably below the subducting crust at shallower depths. The practical importance of these conclusions is that they allow one to infer the position of the plate interface where no data other than the distribution of the dipping seismic zone are available. The precision with which the plate interface can be drawn above the intermediate and deep focus earthquakes will of course depend upon the quality of the hypocentre locations. This will also depend on several other factors including the period of observations (Barazangi and Isacks, 1976). Where there has been tight control over hypocentre determinations, such as those afforded by microearthquake surveys, the thickness of the Wadati-Benioff Zone is usually 7-8km (Hasegawa et al., 1981; Seno and Pongsawat, 1981; Ukawa, 1982). This thickness is remarkably close to the thickness of subducting oceanic crust (Pennington, 1983). However, the thickness of the seismic zone generally appears to be about 20-30km when the events are located teleseismically (e.g. Barazangi and Isacks, 1976; House and Jacob, 1983).

#### DEFINITION OF THE TOP OF THE SUBDUCTING PACIFIC PLATE THROUGH COOK STRAIT

During the last decade a permanent network of sensitive (microearthquake) seismographs has been operated in the Wellington

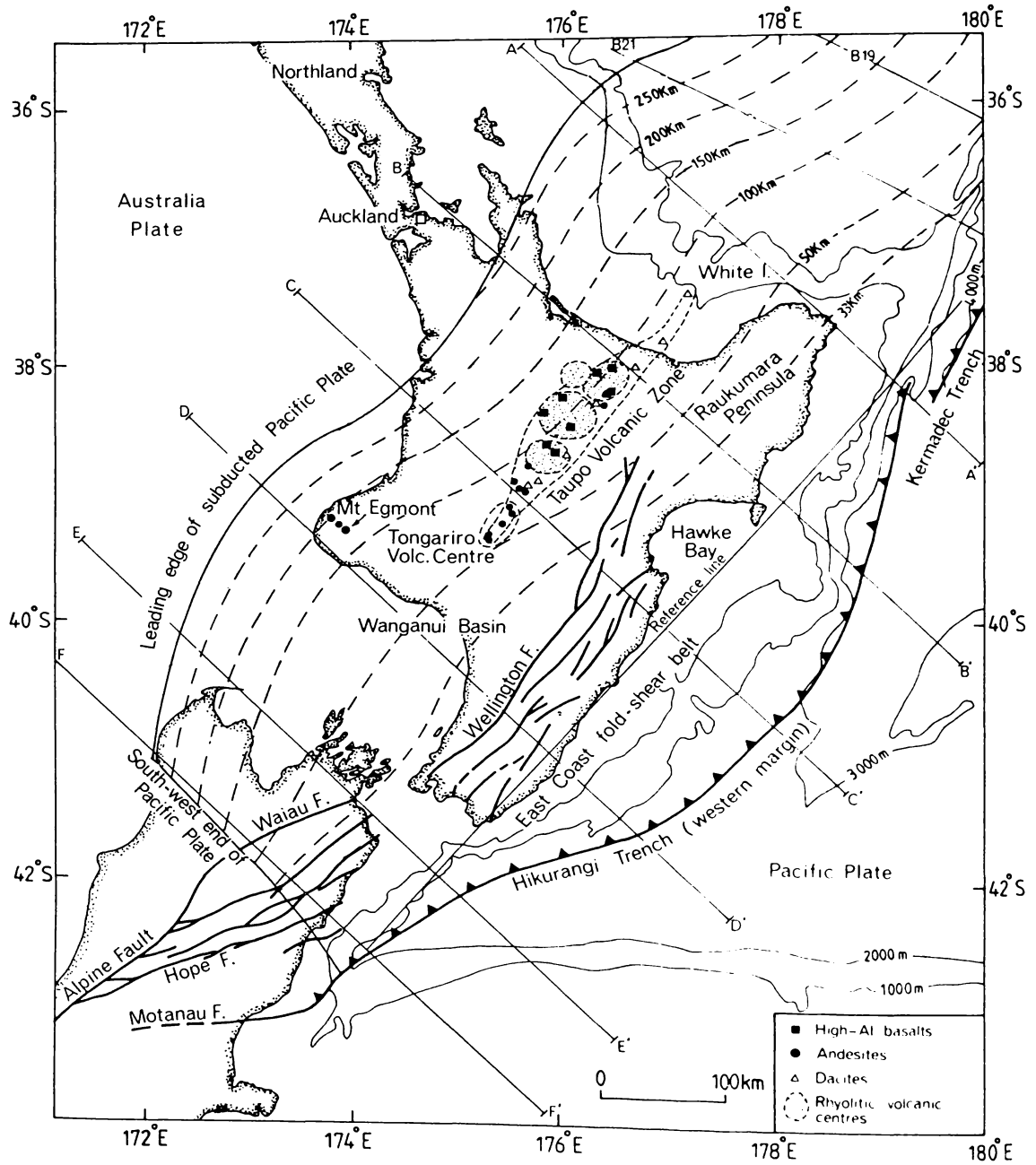


Figure 3 Map of structure contours drawn on top of the subducting Pacific Plate at 50 km depth intervals. Also shown is the position of the Hikurangi Trench and the location of the seismic sections shown in Figures 4 and 5.

region. In addition, marine seismic reflection and refraction studies have been undertaken along a traverse through Cook Strait and out to the Hikurangi Trench. Together, these studies have closely defined the top of the subducting Pacific Plate at shallow depths (< 30km) in a section (E-E') normal to the trench axis (Figures 3 and 4). They also show where the concentrated band of earthquake activity lies in relation to the plate interface. Such combined control is not available for the more northern sections across the Hikurangi Margin, although some microearthquake data are available.

Figure 4A shows the position of three deep reflecting and refracting interfaces beneath Cook Strait. From sonobouy refraction, variable angle reflection and vertical profiling seismic data obtained at the southern end of the Hikurangi Trench, Bennett (in press) showed that the interface a-a' dips 5°NW between a 7km thick deformed turbidite sequence and seismic basement. Bennett considered this interface to be the top of the subducting Pacific Plate, and the crust below it to comprise low velocity greywacke similar in composition to the crust of the overriding plate. In a more western seismic reflection-refraction study, Davey and Smith (1982, 1983) were able to identify two reflecting horizons (Figure 4A, b-b', c-c'). The main reflector (b-b') occurs at a depth of 20-25km below Wellington, and dips 15°NW, for the northwestern half of the profile, and 8° NW for the southeastern part of the profile. Since the eastern end of b-b' is closely aligned with the top of Bennett's seismic basement, it can safely be taken to delineate the interface between the plates.

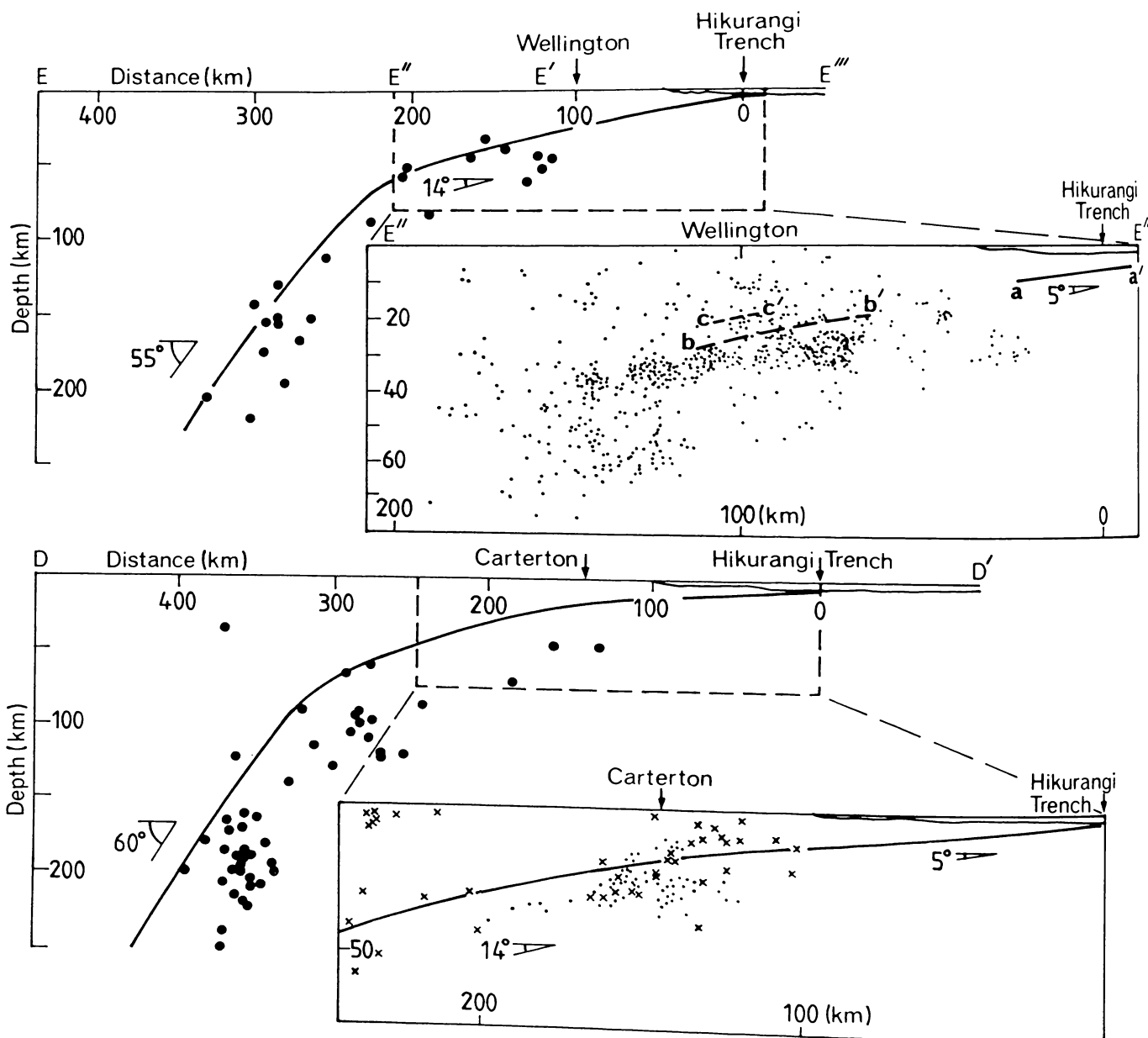


Figure 4 Two seismic sections normal to the Hikurangi Margin in southern North Island showing the relationship of micro-earthquake seismicity in the shallow subduction sections to the intermediate depth hypocentres and the adopted profiles of the top of the subducting Pacific Plate. In section E''-E''' the seismic interface a - a' is from Bennett (in press), and b - b' and c - c' are from Davey and Smith (1983). The sources of the microearthquake inserts, and the mantle seismicity are given in the text.

Importantly, as noted by Davey and Smith (1983), this interface lies nearly parallel with, and 5 km above, the top of the intense band of microseismic activity below the Wellington-Cook Strait region (Figure 4A). This situation is therefore analagous to the one in northern Honshu discussed earlier, where the seismicity at depths shallower than 60km lies within the subducting plate, but 10km below its top. The focal mechanisms of the Wellington-Cook Strait microearthquakes also support the position of the plate interface argued earlier from reflection-refraction studies. The mechanisms of shallow activity above the band of concentrated microseismicity are a mixture of strike-slip and thrust faulting, while the mechanisms within and below the concentrated band indicate normal faulting (Robinson, 1978). The thickness of the concentrated band of microearthquake activity (8-10km), in relation to its distance below the plate interface beneath Wellington (5km) and the average thickness of subducting crust (8km), suggests that the band of microearthquakes below Wellington probably originate at lower crustal and high subcrustal levels within the Pacific Plate.

In the Cook Strait region the concentrated band of microseismicity overlaps with the hypocentres of earthquakes shallower than 70 km relocated by Adams and Ware (1977) (Figure 4A). These intermediate depth hypocentres therefore originated within the Pacific Plate. This indicates that at deeper levels, the plate interface should also lie near the top of the hypocentre distribution, as shown in Figure 4A. Because the Wadati-Benioff Zone appears to be a little thicker (38km) than normal at these depths, suggestive of greater location errors, the plate interface has been drawn slightly within the band of earthquake hypocentres.

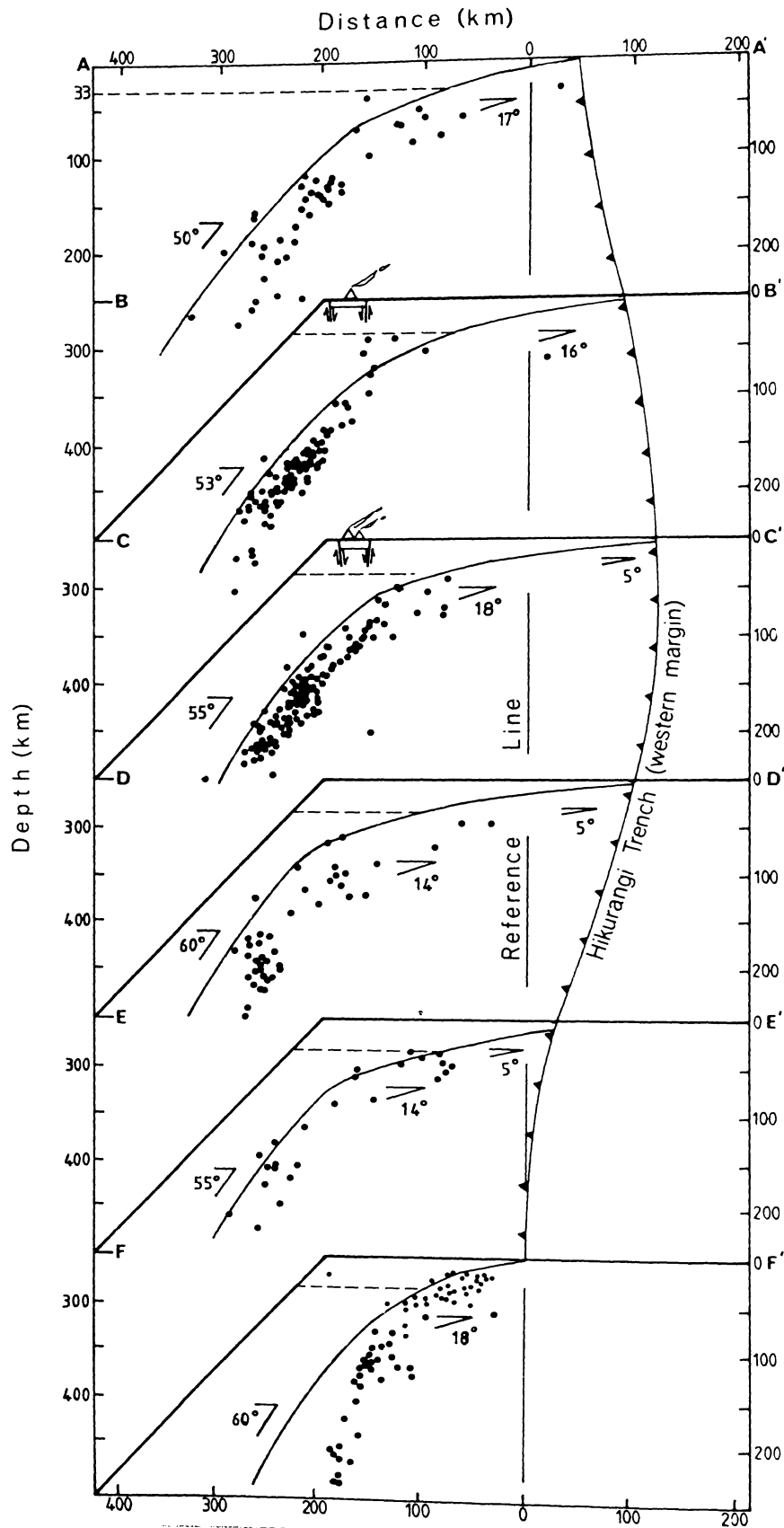


Figure 5

A series of profiles (see Figure 3 for location) showing the extent and dip of the Wadati-Benioff Zone and the top of the subducting Pacific Plate. Earthquake hypocentres from Adams and Ware (1977); only earthquakes of magnitude 4.5 or greater and those more accurately located have been included. Hypocentres in section F - F' from Arabasz and Robinson (1976); smaller dots from microearthquake survey, and larger dots located by the standard N.Z. velocity model (laterally homogeneous).

## GEOMETRY OF THE PACIFIC PLATE BENEATH NORTHERN NEW ZEALAND

Method

I have followed the procedure of Cardwell and Isacks (1978) and Cardwell et al. (1980) in the construction of a structure contour map of the top of the subducting Pacific Plate (Figure 3). Their procedure involved first drawing the interface between the plates on appropriately oriented cross-sections of the Wadati-Benioff Zone, and then, along with the spatial distribution of the earthquakes in map view, involved constructing contours on top of the dipping seismic zone.

The eight sections used here are spaced at about 150km intervals (Figure 3), and for convenience are the same as those given by Arabasz and Robinson (1976), Adams and Ware (1977) and Eiby (1977). Figure 5 shows the vertical distribution of the intermediate depth earthquake foci for the six southern sections and the respective profiles adopted here for the top of the Pacific Plate. The profiles at shallow depths for four of these sections, including the one through Cook Strait (E-E'), have been controlled by microearthquake data. Figure 4B shows how the microearthquake data (Smith, 1979; Arabasz and Lowry, 1980) constrain the depth of the Pacific Plate in section D-D' between the trench and the intermediate depth earthquakes. Focal mechanism solutions have also been used to constrain the depths to the top of the Pacific Plate. Arabasz and Lowry were able to establish composite solutions for earthquakes at different depth intervals below Carterton

(Figure 4B). As in the Wellington case, mechanisms from 7-18km down in the upper plate implied dextral strike-slip with thrusting, and those 20-40km down (now in the Pacific Plate) indicated normal faulting with sinistral strike-slip. The profile in section C-C' (Figure 5) at shallow depths has been constrained by Reyner's (1980) microearthquake hypocentres and focal mechanisms. Sections A-A' and B-B' (Figure 5) are not yet constrained by microearthquake data; the plate interface, considered to lie at the top of the intermediate depth earthquakes, has been simply projected to intersect the Hikurangi Trench at 5km depth. The earthquakes projected onto section F-F' include microearthquake data at shallow depths (sections A-A' and B-B' of Arabasz and Robinson, 1976) and deeper earthquakes located by the standard velocity model. These hypocentres will therefore appear closer to the trench because some of the ray paths will lie wholly within the subducting plate. Accordingly, the profile adopted here has a shallower dip at intermediate depths and has been constrained by the microearthquake epicentres (Figure 5).

#### Variable dip subduction

The variable dip and the buckled morphology this has imparted to the subducting plate are the principal features of the structure contour map (Figure 3). This clearly contrasts with Adams and Ware's (1977) notion of a planar dipping seismic zone. The Hikurangi Margin is normal in that profiles show a knee-type bend of the subducting slab at 70-80km depth (Figure 5). This active margin is somewhat unusual, however, in the length of the upper flat plate section, which varies from 150km wide at both ends to 280km wide in the middle.

Where there is microearthquake and seismic reflection-refraction control, another inflection is evident at about 25km depth; trenchward of this point the slab dips at about 5°, and arcward, at about 14° (Figure 5) (Reyners, 1980). The dip of the lower section of the slab, from 70-250km depth, invariably lies between 50°-60°, although there is a trend of increasing dip towards the southern end of the margin.

The buckled morphology of the structure contours may be viewed as the interference of two main fold orientations. The most obvious one in plan view consists of two NW-SE trending, open, slightly asymmetrical, plunging and inclined folds. Both of the fold axes trend 310° and lie at right angles to the regional trend of the Hikurangi Margin. Within the constraints of the data that define these folds, the axial surface of the southern one dips steeply to the SW and has dextral vergence. The axial surface of the northern one dips NE and has sinistral vergence. The wavelength of these folds is 430km, and 1½ wavelengths occur within the Hikurangi Margin. These folds appear to originate from the longer flat plate subduction section in the case of the southern one, and from some factor (continental margin) related to the offset of the Hikurangi and Kermadec margins in the case of the northern fold. The other main direction of folding has already been partly described, and relates to the asymmetrical knee-like bends at 70-80km depth and possibly at 25km depth. These folds generally trend NE-SW, but because of the interference with the other fold's orientation, the axial traces vary in orientation by as much as 30°.

### Comparison with other circum-Pacific subduction geometries

The scale of the folds in the subducting Pacific Plate beneath New Zealand may be compared with those of subducting plates at other circum-Pacific active margins of both continental and oceanic character (e.g. South America, Bevis and Isacks, 1984: Figure 9; The Bunda Sea, Cardwell and Isacks, 1978: Figure 5; Central Japan, Ukawa, 1982: Figure 2). The wavelength of the folds normal to the trench in New Zealand is greater than in the Bunda Arc and the central Japan examples, but less than the South American example. The apparent amplitude, however, is less than all three of the other cases, and thus the contortions in the New Zealand setting are more subtle. On the one hand these contortions support Davies (1980) assertion that approximately planar zones are exceptional and that contortions are normal, and on the other hand, because the contortions are less than those documented in other settings, there are no rheological problems in the Pacific Plate taking-up this geometry. This last point is also supported by Giardini and Woodhouses' (1984) modelling of the Pacific Plate beneath the Tonga Margin where they find that it is able to deform to no lesser extent than the surrounding mantle.

### PACIFIC PLATE GEOMETRY IN RELATION TO OTHER GEOPHYSICAL PROPERTIES

In the context of a planar Waditi-Benioff Zone (Adams and Ware, 1977), the trends of the other major geophysical features of the North Island (e.g. the boundary between the upper Mantle high frequency transmitting and absorbing areas, the negative gravity anomaly axis, and the boundary between low and high heat flow regions) appear to lie

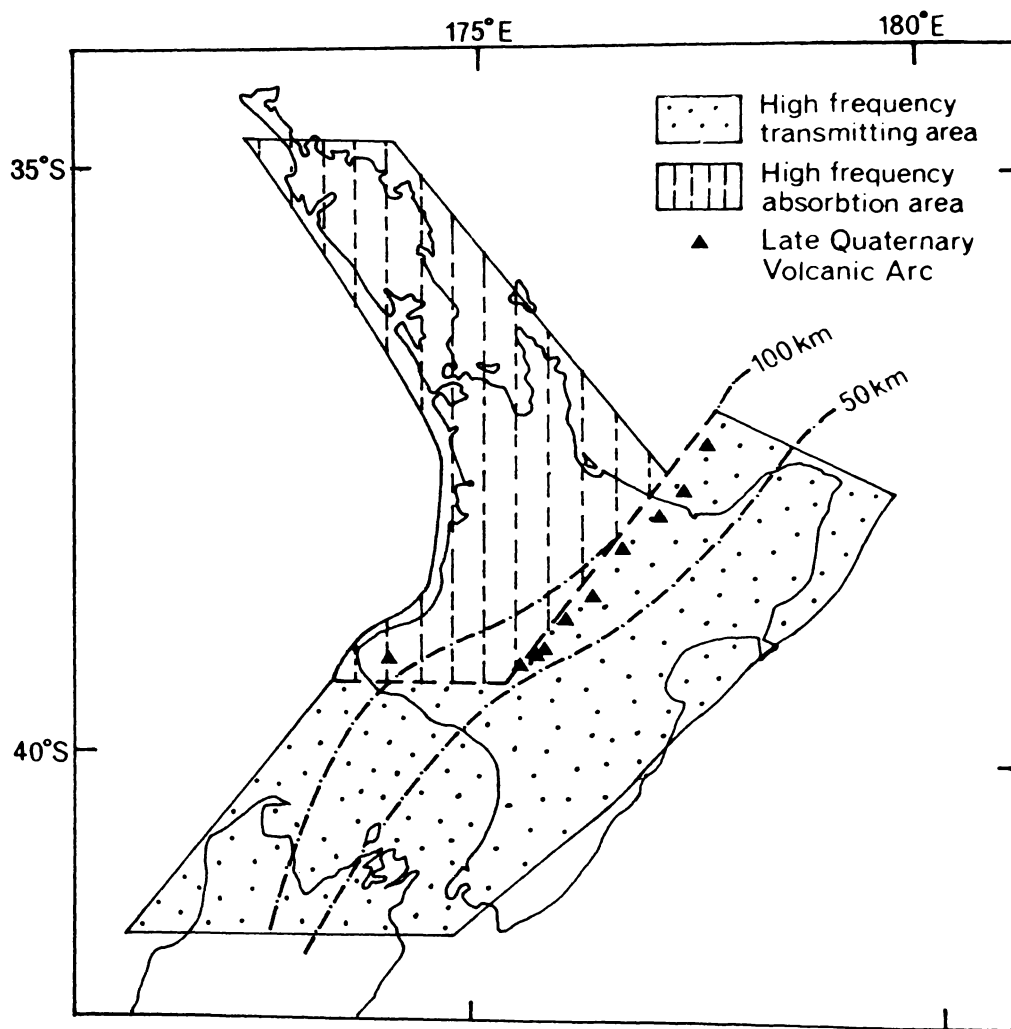


Figure 6 Map showing the extent of the upper Mantle high frequency transmitting and absorbing areas (after Mooney, 1970) in relation to the subduction geometry.

oblique to the strike of the subcrustal seismicity (see INTRODUCTION). The identification of a buckled subducting plate, and, in particular, the westward swing in central North Island of the structure contours, leaves open the possibility that the boundaries of the major geophysical features may actually follow the local strike of the subducting plate rather than diverge from it. In the following subsections I compare the subduction geometry with the upper Mantle structure, the distribution of gravity anomalies, and the heat flow patterns of northern New Zealand to show that they corroborate the geometry inferred earlier from the subcrustal seismicity.

#### Upper Mantle inhomogeneity

Mooney (1970) examined the seismic wave forms originating from deep earthquakes and recorded by the New Zealand seismograph network, and demonstrated that the significant frequency differences could be explained only by inhomogeneities within the upper Mantle.

Frequencies of 3cps and higher will be transmitted to the surface through the upper Mantle beneath eastern and southeastern North Island, whereas energy of these frequencies will be attenuated by the upper Mantle beneath the northwest of the North Island.

Figure 6 shows the distribution of the high frequency transmitting and absorbing areas in relation to the subduction geometry. The boundary between the two areas is in sympathy with the trend of the structure contours. However, between mounts Ruapehu and Egmont the boundary diverges from the structure contours, but the positioning of the seismographs in this region are such that the

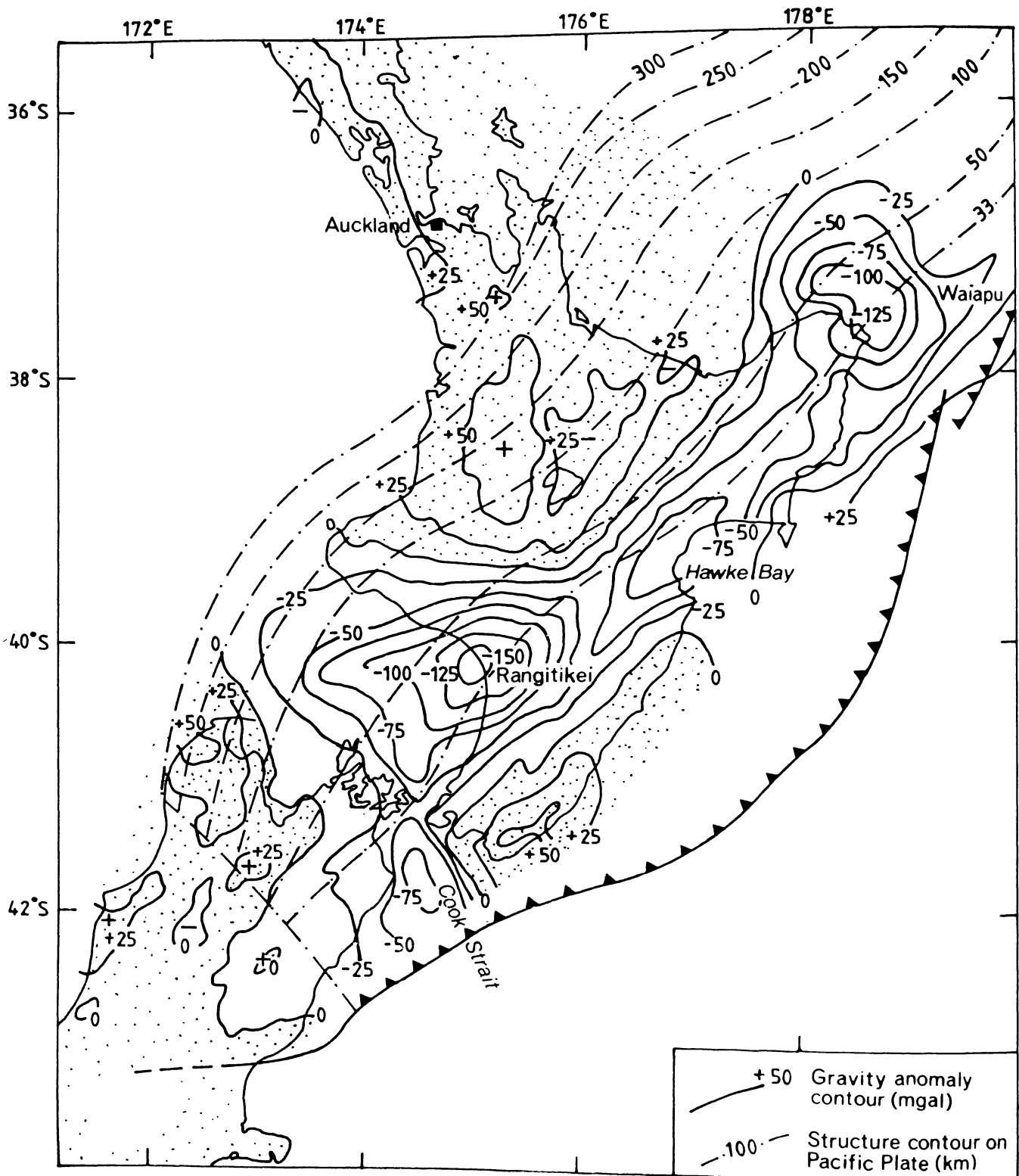


Figure 7 Map showing the isostatic gravity anomalies over northern New Zealand (after Reilly, 1965; Reilly et al. 1977; Hatherton and Syms, 1975) in relation to the subduction geometry.

transmitting/attenuating boundary may not be precisely located; Mooney (1970) cautioned that the position of this boundary was tentative.

Mooney also established that the frequency attenuation was due to an horizontally lying low Q region in the depth range 75-125 km, and therefore, it probably represents an intensification of the upper Mantle low velocity zone. In this context it is predictable that the transmitting-attenuating boundary should follow the 100 to 75km structure contours. Because of the lower angle of subduction beneath the Wanganui Basin, the low velocity zone, or mantle wedge, is excluded, and high frequency transmission is facilitated by the downthrust, cool, high Q Pacific Plate.

#### Gravity anomalies

Northern New Zealand is broadly characterised by positive gravity values between the Hikurangi Trench and the east coast of the North Island, a negative belt from East Cape to Wanganui and through Cook Strait, and positive values over the northern North and South Islands (Reilly et al., 1977) (Figure 7). Since the first Bouger Anomaly map was produced (Robertson and Reilly, 1958) it has been appreciated that only about  $\frac{1}{3}$  (50 mgal; Hunt, 1980) of the large Rangitikei negative anomaly can be attributed to the gravity effect of the Plio-Pleistocene Wanganui Basin sediments. Hatherton (1970a) attributed the remainder of the anomalous gravity field to density contrasts at mantle depths within the subducting Pacific Plate. If the source of much of the large gravitational instability indeed lies within the subducting plate, then the gravity anomaly contours should follow the pattern of the structure contours on the subducting plate.

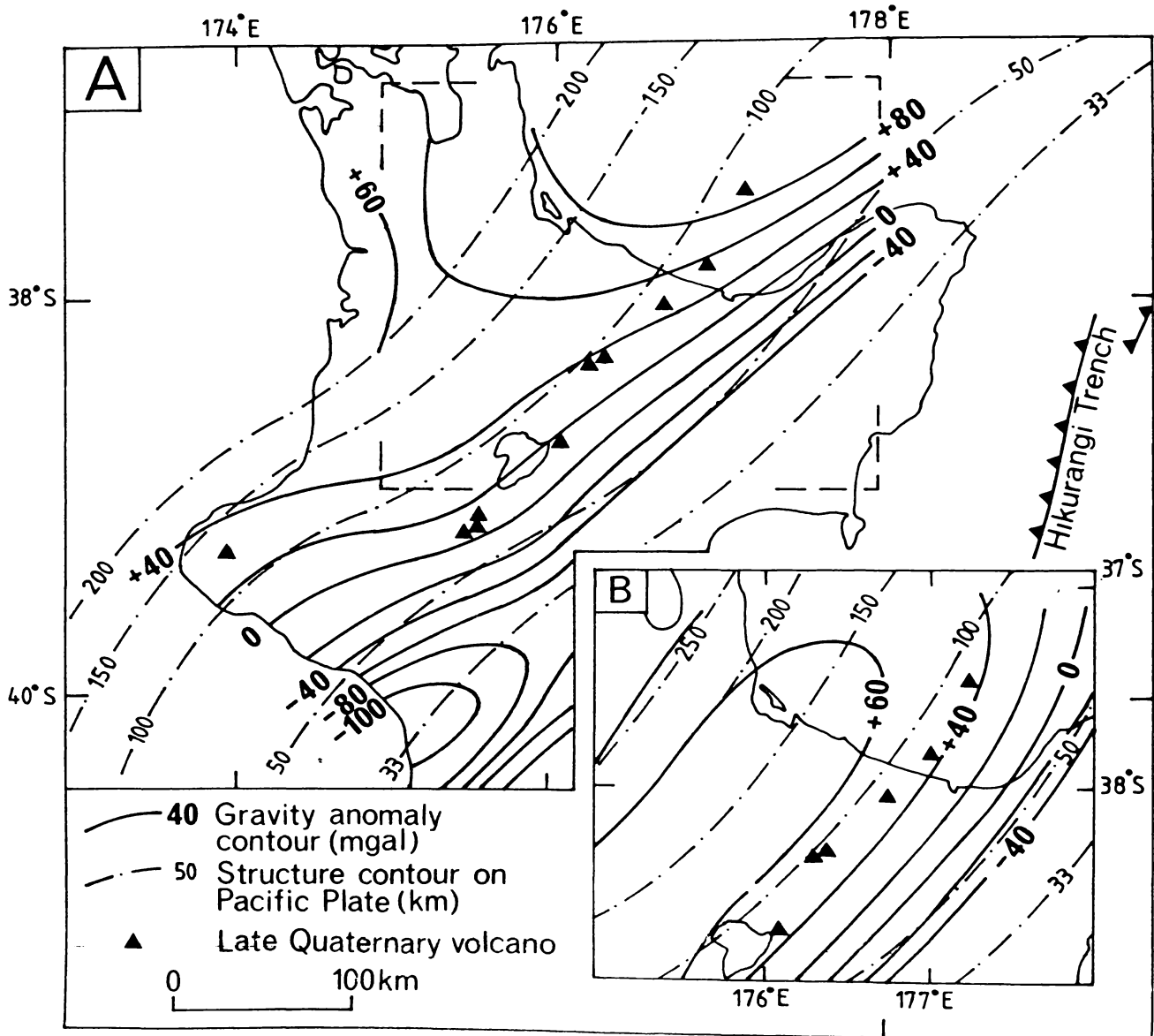


Figure 8 Map of (A) the regional bouguer anomaly field over central North Island and with (B) the regional isostatic anomaly field of the Bay of Plenty-Taupo region inset. After Hunt (1980) and Stern (1979).

Figure 7 compares the gravity anomaly contours with the structure contours. Although the swing of the axis through the negative anomalies, concave to the NW between the Waiapu and Rangitikei anomalies, and concave to the NE from Rangitikei to Cook Strait, mimics the structure contours, the zero anomaly contour and those either side of it diverge from this trend in Taranaki. Because the deep (up to 7km) Taranaki Basin occurs offshore west of the Rangitikei anomaly and the North Wanganui Basin occurs north of it, the regional gravity field has been separately compared with the structure contour pattern (Figure 8). Figure 8A shows that for the regional bouger field the zero contour, and those either side of it in the region of the Rangitikei anomaly, follow the structure contours more closely. This association changes little for the isostatic regional field as the whole region, both onshore and offshore, is underlain by continental crust. However, because there is a transition from continental to oceanic crust in the Bay of Plenty region, the isostatic regional field is also shown (Figure 8B). Importantly, from this regional field (1) the gravity contours parallel the structure contours, and (2), the positive field reaches a maximum NW of the active volcanic arc and between the 100 and 200km depth contours. Considering the North Island as a whole, the zero gravity anomaly contour follows the 70km depth contour, but lies over a deeper contour (80km) where it crosses the SW coastline. In addition, the axis of the negative gravity anomaly belt lies exactly over the 33km depth contour where the combined crustal thickness of the overriding and underthrusting plates reaches a maximum.

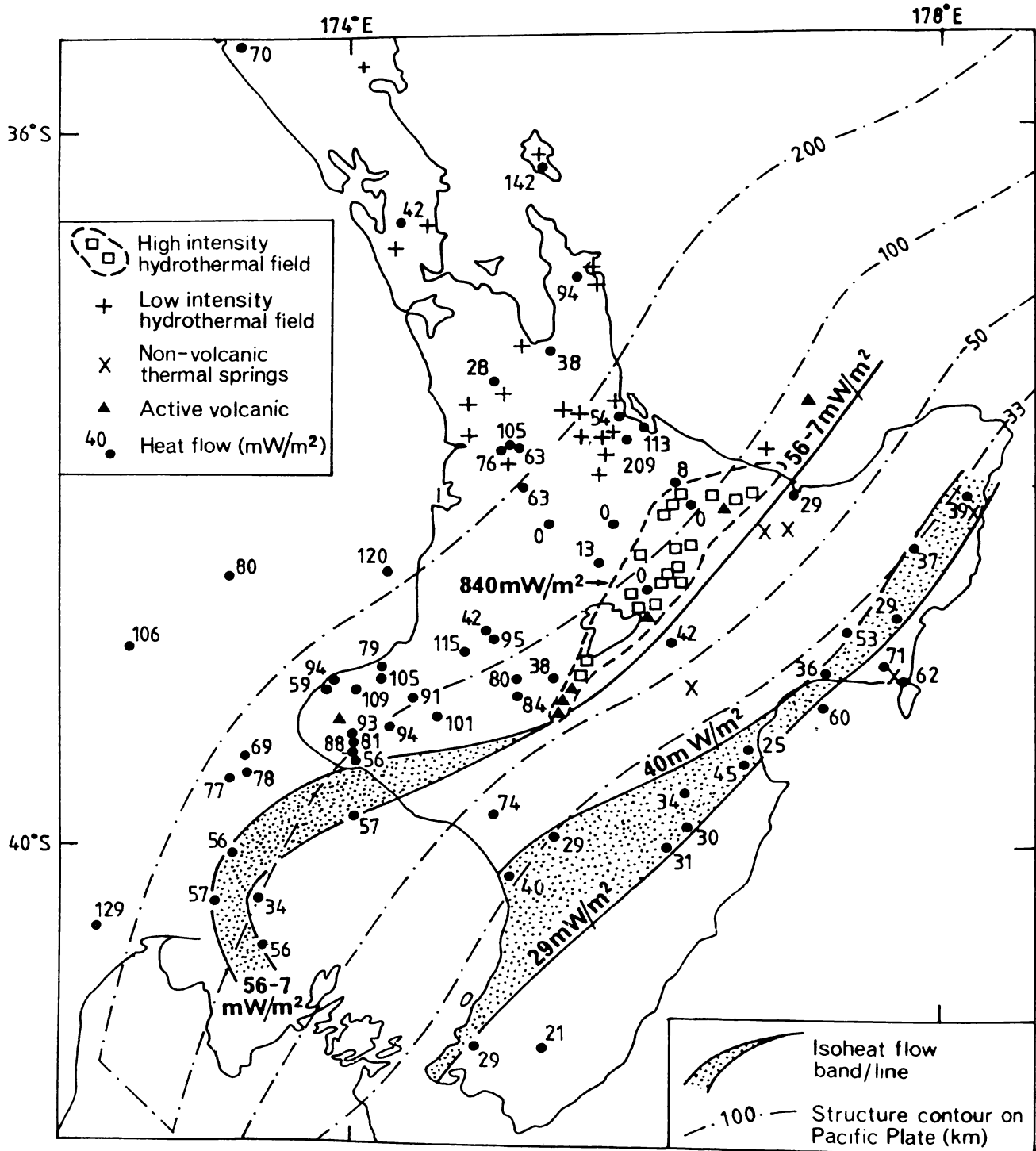
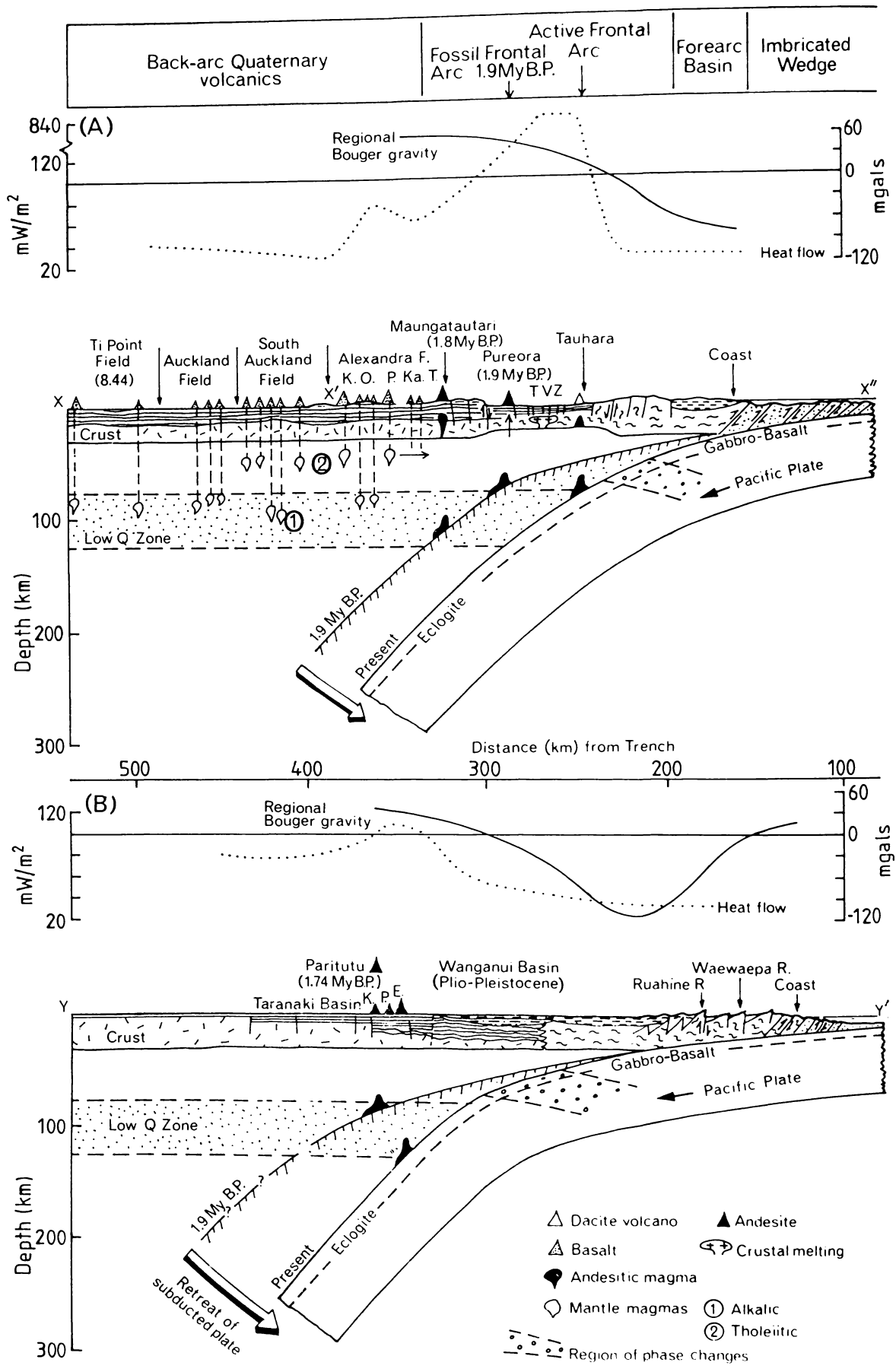


Figure 9 Map of northern New Zealand heat flow (values from Pandey, 1981) with the distribution of hydrothermal fields and thermal springs (After Grindley and Williams, 1965).

## Heat flow

The North Island distribution of heat flow values ( $\text{mW}/\text{m}^2$ ) reported by Studt and Thompson (1969), Thompson (1977) and Pandey (1981) are shown in Figure 9. These writers and Hatherton (1970a) have previously discussed the regional heat flow pattern, and have, in particular, noted that south and east of the active volcanic arc lower than average continental values ( $56.6 \text{ mW}/\text{m}^2$ ) occur, and that northwest of the arc higher than normal values occur. Considering for the moment the eastern and southern regions, it is not strictly possible to draw smooth isoheat flow lines through the data points because of their variability. Nevertheless, a regular band encompassing the heat flow values between  $29^\circ$ - $40^\circ \text{ mW}/\text{m}^2$  can be drawn. With the exception of the Mahia Peninsula region where thermal springs of a tectonic origin occur, the heat flow values south of the band are lower than  $30 \text{ mW}/\text{m}^2$ , and northwest of the band the values are either the same or higher. Interestingly, the northwest margin of this band coincides almost exactly with the 33km depth contour; the southeast margin would approximately parallel the 25km contour.

With some interpretation, another isoheat flow band, now encompassing a more restricted range of values ( $56$ - $57 \text{ mW}/\text{m}^2$ ), has also been drawn in Figure 9. There is good control in the offshore region at the southern end of the band, but apparently, poor control at the northeast end. A major anomaly in the heat flow pattern are the zero and very low values within and immediately to the northwest of the Taupo Volcanic Zone (TVZ). These result from the zero and rarely



negative geothermal gradients which are attributed by Studt and Thompson (1969) and Thompson (1977) to the drawdown of meteoric near surface waters which recharge the active hydrothermal fields in the volcanic zone (Figure 9). The hydrothermal fields are regarded as narrow upflow zones by contrast with the surrounding broad drawdown zones where the groundwater flow is sufficiently high to mask any thermal gradient to a considerable depth. However, the mean heat flow from the TVZ, measured from the heat output of the hydrothermal fields, has been calculated as  $840 \text{ mW/m}^2$  (Gregg, 1958; Studt and Thompson, 1969). This indicates that an extremely steep heat flow gradient lies parallel to the southeast margin of the TVZ, and the  $56\text{-}57 \text{ mW/m}^2$  band should therefore approximate a line. East of the TVZ this line lies above the 70km depth contour, but at the southern end of the TVZ where it becomes a band, it crosses the 100km and 150km structure contours. Importantly, however, the band curves to the west and then back to the east in sympathy with the trend of the structure contours.

Northwest of the  $56\text{-}57 \text{ mW/m}^2$  isoheat flow band and outside the influence of the TVZ, the values are generally higher and correspond to low intensity hydrothermal springs. Over broad regions of north Taranaki, and more locally over northern North Island, the values are high enough to correspond to melting temperatures at the base of the crust (Pandey, 1981).

Figure 10 Two combined geological and geophysical cross-sections, one (X - X' - X'') through the axis of the downward fold in the subducting plate, and the other (Y - Y') through the axis of an upward fold (see Figure 13 for section locations). See the text for discussion and sources of data, but note the amount of trenchward retreat of the subducted slab in the last 1.9 million years. Taranaki Volcanics (Ki, Kaitake; P, Pouakai; E, Mt Egmont). Alexandra Volcanics (K, Mt Karioi; O, Okete; P, Mt Pirongia; Ka, Kakepuku; T, Te Kawa).

## Conclusion

The fact that (1) the boundary between the upper Mantle high frequency transmitting and absorbing areas, (2) the trend of the regional gravity anomaly contours, and (3), the isoheat flow lines all change their trend across northern New Zealand to a similar extent and in sympathy with the structure contours inferred from the subcrustal seismicity, corroborates the interpretation of a buckled subducting plate beneath northern New Zealand.

The spatial associations of the upper Mantle structure, the gravity pattern and the heat flow pattern, in relation to the subduction geometry are shown in two cross-sections perpendicular to the subducting plate and  $\frac{1}{4}$  of a wavelength apart (Figure 10). The physical meaning of these associations are considered further elsewhere (Kamp, in prep.).

## STATE OF STRESS OF THE OVERRIDING (AUSTRALIA) PLATE

In the second part of this paper I wish to show how the variable dip of the subducting plate coupled with the persistent retreat of the slab have controlled the volcanic, structural and tectonic development of the overriding plate.

On the assumption that these volcanic and structural patterns are manifestations of the longer term ( $1 \times 10^6$  yr) state of stress, it is appropriate to first consider the short term ( $1 \times 10^2$  yr) state of stress of the overriding plate and its relationship to the subduction

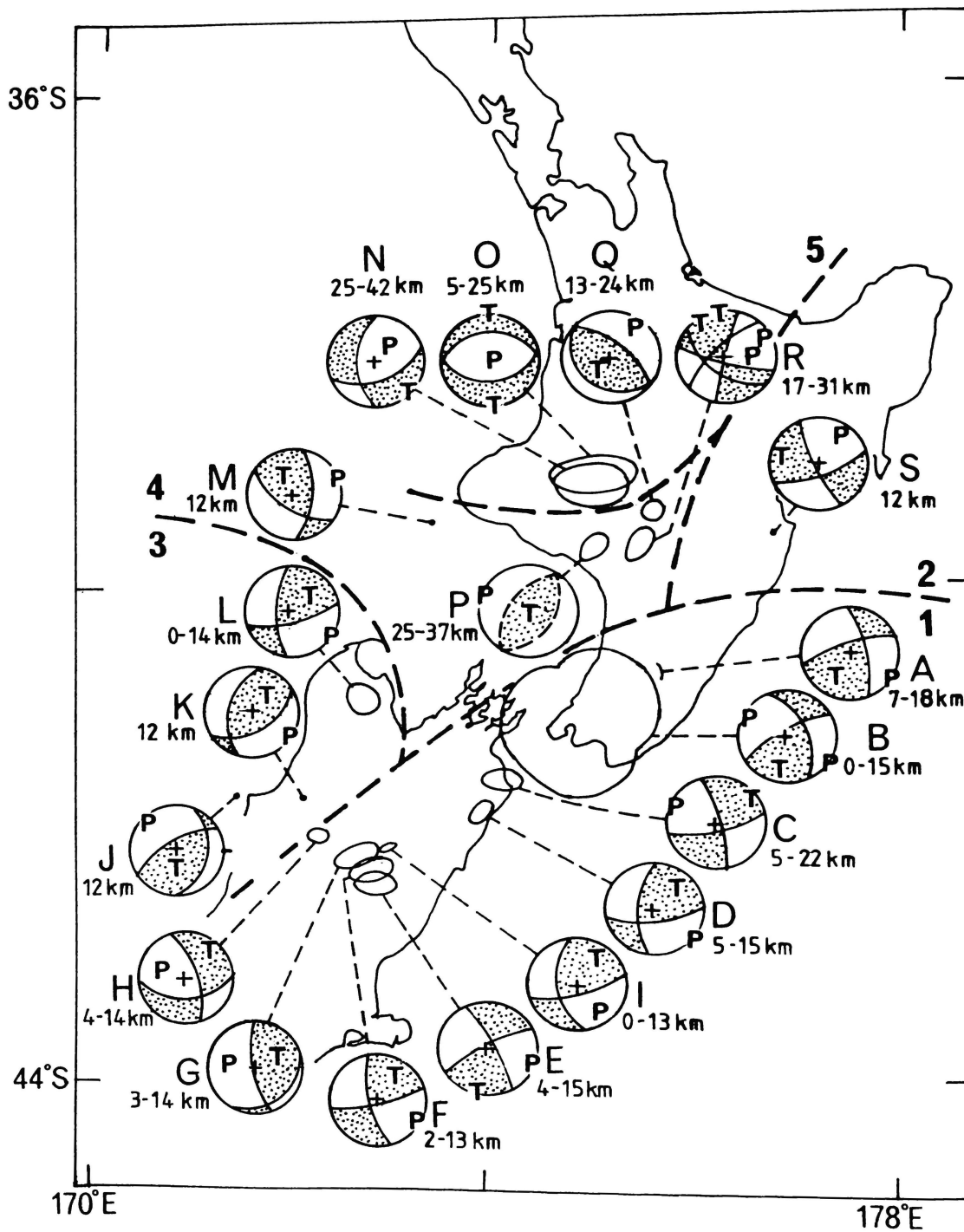


Figure 11

Focal mechanisms for shallow earthquakes in the Indian Plate. All diagrams in the upper focal hemispheres are equal-area projections of the upper focal hemisphere with the compressional quadrants shaded. Solutions are from many sources and were compiled by Reyners (1980, Figure 11).

geometry. The short term state of stress may be determined by two independent means: earthquake focal mechanism solutions and triangulation surveys.

### Focal mechanisms

Figure 11 summarises the published composite focal mechanisms of crustal earthquakes in the Australia Plate. As a basis for discussion these mechanisms have been grouped into five regions. Mechanisms A-I in southeast North Island and Marlborough (region 1), indicate dextral strike slip displacement with reverse thrusting. The NE to ENE nodal plane of each of these solutions coincides with the orientation of nearby oblique-slip faults. The P (compression) axes are all aligned NW to WNW and indicate near horizontal compression.

Few focal mechanisms have been reported for region 2. One (mechanism S) indicates extension normal to the plate boundary zone, but it lies within a region of imbricate thrusting (Pettinga, 1982) and the active growth of anticlines (Lewis, 1971). As discussed further below, the present stress state in region 2 is probably unrepresentative of the long term state. Johnson and Molnar (1972) report a fault plane solution for a 1966 magnitude 6.2 earthquake near Gisborne. It indicates shallow thrusting ( $15^\circ$ ) to the NW on a fault plane striking  $035^\circ$ ; the P-axis is about  $125^\circ$ , oriented roughly normal to the plate boundary.



Composite focal mechanisms J and K in region 3, which actually lies south of the surface projection of the subducted plate indicate mainly thrusting with the greatest compressive stresses oriented NW. Mechanism L shows mixed strike-slip and thrust faulting with the P-axes oriented NW-SE.

Mechanism P beneath the Wanganui Basin is a pure thrust solution with a WNW oriented P-axis. Not shown in Figure 11 are six separate solutions by Garrick and Gibowicz (1983) for earthquakes with epicentres on the coast immediately south of the region of mechanism P. Three composite solutions for small shocks indicate almost pure extensional normal faulting, but three solutions for larger earthquakes correspond to compressional thrust faulting similar to mechanism P. Mechanism M represents about equal components of thrust and strike-slip motion, and the P-axis has an unusual NE-SW orientation.

The composite solutions in region 5 mainly indicate an extensional state of stress. Mechanism O indicates normal faulting and mechanisms N and R indicate NW-SE extension. Mechanism Q is unusual in that it indicates NE-SW thrusting.

### Triangulation Surveys

The geodetically determined azimuths of the principal axes of compression and the rates of maximum shear strain of different parts of New Zealand are shown in Figure 12A after Walcott (1984). The azimuths of the principal axes of compression are clearly very similar to those evident in the focal mechanism solutions.

The maximum shear strain rates have been resolved by Walcott (1984) into two components, one normal ( $\dot{\gamma}'$ ) and the other parallel ( $\dot{\gamma}''$ ) to the plate boundary zone. The distribution of component  $\dot{\gamma}'$  is reproduced in Figure 12B. We wish to compare the sign of this component (+ve, compression; -ve, extension) with the geometry of the subducting plate (Figure 3). Excluding for the moment the region of very shallow subduction (<33km) there appears to be a general relationship between the subduction geometry and the state of stress of the overriding plate. In the crust above downward buckles (Taupo Volcanic Zone, Moutere Depression), extension normal to the plate boundary occurs, and in the crust above upward buckles (Wanganui Basin) compression occurs. One exception is NW Nelson where compression occurs and extension might be expected; the compression there is most probably a response to the continent-continent collision across the Alpine Fault which lies immediately to the south. The region of shallow subduction in eastern North Island is partitioned into a southern part where compression dominates and a northern part where extension presently occurs. Walcott (1978b) has attributed this spatial difference in the state of stress to alternate locking and unlocking of the subduction thrust. At present the southern part is locked and the northern part is subducting freely. The occurrence of imbricate thrusts (Pettinga, 1982), actively growing anticlines (Lewis, 1971) and the pattern of Quaternary uplift (Kamp, 1982) all indicate that compression is actually the dominant mode in northeastern North Island.

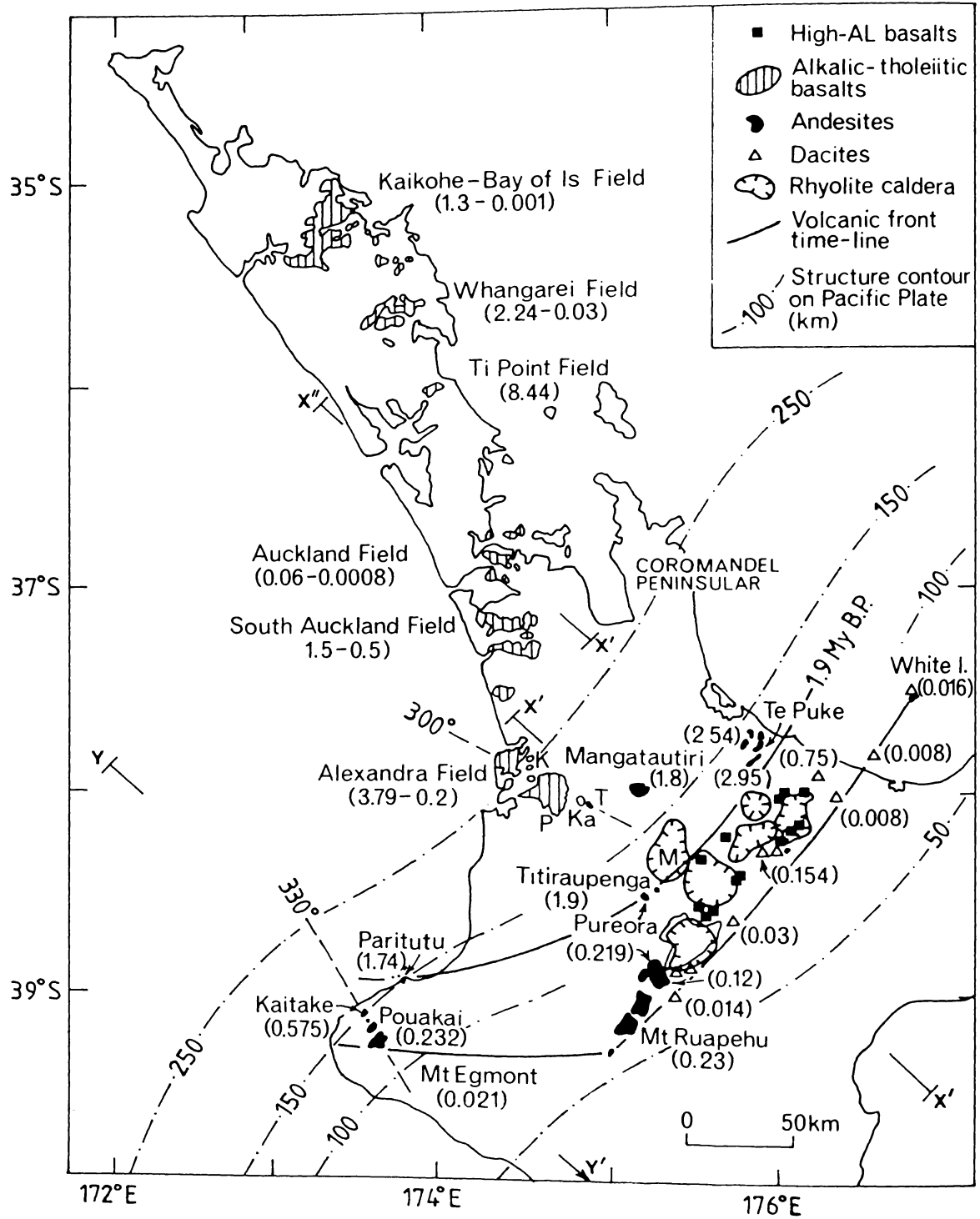


Figure 13 Map showing the distribution of different types of volcanics and their ages over northern North Island in relation to the subduction geometry. Note the orientation (Kear, 1964) of the Taranaki and Alexandra volcanoes in relation to the subduction geometry. It may be possible that the trenchward flow of the upper Mantle (see text) progressively displaced a diapir which erupted initially to form Mt Pirongia (P) and subsequently Kakepuku (Ka) and Te Kawa (T). K stands for Mt Karioi. Sources of ages : Stipp (1968), Duncan (1970), Topping (1973), Kohn and Gladsby (1978), Heming (1980b) and Briggs (1983). 1.9 My B.P. time line partly after Briggs (1985b). Caldera distributions from Wilson et al. (1984). M stands for Mangakino Volcanic Centre.

The distribution of the component of the shear strain rates parallel to the plate boundary zone ( $\dot{\gamma}'$ ) (Walcott, 1984: Figure 3b) shows that the parts of eastern North Island and Marlborough which lie less than about 40km above the subduction thrust are strongly stressed by dextral movement. However, for the parts of the overriding plate that lie above deeper levels of the plate interface, the component of the shear strain rates normal to the plate boundary zone ( $\dot{\gamma}_n'$ ) mainly determine the state of stress.

Thus over northern North Island extension is expected to dominate if the short term state of stress is representative of the long term, and compression is expected to dominate in the eastern Wanganui Basin region if the same condition applies.

In the following sections, the volcanic and structural patterns of the parts of the overriding plate which lie more than 40km above the plate interface are examined to show that the short term state of stress has been in place through the Quaternary. The relationship of the structure of eastern North Island and Marlborough to the short term state of stress and to the geometry of the section of shallow subduction, has been discussed by Bibby (1981), Pettinga (1982), Kamp (1982) and Kamp and Vucetich (1982).

#### QUATERNARY VOLCANISM AND THE SUBDUCTION GEOMETRY

Figure 13 illustrates the distribution of Quaternary volcanics in northern New Zealand from which it is immediately apparent that they

only occur above the northern downward fold of the subducting plate. The petrology together with the chronology of these volcanics shows that this region of the overriding plate has been in a state of extension during at least the Quaternary. The driving force for the extension is considered to be the persistent trenchward retreat of the subducting plate.

#### Frontal arc volcanism

The frontal arc is clearly delineated along the SW margin of the Taupo Volcanic Zone by regularly spaced late Quaternary dacite volcanoes (Figure 13). Frontal arc andesites are spatially more restricted and about 95% of the exposed andesite lavas occur SW of Lake Taupo. Because the frontal arc between Mt Ruapehu and White Island is more gently curved than the underlying subducting plate, the depth to the top of this plate gradually increases northeastwards along the arc from 70km to 88km; there is also a corresponding increase in potash content of the andesite lavas (Cole, 1978; Duncan, 1970). Southwest of Ohakune the frontal arc is displaced due west away from the trench by a further 83km. This is in sympathy with the westward swing in the structure contours on the subducted plate and the trends of the other geophysical properties as discussed earlier. However this displacement is accentuated by the origin of the Taranaki andesite magmas near the base of the low Q zone compared with the top of this zone along the rest of the frontal arc (Figure 10).

According to Adams and Ware's (1977) isobaths, Mt Egmont occurs 200km above the Wadati-Benioff Zone, which is globally recognised as an anomalously deep level for the generation of andesitic melts (Gill, 1981). The interpretation from Figure 13 is that the magmas originated at a much shallower depth of 125km. The andesite lavas of Mt Egmont and the other Taranaki volcanoes (Kaitake, Pouakai) contain unusually high potash concentrations with a  $K_{55}$  value of 2.08 (Hatherton, 1969).

In the Taupo Volcanic Zone six large calderas considered to be the source of numerous Quaternary rhyolitic tephras and ignimbrites occur immediately behind the present volcanic front (Vucetich and Pullar, 1969; Wilston et al., 1984) (Figure 13). Gravity and magnetic modelling calibrated against drillhole data suggests that basement is generally depressed by 2.5km and up to 5km below sea level in the calderas (Rogan, 1982). These depressions are widely viewed as collapse structures resulting from the episodic, voluminous and catastrophic eruption of rhyolite magmas which exceed  $16,000 \text{ km}^3$  (Healy, 1964). This interpretation is supported by petrologic modelling which has shown quantitatively that the TVZ rhyolites originated by partial melting of the Mesozoic greywacke basement (Reid, 1983); a conclusion anticipated by the extreme heat flow values (Figure 9). However, the calderas occur within a major topographic depression aligned NE-SW (Healy, 1982) which is indicative of an overall tectonic origin. The origin of this volcano-tectonic depression, essentially the TVZ, is discussed further below. For the moment it is pertinent to note that all the calderas occur, and are widest, in the crust above the middle of a downward buckle of the subducting plate.

Thus several features of the frontal arc volcanism are consistent with the subduction geometry: the limitation of the active andesite and dacite volcanoes to the region above a downward fold of the subducting plate, the origin of andesitic magmas further from the trench at both ends of the arc, and the distribution of the rhyolite calderas.

#### Back-arc volcanism

To the northwest of the present volcanic front two main compositional groups of Quaternary volcanics occur: back-arc alkalic to tholeiitic suites, and subduction derived calc-alkaline andesites and associated basalts. The former group lies between 140 and 400 km behind the present frontal arc and is distributed as five main volcanic fields; Alexandra (Briggs, 1983; Briggs and Goles, 1984), South Auckland (Rafferty and Heming, 1979), Auckland (Searle, 1960, 1961), Whangarei and Kaikohe-Bay of Islands (Kear, 1961; Heming, 1980). These fields individually comprise as many as 70 vents which are often clustered as monogenetic scoria cones and maars with associated lava flows. A total of about  $100\text{km}^3$  of lava and scoria has been erupted during the last 2.5 million years, with about half of this amount occurring in the Alexandra field as low angle cones or shields.

With the exception of the Auckland field which has erupted the smallest volume of magma, the lavas of each of the other fields can be divided on petrographic and geochemical grounds into two groups. The Alexandra, Whangarei and Kaikohe-Bay of Islands fields comprise an

early alkaline suite, a subsequent dominantly tholeiitic suite and in two cases (Alexandra, Kaikohe-Bay of Islands) a late, slightly differentiated, alkaline suite. The South Auckland field comprises an early alkaline series and a late subalkaline/transitional tholeiitic series. Petrologic modelling has shown that the alkaline series in the Alexandra field (the Okete Volcanics) originated from varying degrees of partial melting of a garnet peridotite probably within the upper Mantle low velocity zone (Briggs and Goles, 1984); such an interpretation is also favoured for the alkalic rocks in the other volcanic fields (Rafferty and Heming, 1979; Heming, 1980).

In most cases the alkalic group of rocks are less voluminous contain ultrabasic xenoliths and xenocrysts, show no evidence of fractional crystallization, tend to be associated with surface faults, and erupted more violently as evidenced by their volcanic form as scoria cones, maars and small lava flows. All these properties indicate rapid magma ascent rates and no residence time in magma chambers, features consistent with crustal extension. By contrast, the tholeiitic suite comprises a much greater volume of lava, lack ultramafic nodules, are associated with late stage high-k andesites formed by fractional crystallization (Briggs, 1985a), and are not obviously associated with surface faults. These properties indicate much slower magma ascent rates and the formation of short-lived magma chambers. The petrology of the tholeiitic suite in the Alexandra Field shows that it was generated from large degrees of melting of a much shallower (45-60km) and different source (Iherzolite) than the associated alkalic suite (Briggs 1985a). A different source for the alkalic and tholeiitic suites is also suggested for the Whangarei and

Kaikohe-Bay of Islands fields (Heming 1980). However, Rafferty and Hemming (1979) have suggested that more voluminous partial melting between 30-45 km of the mantle diapirs from which the earlier alkalic rocks were derived (by small degrees of partial melting) can account for the temporal and petrologic relationships between the two magmas of South Auckland.

In summary, Quaternary back-arc alkalic-tholeiitic volcanism is common above the downward fold of the subducting plate and to the NW behind the present frontal arc. It evidently does not occur above the upward folds of the subducting plate. The occurrence and characteristics of the alkalic rocks are consistent with structural evidence (see below) of extension. The limited amount of differentiation of the tholeiitic lavas, and the short interval between their eruption and the earlier eruption of the alkalic lavas is also suggestive of crustal tension which caused the magma chambers to be short-lived.

#### Fossil frontal arcs and retreat of the subducted plate

The volcanic geology of the behind-arc region in northern New Zealand is further complicated by the isolated, though in some places voluminous (Coromandel Peninsula), occurrence of low and high potash calc-alkaline andesites and basalts (Challis, 1978). There has been much controversy surrounding the age pattern of these rocks, but it is now clear that they represent a mixture of fossil frontal arc and subduction derived behind-front volcanoes which all young towards the presently active arc (Kamp, 1984: Figure 4).

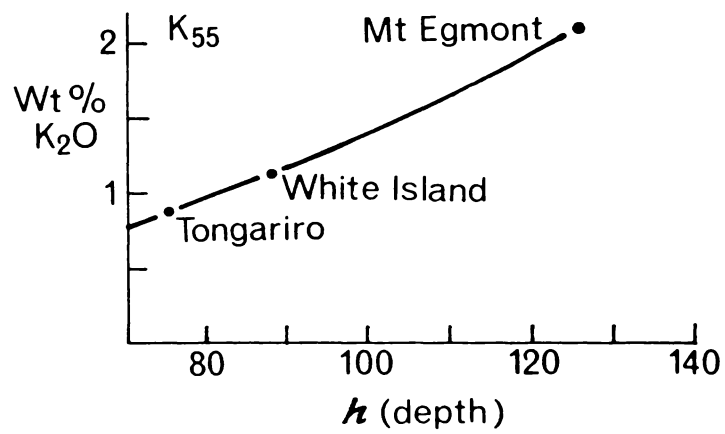


Figure 14 Variation in potash content in late Quaternary andesites at 55 wt% SiO<sub>2</sub> with depth to the top of the subducting plate. Source of potash data : Tongariro (Cole, 1978), White Island (Duncan, 1970) and Mt Egmont (Hatherton, 1969).

From the age-space distribution of these eroded volcanics, and their geochemistry, Kamp (1984) established that during the late Cenozoic the subducting Pacific Plate progressively increased its extent to the southwest beneath the North Island and concomitantly increased its dip thereby causing the trenchward migration of the volcanic front. New data on Mt Maungatautiri (Figure 13), a 1.8 My B.P. subduction derived medium to high K behind-front andesite volcano (Briggs, 1985b) in combination with data from Paritutu, now permits the geometry of the subducted plate at the Plio-Pleistocene boundary to be better constrained. This highlights the amount of trenchward retreat of the subducted plate which has occurred during the Quaternary, and offers a mechanism for the crustal extension evident over northern North Island.

The empirical  $K_2O-h$  relationship (Dickinson and Hatherton, 1967; Dickinson, 1975) is a useful through not uncontroversial means of determining the former depths of subducted slabs beneath subduction derived volcanoes. In view of the number of petrogenetic factors other than depth that may control the  $K_2O$  content of magmas (see Cawthorn, 1977; Whitford and Jezek, 1979; Meijer and Reagan, 1983), it is perhaps more appropriate to infer the depths of magma generation of fossil arc volcanics from a locally derived calibration curve, rather than from a universal relationship such as that presented by Dickinson (1975); at least the same subducted slab, upper Mantle structure and similar crustal composition will be common thus eliminating some of the complicating factors. Figure 14 is a new  $K_2O-h$  relationship at 55 wt%  $SiO_2$  established from the presently active frontal arc. It is based on the revised depths to the top of the subducted plate established in the first part of this paper.

Assuming that large volume andesitic magmas are generated at the top of subducted plates, and given the  $K_{55}$  contents of Pureora (Cole and Teoh, 1975), Paritutu (Hatherton, 1969) and Maungatautiri Lavas (Briggs, 1985b) and Figure 14, the approximate 1.9My B.P. subduction geometry of the Pacific Plate has been reconstructed for two sections normal to the Trench (Figure 10). The paleogeometry is better constrained in section X-X' since two data points (Pureora, 70km; Maungatautiri, 113km) are available; only one point is available for section Y-Y' (Paritutu, 86km) and this is only considered a provisional result because of the limited compositional data which are published. Nevertheless by comparison with the present geometry, both sections show that there has been considerable trenchward retreat of the subducted slab during the Quaternary. The obvious surface manifestation of this in the region above the centre of the downward fold of the subducting plate has been 40km of arc migration. This is the same as the average rate of arc migration through central North Island during the late Cenozoic (20 km/My: Kamp, 1984). However, above the shallow subduction section in Taranaki, the arc has only migrated 25 km during the same interval (12.5 km/My). Another interesting feature, evident from the position of the 1.9 My B.P. arc alone, but confirmed by the  $K_{20-h}$  data, is that the general form of the present downward fold of the subducting plate beneath central North Island already existed in the early Quaternary (Figure 13).

A corollary of the evidence for trenchward retreat of the subducted Pacific Plate must be trenchward flow of the upper Mantle relative to the overriding crust. Simply stated, the upper Mantle

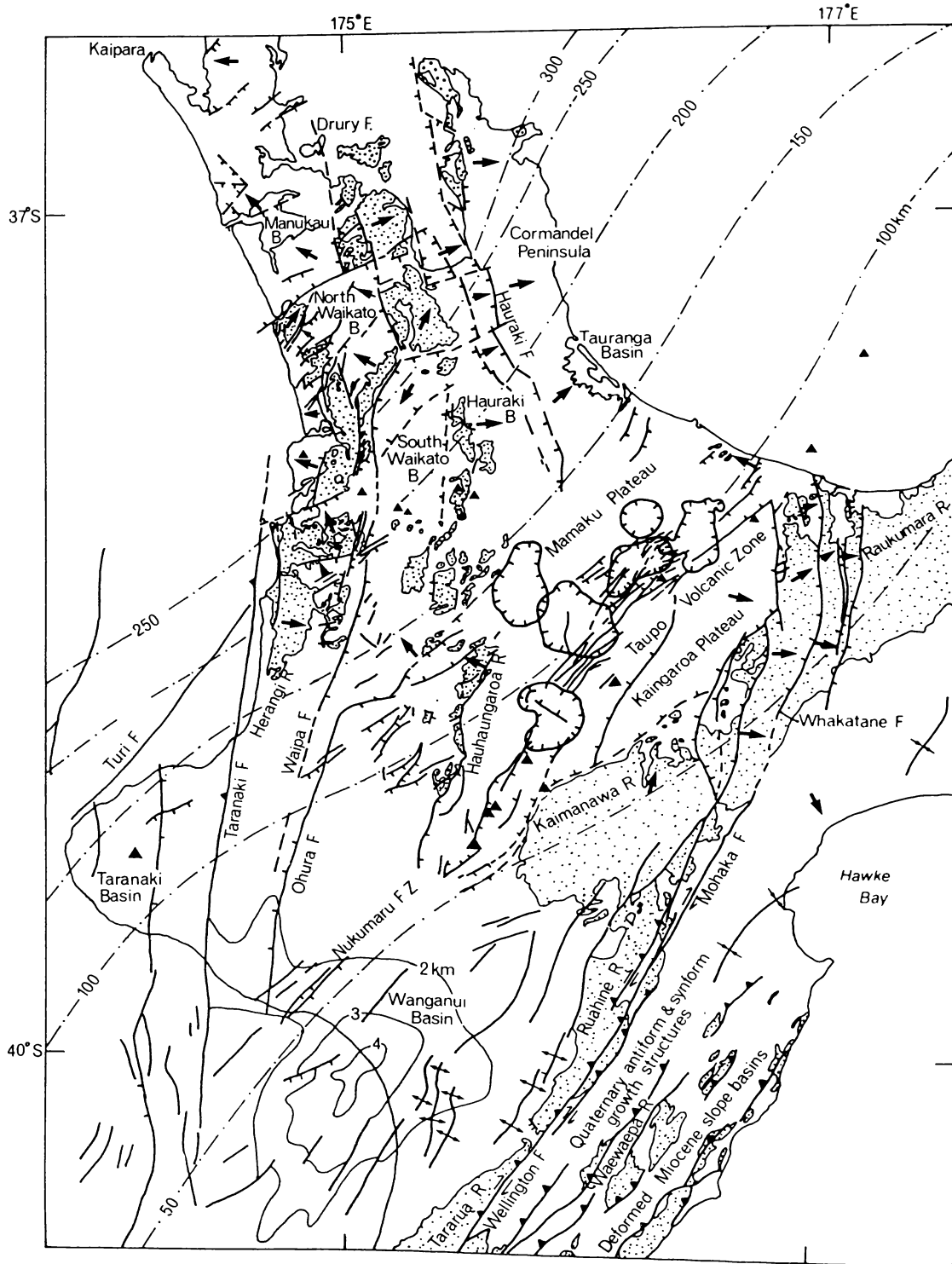


Figure 15 Map of the major late Cenozoic structures of central North Island including the outcrop distribution of Mesozoic basement in relation to the subduction geometry. Structure contours of depth to basement below sea level in the Wanganui Basin from Anderton (1981).

will be drawn towards the trench. A major implication of this subcrustal flow will be crustal tension. In the following section I consider the large scale late Cenozoic structure of the North Island before integrating the volcanic, tectonic and structural patterns of the North Island in terms of the geometry and retreat of the subducted slab.

#### LATE CENOZOIC STRUCTURE

The distribution of the major structural features, especially faults, and the outcrop distribution of the Mesozoic basement throughout most of the North island, are illustrated in Figure 15 in relation to the structure contours on the subducting Pacific Plate. The main proposition of this section is that crust over the downward fold in the Pacific Plate has a different late Cenozoic structure from the region to the south over the upward fold in the Pacific Plate.

Considering the structure of northern and central North Island first, Figure 15 shows that it is dominated by a system of NW-SE, N-S and NE-SW bearing faults; Kear (in Kear and Schofield, 1978) and Nelson and Hume (1977) have previously identified these frequency modes from quantitative analyses of the fault trends in central-western North Island. As a result of vertical displacements on these faults, the region under consideration has been segmented into rectilinear blocks which have commonly been tilted. Consequently, the South Auckland-Waikato region has a basin-and-range type topography. A block faulted topography also characterises the TVZ, but here middle to late Pleistocene volcanics are displaced at the surface since the

downfaulted Mesozoic basement is buried by thick pyroclastic flow deposits. Normally faulted basement is re-established southeast of the TVZ.

Descriptions of the faults north of the TVZ are given by Schofield (1958a, 1967) Kear (1960, 1966), Kear and Schofield (1978), Hochstein and Nixon (1979) and Healy et al. (1964). The faults are all normal, mostly linear or only slightly curved and several show a scissors type displacement with decreasing throw along their trends (e.g. Port Waikato Fault, Hochstein and Nunns, 1976). Although the fault planes are rarely observed, inferences from geophysical surveys and both underground and opencast coal mining excavations suggest that they dip steeply 70-80°, but occasionally as low as 60°. The minimum throws on the major faults bounding basement blocks can be inferred from the present relief and are commonly up to 300m; gravity surveys in the South Waikato (Kear and Schofield, 1978) and Hauraki basins (Hochstein and Nixon, 1979) show that throws of up to 3.5 km occur. Along the West Coast where Oligocene-early Miocene marine strata overlie uplifted basement, within-block fault displacements of up to tens of metres have been mapped (Kear, 1966; Laird, 1967). Further to the east such control is not available as marine cover rocks are not present.

From the pattern of faulting and basement outcrop the tilt directions of many of the fault bounded blocks have been determined and are shown in Figure 15 by arrows. The amount of tilting is often only a few degrees and usually less than 10°. North of TVZ the blocks are tilted in many directions, except to the SE, however, those in the west are chiefly tilted to the west and NW, while those in the east

are chiefly tilted to the east or NE. The occurrence of these differentially uplifted blocks and the character of the faults which bound them are primary evidence of crustal extension. The variations noted earlier in the tilt directions imply NW-SE and E-W as well as NE-SW directions of extension. The triangulation survey data also indicates variable directions of extension (Figure 12). In view of the pattern and extent of extensional faulting over the North Island, the special significance that has been attached to the Hauraki Basin in describing it as a rift (Hochstein and Nixon, 1979) is no longer obvious.

#### Taupo Volcanic Zone

Because of the occurrence of active frontal arc volcanism and the evidence for extensive Pleistocene rhyolitic volcanism, the TVZ is traditionally viewed as a separate structural domain from the South Auckland and Waikato districts. However, apart from the fact that Mesozoic basement does not crop out within the volcanic zone, the structures are extremely similar. They have been mapped and described by Healy (1962, 1982), Healy et al. (1964) and Grindley (1959, 1960, 1965). From Mt Ruapehu northeastward to the coastline the non-volcanic structure is dominated by steeply dipping NE-SW trending normal faults. These faults invariably bound horsts and grabens and differentially uplifted tilt blocks. These faults commonly display variable throw along their traces and Grindley (1965) has documented evidence of repeated displacements on several of the major faults. The pattern of faulting indicates NW-SE extension. Although NE-SW

trending faults are most common, there is increasing evidence for NW-SE oriented faults such as the Horomatangi Fault in Lake Taupo (Wilson et al., 1984). Cochrane and Tianfeny (1983) have also mapped NW-SE lineations from Landsat imagery. It is possible that deep-seated NW-SE structures have controlled the location and distribution of the major calderas (Figure 15).

The area included within the TVZ varies with its definition (Wilson et al., 1984). If it is defined as the region encompassing the high intensity hydrothermal fields (Figure 9) then it has an inverted pear-like shape - narrow at the SW end, widening to include the Rotorua caldera, and then narrowing promptly to the coastline. This shape is also shown by the width of the zone of dense NE-SW faults, and would be even more pronounced if the outline included all the calderas. The pear shape of the TVZ clearly indicates much greater extension in the middle than at the ends of the zone, a point considered further below.

To the southeast of the TVZ Mesozoic basement has been uplifted to 1200 m a.s.l. and forms a series of ranges which collectively parallel the TVZ (Figure 15). Individual ranges have been identified and named on the basis of major curvilinear N-S trending faults. The faults correspond to major valleys which contain northward flowing rivers. From the outcrop pattern of Jurassic and lower Cretaceous rocks within the fault bounded lath-like blocks, and from their topography, the bounding faults are considered to have normal throws and westward dips, and the blocks are considered to tilt to the east and northeast. This is perhaps most clearly shown by the outcrop

pattern of the basement with respect to the Quaternary deposits near the coastline. The largest and westernmost block is the Kaingaroa Plateau which dips eastward at  $1^\circ$  and is underlain by ~200 m of ignimbrite over basement. The Kaingaroa Fault on its NW side displaces basement 1.5 km into the TVZ (Grindley, 1965); faults on the plateau's eastern side displace basement downwards by 0.5 to 1.0 km. The throws on the faults between the tilt blocks further to the east are difficult to assess, but are probably of the order of one to several hundred metres. Hence the structure of the ranges that parallel the TVZ also indicate NW-SE crustal extension, but unlike the basement within the TVZ which is differentially downthrown 2 - 3 km below s.l., basement is differentially uplifted to 1km a.s.l. in the ranges.

#### Crustal Structure in relation to subduction geometry

From the preceding discussion and Figure 15, it is clear that the extensional block-faulted terrain involving basement lies over the downward fold of the subducting Pacific Plate where that plate is ~45 km or more below the Earth's surface. It is also noticeable that the TVZ is widest above the centre of the downward fold and that the TVZ narrows towards the upward folds to either side. The trend of the Kaimanawa-Raukumara ranges, and to some extent the faults which segment these ranges, are oriented in sympathy with the structure contours. Southwest of the extensional province and over the upward fold of the Pacific Plate a different pattern is found. Basement is differentially uplifted above sea level by oblique-slip movement on NW dipping faults between the Ruahine-Tararua ranges and the east coast.

Further west, middle to late Quaternary movement on subsurface thrust faults has formed force folds in Quaternary strata of the eastern Wanganui Basin (Te Punga, 1957) (Figure 15). The origin of the broad downwarping of the Wanganui Basin is not clear; it may result from isostatic instability caused by the shallow subduction or it may be related to the dynamics of thrusting further east, an idea supported by the slightly asymmetrical shape of the basin which is deeper to the SE (Anderton, 1981). The NW part of the Wanganui Basin which lies more than 45 km above the Pacific Plate has been uplifted several hundred metres during the last  $\frac{1}{2}$  million years (Fleming, 1953; Pillans, 1983). There, NE trending normal faults with throws of several tens of metres have displaced middle to late Pleistocene marine terraces. This may indicate that as the subducting plate is retreating, a wedge of upper Mantle is progressively migrating southward and consequently a compressive stress regime is being supplanted with an extensional one. This may explain the mixed focal mechanism solutions in the Wanganui Basin (Garrick and Gibowicz, 1983) discussed earlier.

The emphasis in this section has been on the crustal structure of the North Island. One of the enigmas of the structure of northern South Island is the occurrence of the Moutere Depression which is surrounded to the west, east and south by crust in a state of compression as shown by focal mechanisms (Figure 11), triangulation data (Figure 12) and the distribution of reverse and oblique-slip faults. Interestingly, the Moutere Depression lies at a similar distance above the subducting plate as does the TVZ (Figure 3). I suggest, but do not develop further, the possibility that the Moutere Depression has a similar origin in lying above a downward fold in the subducting plate.

INTEGRATION OF THE SUBDUCTION GEOMETRY WITH THE SHORT AND LONGER TERM STATES OF STRESS OF THE OVERRIDING PLATE

During the last decade there has been increasing evidence for the proposition that subduction geometry is a principal control on the state of stress and thus the deformational style of the overriding plate (e.g. Kelleher and McCann, 1976; Barazangi and Isacks, 1976; Cross and Pilger, 1982). Low angle subduction is associated with compressional stresses that are expressed as interplate thrust earthquakes, imbricate thrusting in the forearc region, basement involved foreland deformation and magmatic nulls or increased arc-trench distances. In contrast, high angle subduction is associated with extensional stresses, active volcanic arc segments, back-arc extension and back-arc volcanism. That both of these end-member associations hold concurrently for different parts of northern New Zealand is evident from the short and longer term states of stress of the overriding crust as discussed in Part 2 of this paper. However there are some differences between the short and longer term states of stress that may be significant.

The focal mechanism solutions and geodetic data show that east of a line approximately through East Cape, Wanganui and Nelson, the crust in the short term is under compression, whereas it is in extension to the NW of this line. All the historic earthquakes in the North Island greater than magnitude 7 lie east of such a line or boundary zone (Eiby, 1978). The occurrence of the mixed thrust and

extensional focal mechanisms of Garrick and Gibowicz (1983) in this boundary zone are indicative of a transition from compression to extension. The boundary zone corresponds to the surface projection of the 33 - 45 km depth contours. This approximates the thickness of the crust and suggests that the extent of the compressive state of stress over the North Island at present is controlled by the outer limit of the mechanical coupling of the crustal components of the two converging plates (Figure 10B).

Over the longer time scale of the middle to late Pleistocene, the structural pattern of faulting and folding, and volcanism, supports the short term pattern of the state of stress. However, even between these time scales there are differences. For example, northwest of the compression-extension boundary zone identified above, the degree of extension during the last 300 000 years has been much greater in the block-faulted TVZ region than NW of Wanganui where only a few faults have displaced uplifted middle to late Quaternary marine terraces. Another example is that the thermal regime west of Wanganui is much colder in the extensional province identified from the short-term state of stress than expected by comparison with the TVZ (Figure 9). The NW displacement of Mt Egmont is another manifestation of this pattern. These features suggest that the upper Mantle low velocity zone is less developed beneath the Wanganui Basin. This is probably related to the fact that the subducted slab has been beneath the northern parts of this basin only since the early Pliocene, and beneath the southern parts of the basin only since the late Pliocene (Kamp, 1984). This leads on to the question of what has controlled the extent and degree of extension to the NW of the surface projection of the 45 km depth contour?

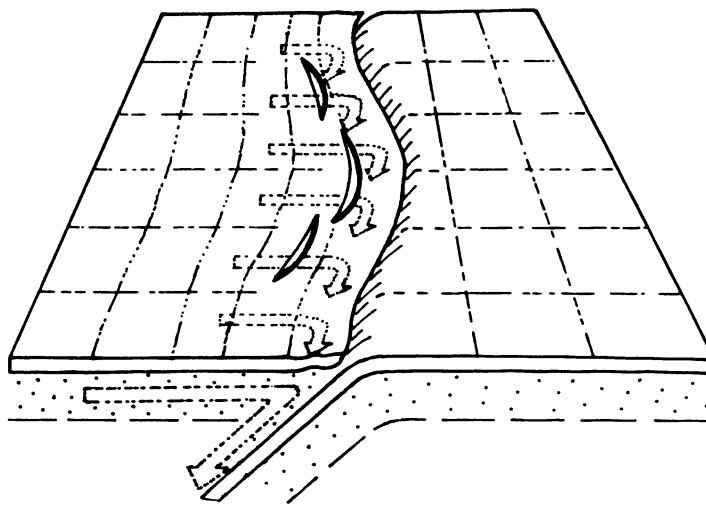


Figure 16 A schematic model of the localised origin of back-arc extension due to upper Mantle flow consequent upon retreat of the subducting slab. Modified from Bayly (1982).

### Mechanism of extension

The origin of back-arc extension and spreading is a complicated and unresolved topic (see Uyeda (1982) and Taylor and Karner (1983) for recent reviews). The early ideas that mantle diapirism or induced asthenospheric convection can cause back-arc extension and spreading have been shown to be unable to universally account for the occurrence and characteristics of back-arc extension and spreading (Taylor and Karner, 1983). The only elements common to back-arc spreading are either the retreat of the subducting plate relative to the overriding plate, or absolute motion of the overriding plate away from a stationary trench/subducting slab (Uyeda and Kanamori, 1979). In the northern New Zealand setting, as demonstrated in detail for the Neogene by Kamp (1984) and the Quaternary in this paper, the subducted Pacific Plate has retreated relative to the overriding plate at 20 km/y. The North Island is also moving northward at an absolute rate of about 50 mm/y (Figure 1). Therefore, these movements require net flow of the upper Mantle towards the Hikurangi Trench as a consequence primarily of the persistent retreat of the subducted slab, and secondarily, because of the direction of absolute motion of the North Island. Herein lies a mechanism for the differential extension evident in the North Island.

Figure 16 illustrates schematically, but yet realistically, how the late Cenozoic structures of the North Island west of the axial ranges originated by the control of subduction geometry on the upper Mantle flow. This is based on a theoretical model which postulates

that as a plate descends into the mantle it develops a series of buckles which grow to a finite amplitude (Bayly, 1982). The model predicts that in the centre of the downward fold of the subducting plate the rate of upper Mantle flow will be at a maximum and its drag effect on the overriding crust will also be at a maximum.

Conversely, least extension will be expected in the crust over the upward folds in the subducting plate. This model explains the structural evidence for greater middle to late Pleistocene extension in central versus western (Taranaki-Wanganui) North Island (Figure 15). In fact, it also explains the position and extent (shape) of the TVZ and why it narrows to the NE and SW.

Since continental crust is being extended by this mechanism, one might anticipate that despite the localised extent of the extension, that many of the normal characteristics of continental rifting will be expressed (e.g. Montadert et al., 1979; Curray, 1980; Illies and Baumann, 1982; Anderson et al., 1983). In this context, the TVZ, where basement has been differentially downfaulted 2 - 3 km and where the crust is thinned to 15 km (Cole, 1985), is viewed as the equivalent of the central rift trough. The Kaimanawa-western Raukumara Range is viewed as the elevated SE rift shoulder, and the progressive downstepping towards the TVZ of the long thin basement blocks defined by the N-S trending curvilinear normal faults, is viewed as the start of crustal thinning of this shoulder. A notable departure from a traditional continental rift setting is the absence of a well developed complementary (NW) rift shoulder. The Hauhaungaroa Range at the SW end of the TVZ may be in part the missing rift shoulder (Figure 10A). This gross rift asymmetry is probably due

to two factors. (1) The upper Mantle flow is asymmetrical in that it flows in one direction only (SE) and acts on a large part of the crust NW of the TVZ. (2) Since the Miocene the subducted plate has progressively steepened and retreated to the SE. Concomitantly, a zone, or front, of crustal extension has migrated to the SE behind the volcanic front. Hence, an elevated rift shoulder to the NW of the TVZ is not expected as the basement has been stretched and thinned as the extensional front migrated towards the southeast. These two factors also explain the origin of the basin-and-range terrain to the NW of the TVZ. Moreover, the proposal that the crustal extension is driven by upper Mantle flow consequent upon slab retreat is testable in that it implies progressive southeastward younging of the extension as well as the persistence of extension well behind the front.

#### A test of the proposed mechanism of extension

While many of the extensional normal faults over central and northern North Island (Figure 15) formed during the late Cenozoic, some of the faults are inherited from earlier and different tectonic settings. For example, the N-S trending Waipa Fault defines the junction of two contrasting basement terranes (Murihiku and Waipapa) and probably originated during the Triassic, but it also displaces Miocene beds. Most of the other N-S trending faults in central-western North Island also predate the late Cenozoic. One of these, the Taranaki Fault has up to 7000 m of displacement and defines the eastern margin of the Taranaki Basin. The origin of these faults and the associated early to middle Cenozoic cover rocks have been attributed by Kamp (1985a) to the development of a western New Zealand

continental rift system. Some of the NE-SW trending faults east of the Taranaki Fault also originated during this rifting interval; Nelson (1978) and Fergusson (in prep.) have respectively documented evidence for Oligocene synsedimentary displacement on the Marokopa and Oparau Faults. In central and northeastern parts of the North Island the absence of Paleogene and early Neogene beds preclude stratigraphic evidence for or against the late Cenozoic reactivation of pre-existing structures.

Given the pre-late Cenozoic origin of many of the normal faults, it is nevertheless clear that since the early Miocene a new episode of normal faulting has affected central and western North Island. In general terms the spatial and temporal trends in this faulting support the pattern predicted by the upper Mantle flow mechanism in that the faulting youngs to the south but has persisted in the more northern regions where it began. In the South Auckland district a regional unconformity extends from the late-early Miocene to the early Pliocene, after which the shallow marine Kaawa Formation was deposited. Kear (1957), Schofield (1958a, b) and Kear and Schofield (1978) infer regional uplift accompanied by faulting during the period when this unconformity developed. At Kaawa, which is one of the few places where the age of faulting is stratigraphically constrained, normal fault displacement of early Miocene beds occurred before the Kaawa Formation was deposited, but significantly, the fault was rejuvenated during the deposition of this formation (Kear, 1957). Schofield (1958b) also conceded that while much of the faulting preceded Kaawa Formation deposition, it has continued since then as shown by displacement of the Quaternary South Auckland back-arc

basalts. He also calculated 80 m of subsidence of the Manukau Basin since the mid-Pliocene. Todd (1982) interpreted 100 m of post-Miocene subsidence of the southern part of the North Waikato Basin from drill-hole data, but my own data shows at least 50 m of post-early Pleistocene uplift on the West Coast south of the Port Waikato Fault. Hence, in the South Auckland district, regional uplift accompanied by faulting and then differential fault block movements have occurred since the early Miocene, about the time the volcanic front migrated through this region.

South of Kawhia Harbour and along the West Coast ranges the age of the youngest strata deposited in the former western rift system become younger southwards. This represents a southward regression which began in the early-Miocene and culminated south of the Herangi Range in the early Pliocene. This regression is a manifestation of the regional uplift which accompanied the southeast migration of the volcanic front, and it was followed by differential subsidence. The subsidence was occurring by the late Pliocene in the Kawhia region as Pirongia lavas and lahars aged about 2.1 My B.P. (Stipp, 1968) were channelled along a fault angle depression bounded by the rejuvenated Oparau Fault. Drill-hole data also show that sedimentation began in the South Waikato Basin in the late Pliocene (Kear and Schofield, 1978). Sedimentation in the southern part of the Hauraki Basin is probably of the same age or younger, as Kear and Tolley (1958) have recorded early Pleistocene sediments over basement. This continuing subsidence has been accompanied by uplift of the adjacent blocks. In the southern Hauraki Basin the 0.84 My B.P. Waiteariki Ignimbrite has been displaced vertically by 300 m, and the late Pleistocene Hinuera

Formation is displaced by active faults (Cuthbertson, 1981). Near Kawhia, Chappell (1970) has recorded tens of metres of post middle Pleistocene uplift. Hence the pattern of regional uplift followed by differential vertical movement on normal faults established for South Auckland, also occurred in the Waikato, but there it is of younger age.

The age of initial faulting in the Taupo Volcanic Zone is difficult to establish. Based on the position of the 1.9 My B.P. time line (Figure 13), the early Pleistocene tephras in sedimentary sequences in Hawke's Bay (new data) may well have originated from the Mangakino Volcanic Centre. This would suggest that initial faulting of the northwestern parts of the TVZ probably started in the early Pleistocene. In the axis of the TVZ, middle Pleistocene ignimbrites are clearly tilted, and displaced in places by more than 1 km (Grindley, 1965). On the other hand, historical records show that normal faulting immediately behind the volcanic front is still very active; this is confirmed by the degree of fault displacement of the 50,000 yr B.P. Earthquake Flat Breccia (Nairn, 1976). Southeast of the TVZ Healy (1982) records that the normal faults within the ranges displace ~300,000 year old ignimbrites, and that the faults have also controlled the deposition of younger (150,000 yr B.P.) ignimbrites.

In conclusion, a reconnaissance study of the age of the late Cenozoic faulting of northern and western North Island supports the proposed mechanism of crustal extension in the back-arc region. It is possible that a wave of regional uplift accompanied the southeastward migration of the volcanic front but this is the subject

of continuing investigations. This was followed by the propagation of crustal extension to the SE behind the volcanic front which was manifest as differential vertical movements.

#### CONCLUSIONS

- (1) From a combination of mantle seismicity recorded by a local New Zealand seismograph network, microearthquake traverses over the shallow subduction sections (<50 km) and the results of marine seismic reflection and refraction studies, where available, a map of the structure contours drawn on the top of the subducting Pacific Plate has been made. This map reveals that the Pacific Plate has a buckled morphology. This contrasts with the planar Wadati-Benioff Zone inferred by Adams and Ware (1977) from the mantle seismicity alone.
- (2) Considerations of the extent of the upper Mantle low velocity zone, the trends of the negative and positive gravity anomaly contours, and the heat flow pattern over northern New Zealand, corroborate the buckled subduction geometry inferred from the seismicity and velocity structure.
- (3) In the second part of this paper I show how the variable dip of the subducting plate, combined with the persistent retreat of the slab, have controlled the short term state of stress of the overriding plate and the longer term surface manifestations expressed as volcanism and structural deformation.

- (4) Focal mechanism solutions and geodetic data show a broader zone of compression in the crust above the more shallow dipping upward fold in the subducting plate; these short term monitors of the state of stress show that extension dominates in the crust which lies more than 33-45 km above the slab. The extent of compression appears to be controlled by the outer limit of the mechanical coupling of the crustal components of the two converging plates.
- (5) The short term pattern of the state of stress of the overriding plate is supported by the longer term (Quaternary) volcanic and structural patterns. Two end-member associations occur in relation to the subduction geometry. The region above the downward fold in the slab is characterised by an active andesite-dacite arc, bimodal volcanism behind the arc, low heat flow values in the forearc region and high values behind the arc, and a foreland basin-and-range topography. In contrast, the region above the more shallow dipping section, corresponding to the upward fold in the slab, is characterised by a discontinuous andesite arc displaced 83 km further from the trench than the neighbouring steeper subduction section, no back-arc volcanism, low heat flow values up to 300 km from the trench, and a broad zone of basement-cored thrust deformation.
- (6) The age, position and potash content of the frontal arc, fossil (1.9 My B.P.) frontal arc and fossil (1.8 my B.P.) behind-front andesites, in relation to a locally developed  $k_2O-h$  relationship, suggests that the subducted slab has retreated 40 km towards the trench during the last 1.9 million years at a rate of 20 km/My.

- (7) It is proposed that the persistent retreat of the buckled slab causes upper Mantle flow towards the trench, and this in turn causes crustal extension behind and in front of the arc by way of drag on the base of the crust. This mechanism predicts that foreland extension should migrate with the frontal arc but persist well behind the arc where it began. This is supported by the age of faulting in the basin-and-range terrain behind and within the present frontal arc.

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Cross-referencing to thesis papers

Kamp, P.J.J., 1982, is equivalent to paper 2.

Kamp, P.J.J., 1984, is equivalent to paper 6.

Kamp, P.J.J., 1985, is equivalent to paper 1.

Kamp, P.J.J. and C.G. Vucetich, 1982, is equivalent to paper 3.

## CONCLUSIONS

A model of the Cenozoic tectonic development of New Zealand

## A MODEL OF THE CENOZOIC TECTONIC DEVELOPMENT OF NEW ZEALAND

### INTRODUCTION

A century of geological exploration and mapping has permitted identification and documentation of the nature, complexity and intensity of Cenozoic tectonic activity in New Zealand. This tectonic activity has included, for example, up to 7 km of subsidence in some parts of New Zealand (Taranaki Basin) and 3 km of uplift in other parts (Southern Alps), as well as widespread calc-alkaline frontal arc volcanism, back-arc volcanism and the obduction of ophiolite seamounts. The concept of plate tectonics offers a basis for understanding the nature and complexity of this tectonic pattern and simplifying it into its essential elements. Previous attempts to rationalise aspects of New Zealand's Cenozoic record in terms of plate tectonics were reviewed in the introduction to this thesis. The model by Carter and Norris (1976), subsequently developed by Norris et al. (1978) and Norris and Carter (1982), has been the most influential one. It proposed that much of the Cenozoic structural and sedimentary geology of New Zealand can be reconciled by a latest Eocene inception of the Australia-Pacific plate boundary as a zone of slow oblique extension, followed by a through-going continental transform (early Miocene to late mid-Miocene), and then by a late Miocene-Recent compressive transform system.

The Carter and Norris model and the others proposed until now (e.g., Cole and Lewis, 1981; Ballance et al., 1982) are not

completely acceptable as they fail to explain some major aspects of both the Cenozoic and Mesozoic geology. The limitations of these models have been referred to in the preceding papers of this thesis. These limitations may have arisen for several reasons:

(1) The models were proposed to solve regional problems, and their implications for other parts of New Zealand's Cenozoic geology were not totally considered. For example, the Carter and Norris model is only constrained by South Island Cenozoic geology; it includes an unacceptable dislocation of eastern North Island on a simple extension of the Alpine Fault.

(2) The models have been designed to solve Cenozoic problems and, while apparently consistent solutions have been proposed, their implications for the basement geology are unacceptable. For example, the idea of Cole and Lewis (1981) and Ballance et al. (1982) of transferring eastern North Island along an extension of the Alpine Fault and the Vening Meinesz Fracture Zone (VMFZ), is at variance with age and lithological trends in the basement.

(3) The models have not incorporated constraints of the ocean crust surrounding New Zealand, and especially its age. This is understandable as many of the models (e.g., Brothers, 1974; Ballance, 1976) predated the availability of these data.

For these reasons, one must critically examine the whole of the New Zealand Cenozoic record, both onshore and offshore, as well as appreciate aspects of the Mesozoic basement geology, to be in a position to propose an integral model of the Cenozoic tectonic development of New Zealand. This is a tall order. Realistically,

such a comprehensive model may never be attained; we should, however, advance towards it by a series of approximations, each one accounting for more and more detail as the catalogue of geological data enlarges. With this philosophy in mind, a conceptual model of the Cenozoic tectonic development of New Zealand is outlined and discussed.

The preceding papers in this thesis have been a necessarily lengthy prelude to the model as they have addressed critical problem areas directly related to the character and age of the different types of plate boundaries in the New Zealand region, and the response of the continental crust to the relative plate motions. The proposed solutions to the problems identified in the thesis introduction are briefly summarised, using the same enumerations as in the introduction:

- (1) The New Zealand sector of the Australia-Pacific plate boundary, including the Alpine Fault, was incepted during the early Miocene and probably about 23 million years ago.
- (2) The tectonic setting during the Paleogene was characterised by the development of a continental rift system through western New Zealand. This rift system was a direct response, within the New Zealand subcontinent, to seafloor spreading along oceanic ridges aligned to the north and south.
- (3) The relative plate motion evident as horizontal fault displacement on the Alpine Fault was expressed in Marlborough and eastern North Island as a combination of brittle and ductile deformation. Thus a recurved arc formed in Marlborough and eastern North Island while fault displacements occurred on the Alpine Fault.

(4) The total amount of Cenozoic horizontal displacement through New Zealand has been about 500 km. This is half of the currently adopted figure of 1000 km that has been built into previous models of the plate tectonic evolution of the southwest Pacific region.

(5) The age, location and composition of the calc-alkaline frontal arc and behind arc volcanics in northern North Island, together with different geophysical parameters, have been used to monitor the extent and geometry of the subducted Pacific Plate at present and for the Neogene-Quaternary. The geometry of the slab, together with its persistent trenchward retreat, has been shown to control the Neogene and Quaternary tectonics of the overriding Australia Plate in northern New Zealand.

These solutions enable one to propose and discuss a new model of the Cenozoic tectonic development of New Zealand.

#### A MODEL OF TECTONIC SUCCESSION

The basic proposition is that the Cenozoic geology of New Zealand developed under two fundamentally different tectonic regimes, one succeeding the other. The first was a regime of continental extension. Active extension started during the Eocene and the resulting crustal thinning was most pronounced through western New Zealand where a north-south trending continental rift system formed. In the early Miocene, the Australia-Pacific transform plate boundary propagated through New Zealand. This may be considered the start of

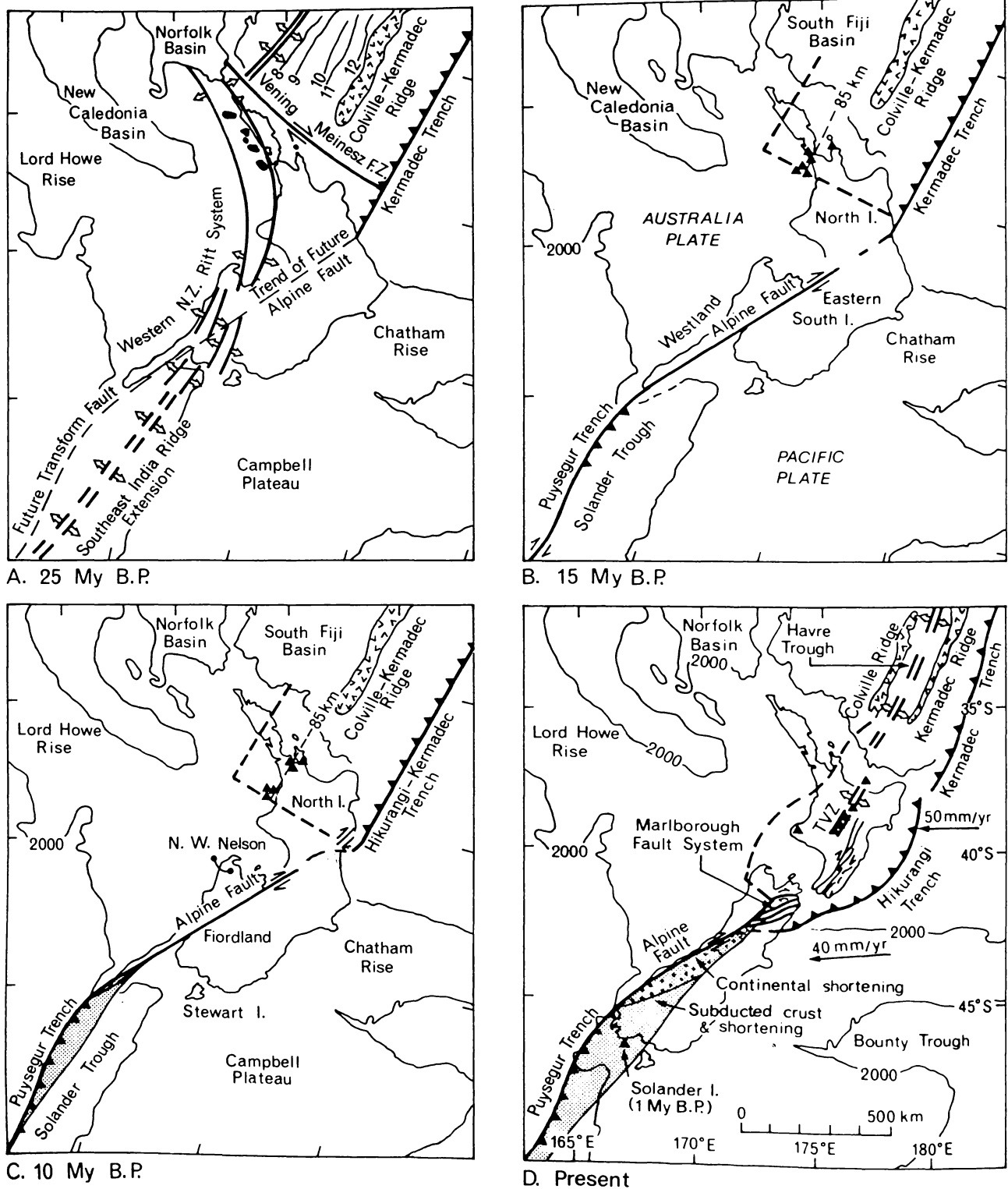


Figure 1 A series of four maps showing the essential elements of the Cenozoic plate tectonic development of the New Zealand subcontinent. See text for discussion, but note how with time the extent of subducted oceanic lithosphere beneath New Zealand increases. The extent of the Pacific Plate beneath northern New Zealand is from Paper 6, and beneath southern South Island from Davey and Smith (1983).

the second phase in the Cenozoic tectonic development of New Zealand, that of plate convergence. However, and importantly, there was not an instantaneous cessation of crustal extension over the whole of New Zealand; away from the new plate boundary, especially along the axis of the rift system, crustal extension persisted well into the Miocene. Hence there was a gradual tectonic overprinting during which the extensional regime was supplanted by one controlled by the oblique convergence of the Australia and Pacific plates. It is difficult to give an exact date when the extension, initiated during the Eocene, finally ceased; it probably occurred during the late Miocene.

The fundamental difference between the ideas put forward by Carter and Norris (1976), Norris et al. (1978) and Norris and Carter (1982), and the model proposed here, is that the previous modellers viewed the Cenozoic geology as arising from progressive changes in the tectonic character of the Australia-Pacific plate boundary alone, whereas I propose two discrete tectonic zones (the western rift system and the Australia-Pacific plate boundary) with one obliquely bisecting and overprinting the other in time and space (Fig. 1). The ultimate test of these different models is whether they can satisfactorily account for the regional complexities of New Zealand's Cenozoic geology. In the following section I discuss the model of tectonic succession with a view to explaining some of the regional complexities.

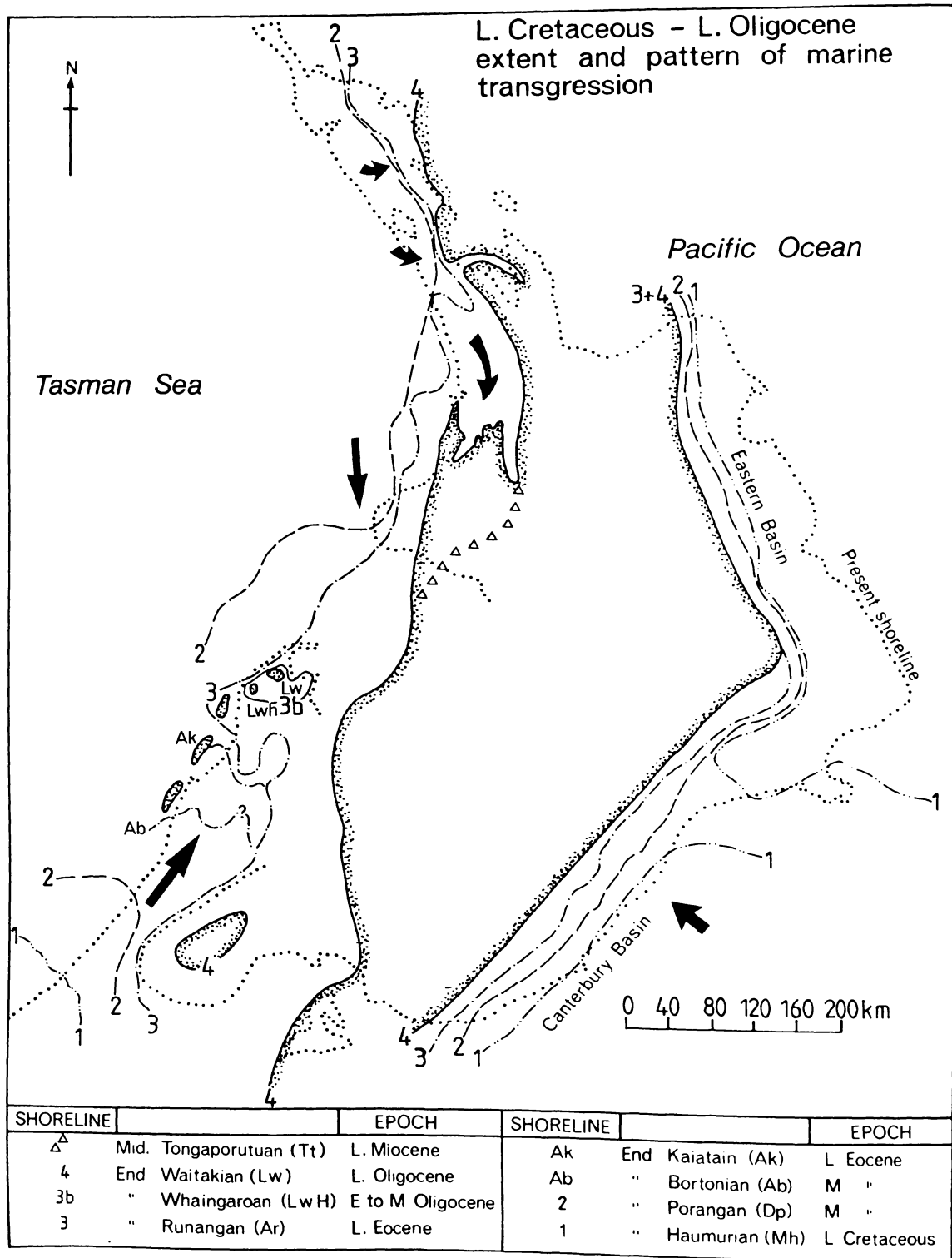


Figure 2 Map showing the late Cretaceous to late Oligocene extent and pattern of marine transgression over New Zealand. Map compiled from numerous sources. The shorelines are very poorly constrained in the Eastern Basin.

## DISCUSSION OF THE MODEL

### Prelude to the Cenozoic

Following the late-early Cretaceous breakup of eastern Gondwanaland, seafloor spreading on the Tasman Sea spreading centre and the Pacific-Antarctic Ridge caused the New Zealand subcontinent to drift eastward into the Pacific Ocean. Soon after the start of this seafloor spreading, thermally induced subsidence of the formerly rifted continental margins caused the subcontinent to start foundering. By the end of the Cretaceous, much of the subcontinent had already subsided below sea level, judging from the position of the shoreline in New Zealand (Fig. 2) and the stratigraphy of DSDP cores in the New Zealand region (Kennett *et al.*, 1975). The extent of submerged continental crust is consistent with the thickness of this crust which would have been isostatically unstable; earthquake surface-wave dispersion measurements show that the sialic crust averages 17-25 km thickness below the submerged plateaux and ridges (Officer, 1955; Adams, 1962), versus truly continental thicknesses of 30-35 km beneath the New Zealand mainland (Thomson and Evison, 1962). The extent of the crustal thinning was probably due to the extent of the rifted continental margins within the Lord Howe Rise (Jongsma and Mutter, 1978) and around the Campbell Plateau (Katz, 1982). It was no doubt also due to crustal thinning about the re-entrants of the New Caledonia Basin and Bounty Trough.

Paleogene - a time of extension

At the time of anomaly 24 (57 My B.P., mid-Paleocene), spreading in the Tasman Sea suddenly stopped and the rate of spreading on the western end of the Pacific-Antarctic Ridge reduced in rate by 70% (Paper 5). For the next 5 million years (late Paleocene to early Eocene) New Zealand lay in a stable intraplate position and was not subjected to plate boundary processes. However, a 100-200 km wide north-south trending zone of differential vertical crustal movements started to develop through western New Zealand during the middle Eocene. In Paper 1 I showed that the mid-Eocene to Oligocene geological development of this region, characterised by the formation and infilling of 2-4 km deep troughs and half grabens, is consistent with the formation of a continental rift system. Four phases of rift development were identified. (1) A 10 My middle to late Eocene infra-rift phase of slow subsidence in broad depressions or half grabens was characterised by the accumulation of coal measures and then shallow marine transgressive lithofacies. (2) An active latest Eocene-early Oligocene phase of subsidence, in as little as 2 to 3 My, created steep-sided central troughs, in which submarine fan deposits accumulated. Faulting was mainly localised on master fault zones at the trough margins. (3) An Oligocene expanded rift phase, was characterised by the isostatic subsidence of the basement shoulders marginal to the central troughs, and the creation of an expanded zone of tilt blocks and half grabens up to 2 km deep, in which flysch deposits or shelf limestones and mudstones accumulated. This phase occurred during the early Miocene in central-western North Island, as is discussed further below. The regional subsidence accompanying this

phase submerged many of the remaining terrigenous source areas and permitted the widespread Oligocene development of skeletal shelf and deep-marine foraminiferal limestones. Phase (4) involved the incipient introduction of oceanic crust into the rift axis, and this occurred only in the northern part of the rift system (Paper 7).

In eastern New Zealand, outside the zone of active rifting and crustal extension, the Paleogene sedimentation patterns accord with the evidence for a rift system to the west. The regular sub-parallel displacement of the lower Tertiary shorelines to the NW in the Canterbury Basin (Fig. 2), and less certainly to the SE in the Eastern Basin, suggest that the sea transgressed up a gently dipping basement surface tilted outwards from the elevated eastern shoulder of the rift system. The deposits in these basins become increasingly calcareous and glauconitic into the Oligocene; this may have resulted from a combination of the diminishing elevation of the land to the west, and the partial reversal of drainage back to the west as the rift expanded. The generally finer grained, more terrigenous, and deeper marine deposits of the eastern Basin compared with the Canterbury Basin, may reflect the location of the former basin at the northeastern margin of the subcontinent, compared with the intra-continental position of the Canterbury Basin (Fig. 1).

Throughout the development of the rift system, but in particular at the end of the Oligocene, it is evident from the spatial distribution of the four phases (Paper 1) of rift development that the rift system had a northern and a southern segment. The northern segment propagated to the south, while the southern segment propagated

to the north. This is clearly evident from the extent and pattern of the marine transgression (Fig. 2). The major difference between the two segments of the rift system is that the northern one consisted of a regular north to south progression of phases, 4, 3, 2 and 1, whereas the southern segment seems to have developed alternate rift nucleation zones and locked zones. Thus, even within the one tectonic regime (extensional), significant regional differences in the Paleogene geology of New Zealand existed.

An important difference between my model and the one proposed by Carter and Norris, is that they view the Eocene-Oligocene basins in western South Island as originating in an obliquely extensional (transtensional) manner, whereas I invoke pure extension. No evidence of displaced marker beds or other hard evidence has been documented to support the transcurrent component of the oblique extension; it was inferred by Carter and Norris from the southwest Pacific plate tectonic synthesis of Molnar et al. (1975). However, the patterns of rift development I have described are directly comparable with recognised models of rift development (c.f. Vink, 1982; Courtillot, 1982).

Whether or not there was a transcurrent component to the rifting is an important point as its occurrence implies an Eocene-Oligocene rather than a Neogene age of inception of the Australia-Pacific plate boundary.

Unfortunately, the problem cannot be resolved from study of the age of the oceanic crust alone, as there are two non-spreading plate boundaries in the Australia-Antarctica-Pacific-New Zealand plate circuit. Geological constraints, including at the very least the age and total amount of lateral displacement across either the Australia-Pacific plate boundary through New Zealand or the plate boundary within Antarctica, are required to obtain a unique solution to the plate tectonic development of the southwest Pacific Region (contrast Stock and Molnar, 1982). These data have been obtained in this thesis for the plate boundary through New Zealand (see papers 1 and 4). I discuss first, geological data for the age of the plate boundary and then the total amount of displacement on it.

1. Age of the New Zealand sector of the Australia-Pacific plate boundary

In western South Island the Eo-Oligocene rift system is offset by about 480 km on the Alpine Fault. The age of the start of dislocation and disruption of this system will therefore date the start of plate boundary movements. Close to the Alpine Fault, in central Westland, what became a major reversal in the direction of vertical crustal movements, from those which characterised the rifting (subsidence), started in the early Miocene. There, a post-Oligocene to mid-early Miocene unconformity separates limestone deposits from terrigenous deposits (Nathan, 1978a) (Paper 1: Fig. 8). The development of the unconformity and the change to terrigenous sedimentation is interpreted in this thesis as the start of Alpine Fault movement. On the opposite side of the Alpine Fault in the Waiiau Basin, the early Miocene start of Alpine Fault movement is recorded by the

establishment of new terrigenous source areas, and in particular, the derivation of a thick succession of sandy flysch from the north (Norris et al., 1978). A very early Miocene age (about 23 My B.P.) of plate boundary formation is also indicated in eastern North Island, where Kingma's Eastern Basin (Fig. 2) from that time became differentiated and kneaded into numerous and discrete basins as the subduction thrust developed. It is important to appreciate that the Paleogene extensional tectonic regime, which was characterised by the effects of differential and regional subsidence and transgression, changed from the early Miocene onwards to one characterised by the effects of transcurrent displacements, compression, subduction, calc-alkaline volcanism, ophiolite obduction and marine regression.

## 2. The total amount of dextral displacement through New Zealand

In Paper 4 I conclude that there has been about 500 km of dextral displacement on the New Zealand sector of the plate boundary since its inception 23 million years ago. This subject is inextricably linked to the age and origin of the recurved arc structures in the basement and cover rocks, and to the age of the Alpine Fault. Based on paleomagnetic constraints, and age and lithology trends in the basement, it was proposed in Paper 4 that the orocline actually comprises two recurved arcs. A Western Arc has a multiple origin and formed mainly during the late Triassic phase of the Rangitata Orogeny, whereas an Eastern Arc formed with the late Cenozoic development of the Australia-Pacific plate boundary. The Eastern Arc is viewed as a mega, brittle-ductile, shear zone that formed immediately northeast of the Alpine Fault and represents the relative plate motion which was

expressed as dextral fault displacements on the Alpine Fault (Paper 4: Fig. 6). Therefore the total displacement through New Zealand has been about 500 km, rather than the commonly adopted figure of 1000 km derived from the notion that the recurved arc is a single structure which formed immediately before Alpine Fault movement.

#### The plate tectonic development of the southwest Pacific region

The derivation of the critical information of the age and total amount of dextral displacement on the New Zealand sector of the Australia-Pacific plate boundary, made it possible to formulate a new and different interpretation of the tectonic development of the southwest Pacific region. This was achieved in Paper 5. This model corroborates the onland geological evidence for an Eocene-Oligocene western rift system, as throughout the rifting, spreading centres were aligned with the ends of the rift system (Paper 5: Fig. 8). It is clear that when the Southeast Indian Ridge broke through into the south Tasman Sea in the early Eocene (An 21), it rapidly propagated eastwards and directly into the South Island segment of the rift system. Moreover, the phases of rift development can be matched to the degree of spreading. The middle to late Eocene infra-rift phase of subsidence coincides with the generation of An21-An18 seafloor on the spreading ridge a few hundred km west of the South Island. The late Eocene-Oligocene transition to active rift subsidence coincides with the introduction of An 15 - An 13 aged seafloor adjacent to the South Island.

As the linear magnetic anomalies 12-18 are symmetrically disposed either side of the fossil spreading ridge (Macquarie Ridge), and are parallel to the Auckland Island Slope and the older Tasman Sea seafloor (Paper 5: fig. 8), there is no evidence to indicate that the spreading, and hence rifting, was oblique - as suggested by Molnar et al. (1975) and adopted by Carter and Norris (1976) and Norris et al. (1978).

Unfortunately, the weakly defined seafloor magnetic anomalies in the Norfolk Basin have not yet been analysed (Malahoff et al., 1982). Therefore it cannot be stated with certainty that the Norfolk Basin formed by seafloor spreading at the same time as crustal extension in the North Island segment of the rift system. However, all the geological and geophysical indications are that it formed at the same time as back-arc spreading in the South Fiji Basin (see Paper 7), paleomagnetically dated as Oligocene (An13 - An7A).

Although extension and seafloor spreading dominated in and adjacent to northern New Zealand, one of the consequences of South Fiji Basin back-arc spreading was dextral transform movement on the Vening Meinesz Fracture Zone along the continental margin of northeastern North Island (Fig. 1A). This motion appears to have had little effect upon the adjacent rifting in Northland. The motion was important, though, in creating ophiolite seamounts by the shearing of Cretaceous MORB ocean crust that was added to by alkaline igneous activity before their obduction onto northland and East Cape 23 million years ago (Brothers, 1983).

The new synthesis of the southwest Pacific plate tectonic development (paper 5) also provides a good reason for the propagation of the Australia-Pacific plate boundary through New Zealand. It appears that soon after An7 time (26 My B.P., late Oligocene) spreading ceased on the extension of the southeast Indian Ridge (Fig. 1a). This caused a sudden disparity in the spreading rates between the eastern end of the Southeast Indian Ridge (west of Fracture Zone Z) and the western end of the Pacific-Antarctic ridge. As a geometric consequence, a transform fault was required to resolve the differences in relative plate motions. Such a fault formed about 23 million years ago through New Zealand between the southern end of the Kermadec Trench and the Southeast Indian Ridge (Fig. 1).

During the Neogene and Quaternary, the original transform fault has evolved into alternating short trench and transform fault sections (Paper 5: Figs 1 and 9). Subtle changes in the plan shape of the original fault, together with changes in the migration direction of the Australia-Pacific pole of rotation, are considered to be the reasons for this (Paper 5). Prior to An5 (9.5 My B.P.) the pole of rotation migrated SSE more or less parallel to the transform fault, and therefore underthrusting could only occur where the plan shape of the transform fault allowed it; after An5 the pole migrated to the SW, oblique to the trend of most of the plate boundary, causing a large additional component of underthrusting to occur. The immaturity of the Hjort and Puysegur active margins explains the scarcity of calc-alkaline volcanism. The only volcano of this type is Solander Island (Harrington and Wood, 1958) which erupted 1 million years ago (Fig. 1d). This contrasts with the extensive record of late Cenozoic

frontal arc calc-alkaline volcanism in northern North Island (see Paper 6).

The Oligocene occurrence of back-arc spreading in the South Fiji Basin indicates that a slab of subducted oceanic Pacific Plate lay immediately to the NE of northeastern North Island at the end of the Oligocene. Based on the age-space distribution of the Neogene frontal arc volcanics in Northern New Zealand, it was proposed that with the start of relative motion on the Australia-Pacific transform, the slab was dragged laterally beneath northern New Zealand (Paper 5). By this mechanism there would not be a long delay before volcanism started while the slab was subducting from the trench to an appropriate depth to permit the generation of andesitic melts. Rather, the volcanic manifestations of subduction could occur, as they did in the early Miocene in Northland, after only a few tens of kilometres of lateral displacement. Of course, this explanation is only valid as long as the volcanic arcs are viewed as having migrated to the SE, rather than to the east or NE as proposed by Ballance (1976) and Ballance *et al.* (1982). The question of southeastward migration of the Neogene and Quaternary volcanic arcs is argued in Paper 6.

#### Tectonic overprinting of the rift system

With the early Miocene inception of the Australia-Pacific plate boundary and dextral displacement on the Alpine Fault, the rift system lost its continuity through western New Zealand. Early on in the development of the plate boundary the rift basins adjacent to the Alpine Fault ceased to subside, and in fact became uplifted, while the

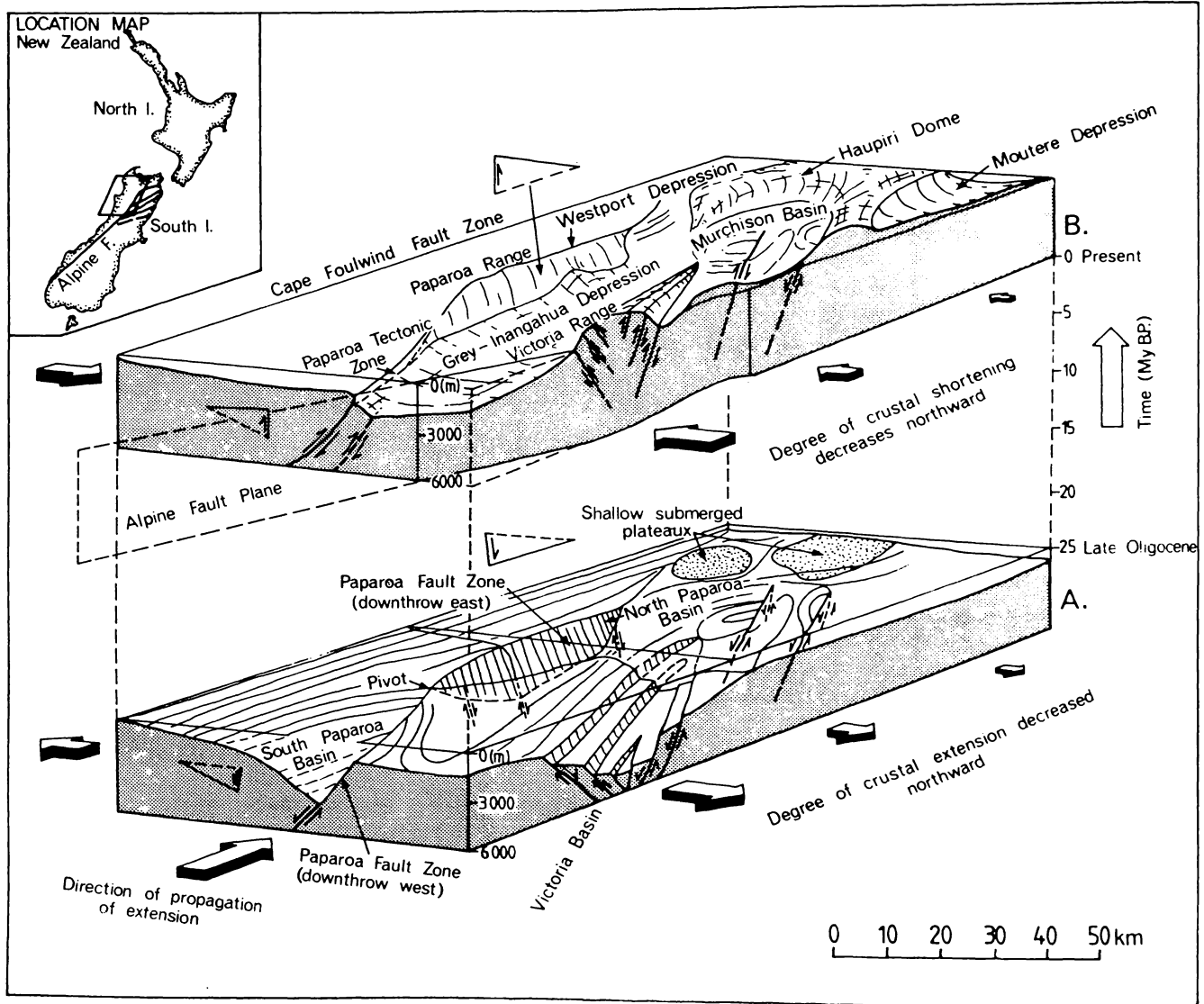


Figure 3 A block diagram schematically showing the change from crustal extension and rifting to crustal shortening in central Westland following the inception and development of the Australia-Pacific plate boundary through the South Island. The Victoria Basin and Range is shown as continuing to the right hand edge of the block, which approximates the position of the Alpine Fault. In reality the basin closed west of the fault; it is drawn in this way to show a section of the eversion. Note how the rift structures were re-activated in the opposite direction after the late Oligocene. Based on Figs 7 and 9, Paper 1.

parts of the rift further away from the Alpine Fault continued to develop by extension. The result, after 23 million years of plate boundary development, is that the rift system has been totally disrupted and uplifted adjacent to the Alpine Fault, and for a distance of 150-200 km both to the north and to the south of this fault. However, in the North Island, only the eastern margin of the rift and its related basins have been uplifted, except for Cape Egmont where a small part of the central rift trough (Taranaki Basin) now lies above sea level. From the sedimentary geology of the former rift basins in the South Island, it can be demonstrated that the manifestations of compression across the Alpine Fault were recorded progressively later in time at increasing distances from the fault. This pattern continued northward into the Taranaki Basin. By contrast, it seems that in the North Island the more northern parts of the eastern rift shoulder were uplifted before central-western North Island. I discuss first the pattern of overprinting in the South Island, and then in the North Island.

#### South Island rift segment

Figure 3 attempts to show schematically for Westland and Nelson the effects of the Neogene and Quaternary tectonic overprinting which were caused by compression across the plate boundary. The general pattern is that in central Westland opposite, and to the SW of, the pronounced bend in the Alpine Fault, the former rift basins (Paparoa and Victoria) have been everted to become structural highs and the former structural highs have become late Cenozoic depressions, whereas in north Westland and Nelson, the former basins are still the current depressions. The regional difference is a manifestation of greater

compression and crustal shortening in central Westland than further to the north, and is probably related to proximity to the plate boundary, and to the orientation of the Alpine Fault in relation to the direction of relative plate motion (Fig. 1D).

Geological maps of central Westland (e.g. Gage, 1952; Suggate, 1957; Nathan, 1975, 1978b) show that the overturning of steep limbs of folds is widespread and that all the major faults are reverse, indicating east-west crustal shortening. That the reverse faults are inherited structures from the early Tertiary and possibly the late Cretaceous, but with the opposite sense of movement, was emphasised by Laird (1968). He documented how the direction of vertical displacement on the north-south trending Paparoa Fault Zone changed between the early and late Tertiary, and (he) attributed this to a change from east-west extension to compression. This interpretation is strongly supported here. Figure 3 shows how, following the inception of the plate boundary, the directions of vertical movement have changed such that the basement blocks that subsided during the Eocene-Oligocene to form half grabens and troughs, have now returned to sealevel, and even above, on the same fault zones; the sedimentary sequences that the rift basins once contained have been extruded and greatly eroded. The regional late Oligocene to mid-early Miocene unconformity in central Westland (Nathan, 1978a) records the change-over interval when the rift basins were no longer depocentres and before the adjacent Neogene depressions evolved by overthrusting. These depressions, notably the Grey-Inangahua and Westport depressions, were shortlived as marine basins; by the late Miocene, continuing compression and crustal thickening had initiated a marine

regression, and during the Plio-Pleistocene they received molasse deposits, mainly from the Southern Alps (Paper 1: Figs 8 and 15B).

The Murchison Basin has a different post-Oligocene history as it lay north of the pronounced bend in the Alpine Fault. The inception of the plate boundary is not recorded by an unconformity: rather, field data indicate a transition from calc-flysch to terrigenous flysch deposits (Matiri to Mangles Fm). Neither is there any indication of an abrupt change in the direction of basement movement: a gradual late-early Miocene decrease in the rate of subsidence may be inferred from the change from turbidite deposition in the lower Mangles Formation to shelf and neritic sedimentation in the upper Mangles Formation. However, the deposition of several kilometres of non-marine greywacke conglomerates during the late Miocene-early Pleistocene shows that subsidence did not cease despite the obvious evidence that substantial uplift was occurring on the other side of the Alpine Fault (Spencer Mountains) (Cutten, 1979). From this stratigraphy, extension and rift development probably continued until the late-early Miocene. Thereafter, the development of the basin was probably controlled by plate boundary dynamics.

The sedimentary manifestations of the inception of the plate boundary, and the subsequent cessation of rifting, both occurred slightly later in NW Nelson than in central Westland and the Murchison Basin. During the early Miocene, while the plate boundary was forming to the south, the sea was still transgressing over NW Nelson (phase 1, rift development) and depositing the Takaka Limestone. The mid-early Miocene change to the deposition of the terrigenous Tarakohe Mudstone

is the first manifestation of a new tectonic regime. Sedimentation continued in the Takaka and Aorere half grabens (Paper 1: Fig. 9) until the late Miocene when the bounding structural highs, especially the Pikikiruna Anticline, became uplifted above sealevel. Like the Mangles Formation in the Murchison Basin, the lower half (early Miocene) of the Tarakohe Mudstone comprises hemipelagic mudstone and turbidites, and the upper (mid-Miocene) half comprises shelf to estuarine sandstones and mudstones (Leask, 1980). From this record, extension and rifting probably ended at the early to middle Miocene boundary (about 16 million years ago).

That the Taranaki Basin should still be offshore is a logical consequence of the younging direction, identified above, in the tectonic overprinting of the former rift-system: evidently it is too distant for the crustal rethickening, stemming from the continent-continent collision across the Alpine Fault, to cause uplift of the basin above sealevel. Nevertheless, Knox (1982) has documented seismic evidence of the significant submarine uplift of blocks by reverse movement on previously normal faults. He reported 2000 m of late Miocene-Recent uplift near the southern end of the Taranaki Basin, with progressively lesser amounts to the north. Extension therefore continued until at least the late Miocene (13 My B.P.) in the Taranaki Basin.

South of the Alpine Fault in Southland, the same pattern of overprinting of the rift is evident, with a progression from completely everted basins (northern Moonlight Tectonic Zone c.f. central Westland), to uplifted and compressed basins (Waiau Basin c.f.

Murchison Basin), to rift basins still in the marine realm (Solander Basin c.f. Taranaki Basin). Although detailed sedimentary studies have not been done, and detailed age control is not available, the regional indications are that the rate of overprinting was similar to that in Westland-Nelson. A complication south of the Alpine Fault is the Fiordland block. It appears to have been driven like a wedge to the NE between the Alpine Fault and the Waiiau Basin, during the late Cenozoic, and as a result caused tremendous shortening in the Te Anau basin (Norris and Carter, 1980). That Fiordland could behave as an independent block results from the Oligocene pattern of rifting and the oblique bisection of the rift system by the Alpine Fault, making it an isolated mobile block sitting between the main part of the rift and the Alpine Fault.

North Island rift segment

From stratigraphic changes in various sedimentary properties of the North Wanganui Basin, Nelson and Hume (1977) inferred an Oligocene to late Pliocene tectonic timetable for central-western North Island. They related a sudden increase in tectonic activity at the Oligocene-Miocene boundary to initiation of predominantly dextral transcurrent movement on the Alpine Fault and the establishment of the Indian-Pacific plate boundary through New Zealand. However, they did not indicate in detail how the plate kinematics modulated the sedimentary record in the North Wanganui Basin. In view of their interpretation, it was surprising to find that extension was the dominant mode in the development of the North Wanganui Basin (Paper 1). This extension, which led to the basin's formation, could naturally be interpreted as the expansion of the rift system (phase 3) through isostatic collapse

of the eastern rift shoulder. In fact, it was from the analysis of the North Wanganui Basin that the concept of a western rift system grew. The reason for this is now clear - the evidence for the extensional origin of this basin has not been masked by the degree of tectonic overprinting evident in the South Island segment of the rift system. However, this reason was not fully appreciated until the continuity and age of the rift system through the South Island had been established, and the evidence for the early Miocene inception of the plate boundary recognised. In view of the progressive south to north overprinting of the rift system there is no problem with an early Miocene expansion of the rift system at the latitude of the North Wanganui Basin. Hence the North Wanganui Basin tectonic timetable identified by Nelson and Hume (1977) more probably relates to the development of the western rift system that started well before the formation of the Australia-Pacific plate boundary. In Paper 1, the cessation of extension in the vicinity of the North Wanganui Basin was placed in the late Miocene.

One of the main features of the North Island segment of the western rift system is the comparative longevity of rifting at the latitude of the North Wanganui Basin after the Australia-Pacific plate boundary was incepted. North of this basin, the eastern rift shoulder was completely uplifted by the time of the early to middle Miocene boundary. Hence, the longevity of the North Wanganui Basin may be related to its position with respect to progressive north to south tectonic overprinting (uplift) along the present west coast of the North Island, and to south to north overprinting as discussed in the preceding section. Before discussing the cause of the north to south

overprinting of the North Island rift segment, the pattern of this uplift is considered.

The early Miocene Waitemata Basin, which occurs north of the North Wanganui Basin, also originated through extension in response to the collapse of the eastern rift shoulder (Paper 1: Fig. 2). However, its life as a depocentre, or series of depocentres, was short-lived. The inferred paleogeographic development of the basin, in relation to biostratigraphic ages (Hayward, 1979), suggests that the uplift occurred from north to south. Hayward (1979) recorded substantial mid-early Miocene (mid-late Otaian) uplift of the northern region (Kaipara) while the more southern region (Auckland) accumulated turbidities at bathyal depths. The central to southern regions were subsequently uplifted during the late-early Miocene (late mid-Altonian). From Hayward's paleogeographic development of the basin, it is clear that the uplift and regression, first in the north (Kaipara) and then further south (Waitakere Ranges), was closely associated with the construction of volcanic centres. The identification of this association is important in postulating a cause for the pattern of overprinting. Moreover, the association permits better resolution of the spatial and temporal pattern of overprinting, as representative lavas have been K-Ar dated (Stipp and Thompson, 1971). The age-space pattern, identified in Paper 6, is one of a southeastward younging in frontal arc volcanism. This pattern very closely matches the pattern evident from the biostratigraphic ages which, by their very nature, cannot be as precise.

In Paper 6 I inferred from the record of frontal arc volcanism the Neogene extent and geometry of the subducting Pacific Plate beneath the North Island. I implied that the late-early Miocene trenchward retreat of the subducted slab permitted an upper Mantle wedge to be inserted beneath southern Northland and then Auckland, and that this was the cause of the north to south uplift and regression. I extend this interpretation here, and postulate that the increasing extent of the subducted slab, together with changes in its geometry, caused the progressive north to south tectonic overprinting of the North Island segment of the rift system. Figure 1 (B to D) summarises the increasing extent of the slab beneath the North Island. From this figure it is clear that the North Wanganui Basin was one of the last parts of the former rift system to be influenced by the interaction of the Australia and Pacific Plates. This did not happen until the late Miocene.

Accompanying the southward migration of the volcanic arc and the associated uplift of the basins which were formerly part of the eastern margin of the rift system, a new extensional regime was established over the North Island. The extension originated primarily from the persistent retreat of the subducting Pacific Plate (Paper 6). However, the degree of extension and its associated volcanic manifestations have not been distributed evenly over the North Island outside the east coast region where there has always been (Neogene-Quaternary) very shallow subduction and compression. In Paper 8 I show that the subducted slab of Pacific Ocean lithosphere is actually buckled in the general plane of subduction. This has resulted in a section beneath northern New Zealand (west and NW of the TVZ) with a

higher subduction angle, and a southern section (Taranaki, Wanganui) with a lower angle. The crust above the steeper dipping section is characterised by an active andesite-dacite frontal arc, extensive rhyolitic volcanism in a narrow zone behind the arc, a broad zone up to 400 km behind the arc of basaltic volcanism, and the extensive development within and behind the arc of a basin-and-range topography. By contrast, andesitic volcanism is displaced further from the trench above the shallower dipping section; there are no rhyolitic or basaltic volcanics onshores; and extensional normal faulting with differential fault block displacements are not well developed. Rather, a broad zone of downwarping (the Wanganui Basin) accompanied emplacement of the subducted slab beneath this region; only in the last 700 000 years has part of this basin been uplifted. These regional differences probably started to develop during the Neogene, but they were accentuated during the Quaternary. In Paper 8 I attribute the origin of the differential extension over the North Island (except the east coast region) to differential rates of trenchward flow of the upper Mantle, which has been driven by the development of the buckled slab during its persistent trenchward retreat.

Trenchward flow of the upper Mantle would cause drag on the base of the crust and would extent it in a NW-SE direction. Hence, this mechanism may well be the origin of the prominent set of NE-SW oriented faults in northern and central North Island (Paper 8: Fig. 15). However, some of these faults already existed, having formed during the earlier rift phase (e.g. Port Waikato, Oparau, Marakopa faults), and were reactivated during the late Cenozoic. So too were

many of the north-south trending faults that were involved in the preceding rift phase; some of these structures may even have been inherited from the Mesozoic (Kear, 1964). The intersection of these two fault directions has effectively subdivided the eastern margin of the former rift system and permitted the differential vertical movements that are largely responsible for the present landscape.

*Style of overprinting of the western rift system*

From the preceding discussion it is clear that the North Island and South Island segments of the western rift system were overprinted in two contrasting styles. The different structural, sedimentary and volcanic associations are manifestations chiefly of the fact that western North Island was overprinted by an ocean-continent subduction system, and western South Island by a classic continent-continent convergent setting (Fig. 1). However, there are common elements to the overprinting of both segments that deserve comment. These relate to age-space patterns in the manifestations of overprinting and may be important to consider when basins are investigated in isolation.

In central Westland adjacent to the Alpine Fault, the response of the rift basins to formation of the plate boundary was a near-instantaneous reversal in the vertical direction of crustal movement, followed immediately by uplift and erosion to form a regional unconformity. At intermediate distances from the new plate boundary (e.g. Murchison Basin) the tectonic event was recorded as a change in petrography, but the preceding direction of vertical movement persisted for a time, indicating that the tectonic regime had not yet changed at that locality. Later, the rate of vertical crustal

movement (subsidence) slowed, and stopped. This is recorded in the sedimentary succession as a regression. Finally, the basin became uplifted and an erosion surface was cut across the sedimentary pile.

(1) The first principle derived from this sequence is that as the distance from the plate boundary increases, there is a greater separation in time between the different manifestations and the severity of tectonic overprinting. Furthermore, at greater distances from the plate boundary, even though the early manifestations are recorded in the sedimentary succession, the tectonic regime controlling the basin subsidence has not changed.

In the North Island segment the same principle applies. In southern Northland (Hukatere-Kaipara region), where the manifestations of the steepening slab were first felt, the first indications of volcanism appeared immediately before regression and uplift of the basin. Further south in the Waitemata Basin (Auckland), this event is recorded by the intercalation of tephra and mass-emplaced volcanic grits within bathyal deposits. Their deposition may have occurred up to 4 million years before volcanic piles were actually constructed in the Auckland region, and the subsequent uplift of the basin occurred. The comparison may be taken further. In NW Nelson, the change from limestone to terrigenous sedimentation was delayed until the mid-early Miocene, just as in the North Wanganui Basin the first appearance of andesitic material (derived from the volcanic arc) is not recorded until the early-middle Miocene (in the Purupuru Volcanic Sandstone). In the North Wanganui Basin, as in NW Nelson, the sequence of overprinting to the point of uplift above sea

level took about 15 million years. This duration progressively reduces towards the north and south respectively. Paper 7 discusses more fully the pattern of volcanic overprinting of the North Island segment of the rift system.

(2) The second principle that may be drawn regarding the pattern of overprinting, is that, irrespective of whether a compressive (South Island) or extensional (North Island) regime overprinted the rift system, the rift faults were reactivated to achieve, at least in part, the vertical crustal movements caused by the new tectonic regime.

#### Tectonic development of eastern North Island and Marlborough

The structure of eastern North Island and Marlborough is extremely complex. The degree of deformation of the Paleogene succession, where it is preserved and exposed, is so intense that it is difficult to reconstruct with certainty the characteristics of the tectonic regime which prevailed before the current subduction-transform system was imposed in the early Miocene. The off-shelf, fine grained, often calcareous, lithologies are suggestive of a passive continental margin.

Papers 2 and 3 highlight the tectonic control that the shallow dipping and oblique ocean-continent subduction system has had in the forearc region of Hawke's Bay and Wairarapa. The importance of contemporaneous Neogene and Quaternary sedimentation and imbricate thrust deformation is quite clear both in the geology of the coastal ranges and offshore to mid-shelf depths. The process of subduction

kneading may best describe the deformation of the presumed former passive margin into which the late Cenozoic deposits have been incorporated. The lower trench slope probably originated by the process of subduction accretion.

Between the coastal ranges and the trench zone of imbricate thrusting, there is no evidence for major dextral transcurrent displacement (van der Lingen and Pettinga, 1980; Pettinga, 1982). Dextral displacement on oblique-slip faults has apparently been confined during the Quaternary to a zone of faults trending along the eastern margin of the Tararua and Ruahine ranges. Walcott (1978) found that this spatial partitioning of the compressive and transcurrent components of the oblique subduction was also evident in the short-term geodetic data, and he invoked a model proposed by Fitch (1972) to explain this.

In Paper 4 it is proposed that in addition to relative plate movement on the subduction thrust, there has also been substantial relative plate movement within the overriding plate in Marlborough and eastern North Island. The latter type of movement formed the recurved Eastern Arc as a mega shear zone by brittle-ductile deformation, which is considered to be the expression in Marlborough-eastern North Island of the 480 km of dextral fault displacement on the Alpine Fault (Fig. 1). The principal manifestation of the brittle-ductile shearing was major crustal shortening in eastern North Island and northern Marlborough normal to the shoreline, and stretching parallel to the shoreline. This mechanism explains: (1) the width (up to 110 km) of the zone of crustal shortening across southern North Island where the

basement is reverse faulted; and (2) the fact that the basement stands higher in Wairarapa than it does further north along the east coast, where, in fact, there is a greater compressive component across the subduction thrust to the north.

The contrast in competence between the soft accreted materials of the Rangitata Orogen, which have not been extensively kratonised by magmatic intrusions, and the rigid Tuhua Orogen, which has suffered multiple magmatic intrusions, is considered the main reason for Alpine Fault movement in central and southern South Island, versus brittle-ductile shearing in Marlborough and eastern North Island. In effect, the Rangitata Orogen was stretched around the comparatively rigid NW Nelson-Westland block of Tuhua rocks, while the previously juxtaposed Fiordland-Campbell Plateau block was displaced to the southeast (Fig. 1).

#### Final comments

Most of the regional complexity in the Cenozoic tectonic development of New Zealand can be accounted for by the following five factors:

- (1) The Eocene-Oligocene development of a continental rift system through western New Zealand, which had two segments (North Island and South Island) that developed in different ways.

- (2) The early Miocene, about 23 My B.P., inception of the NE-SW trending Australia-Pacific plate boundary through New Zealand as a continental transform, which obliquely bisected the north-south trending western rift system and tectonically overprinted the South Island Segment. A related factor was the development (mainly since 10 My B.P.) of oblique convergence across the Alpine Fault.
  
- (3) The progressive emplacement of subducted oceanic lithosphere beneath northern and southern New Zealand, and changes in the subduction geometry of the subducted Pacific Plate.
  
- (4) Regional differences in the competence of the Rangitata versus Tuhua basement, which caused the relative plate motions to be expressed in different ways.
  
- (5) The proximity of different regions to the margin of the New Zealand subcontinent. Northland and eastern North Island lie on the margin of the subcontinent, whereas eastern South Island, for example, lies in an intra-continental position.

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## APPENDICIES

- I Geological Time Scale of the Cenozoic (after Stevens, 1980).
- II Kamp, P.J.J., 1980: Pacifica and New Zealand: proposed eastern elements in Gondwanaland's history. Nature, 288, 659- 664.
- III Nelson, C.S., Briggs, R.M. and P.J.J. Kamp,: Nature and significance of volcanogenic deposits at the Eocene-Oligocene boundary, Hole 593, Challenger Plateau, Tasman Sea. (Abstract). DSDP V. 90 (in press).



# GEOLOGICAL TIME SCALE

Compiled By G.R. Stevens

Drawn by M.A. Haronga

MILLION YEARS	INTERNATIONAL DIVISIONS				NEW ZEALAND DIVISIONS						
	ERA - THEM/ ERA	SYSTEM/ PERIOD	SERIES/ EPOCH	STAGE/AGE	SERIES/EPOCH	STAGE/AGE	Symbol				
	QUATERNARY										
0	CENOZOIC	TERTIARY	PLIO-CENE		Wanganui	Managopian	Wm				
						Waipipian	Wp				
						Piacenzian Zanclean	Wo				
						Tabianian	Tk				
5			NEOGENE	MIOCENE		Taranaki	Messinian	Tongaporutuan	Tt		
					L		Tortonian				
					M		Serravallian		Southland	Waiauian	Sw
							Langhian			Lillburnian	Sl
										Clifdenian	Sc
					E		Burdigalian		Pareora	Altonian	Pl
					Aquitanian	Otaian	Po				
20					OLIGOCENE		Landon		Whaingaroan		
				L		Chattian		Waitakian		Lw	
								Duntroonian		Ld	
				M		Rupelian		U		Lwh	
				E		Tongrian					L
				Lattorian							
35			PALEOGENE	EOCENE		Arnold	Priabonian	Runangan	Ar		
					L		Bartonian	Kaiatan	Ak		
								Bortonian	Ab		
					M		Wemmelian				
							Lutetian	Porangan	Dp		
							Cuisian	Heretaungan	Dh		
50		PALEOCENE			Dannevirke	Ypresian	Mangaorapan	Dm			
	E					Waipawan	Dw				
	L			Landenian		U	Dt				
				Thanetian				M			
				Selandian							
	M			Montian							
60											
	E	Danian	( " Wangaloan " )	L							
65											

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# Pacifica and New Zealand: proposed eastern elements in Gondwanaland's history

P. J. J. Kamp

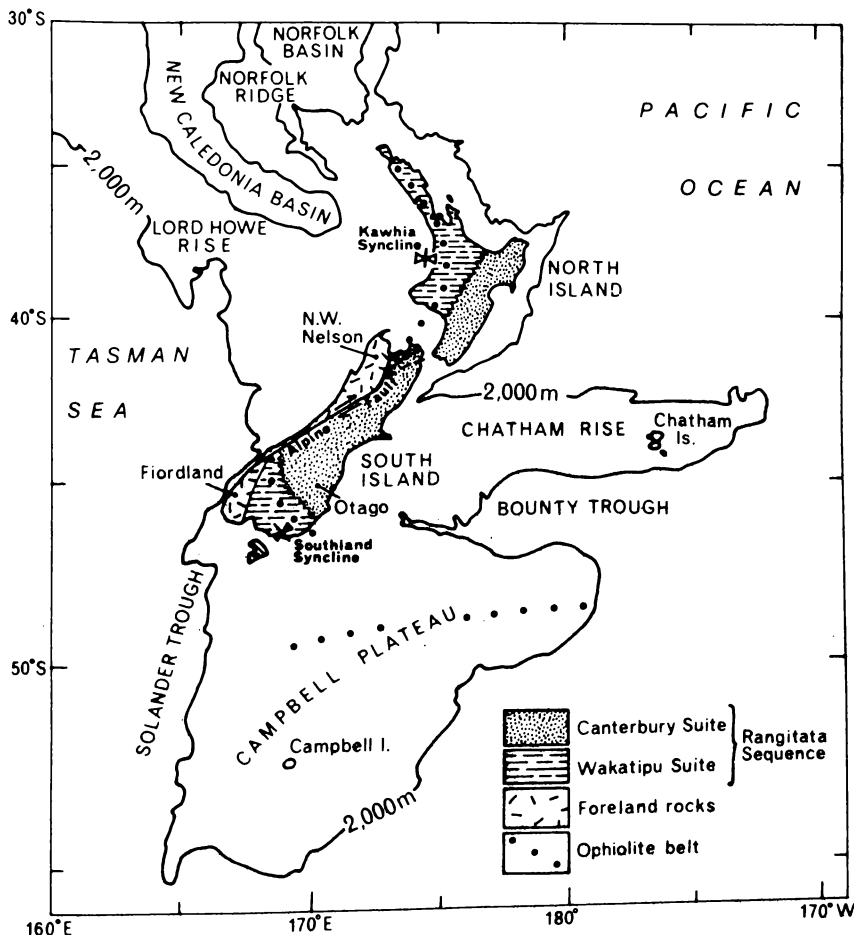
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*The origin of the sediments of the Canterbury Suite to the east of the Alpine Fault in New Zealand, cannot have derived from Marie Byrd Land before or during the breaking up of Gondwanaland. It is argued that the sediments may have derived from the lost continent of Pacifica, which is supposed to have separated from Gondwanaland in the late Palaeozoic. Such a mechanism can also account for the recurrence of similar quartzo-feldspathic sediments in California and thus of the Mesozoic dolerites and basalts in southern Africa, Antarctica and Tasmania.*

THE source of voluminous continent-derived sandstones<sup>1</sup> deposited on the Pacific margin of Gondwanaland, but oceanwards of an active arc-trench environment<sup>2</sup>, is a critical problem in the late Palaeozoic-Mesozoic geology of New Zealand and one which has wider implications for Pacific geology. Eastern Gondwanaland (Australia-Antarctica) is precluded as the chief source of the quartzo-feldspathic detritus, known as the Canterbury Suite<sup>1</sup>, for several reasons: (1) the sedimentology of the suite indicates derivation of the sediment from a source in the east (Palaeo Pacific Ocean); (2) the bulk petrography is inconsistent with transportation through the then active volcanic arc bordering eastern Gondwanaland; and (3) alternative explanations, especially of post-depositional juxtapositioning of the Canterbury and Wakatipu<sup>2</sup> Suites by strike-slip faulting subparallel to Antarctica, are excluded by the Mesozoic position with respect to Gondwanaland of the Lord Howe Rise and

Campbell Plateau. I propose that this sediment was derived mainly from Pacifica<sup>3</sup>, a continent contiguous with eastern Gondwanaland until its separation from the supercontinent during the late Palaeozoic, its fragmentation in the Triassic and inclusion within the circum-Pacific Cordillera in the early Cenozoic. Pacifica may also be the hitherto unknown source of other anomalous occurrences of quartzo-feldspathic detritus around the Pacific such as the Franciscan assemblage in California<sup>4</sup>. Furthermore, the origin of the extensive Jurassic basalts and dolerites of southern Africa<sup>5</sup>, Antarctica<sup>6</sup> and Tasmania<sup>7</sup> may be related to the separation of Pacifica.

The source of the Canterbury Suite has been debated for many years, and this problem is considered here in three ways. (1) The nature of the Canterbury Suite and the evidence for derivation from an eastern continent is outlined. (2) A new Mesozoic reconstruction of New Zealand relative to



**Fig. 1** A map of the New Zealand sub-continent, defined by the 2,000-m isobath, showing the on-land distribution of Palaeozoic foreland rocks<sup>52</sup> and the late Palaeozoic-Mesozoic basement rocks of the Rangitata Sequence<sup>43</sup>. The Canterbury Suite-Wakatipu Suite boundary in southern South Island lies within the Haast Schist belt<sup>1</sup>, and has not been mapped; the boundary shown here is estimated. In North Island the boundary is placed between the Torlesse and Waipapa terrains<sup>16</sup>. Distribution of the ophiolite belt is taken from ref. 53.

Gondwanaland is presented; it is important to consider New Zealand's position as close as possible to the time of Canterbury Suite deposition because the position of accumulation is a constraint on potential source areas. (3) Other problems in Pacific geology are considered to show that the Canterbury Suite is not an isolated anomaly, and that Pacifica is a general as distinct from a merely local explanation of the source problem.

The fundamental difference between previous hypotheses of the source of the Canterbury Suite and the hypothesis advanced here is one of invoking present continents (Australia–Antarctica) as opposed to a lost continent—Pacifica. In addition to providing a source, the Pacifica model provides a mechanism, through continental fragmentation, for the periodic and rapid derivation of huge volumes of quartzo-feldspathic sediment. Further, the separation and fragmentation of Pacifica are consistent with a generally accepted plate tectonic interpretation<sup>2</sup> of the arc–trench system that formed the adjacent Wakatipu Suite.

### Late Palaeozoic–Mesozoic New Zealand

The late Palaeozoic–Mesozoic geology of New Zealand is dominated by the juxtaposition of two contrasting detrital mineral suites, one the western volcanoclastic Wakatipu Suite of andesitic composition deposited next to the foreland, and the other the quartzo-feldspathic Canterbury Suite deposited in the Pacific Ocean further to the east<sup>1</sup> (Fig. 1). These coeval suites are considered to have formed in contrasting tectonic environments and to have been rafted together in the Mesozoic which culminated in a collision—the Rangitata Orogeny—with intense deformation, metamorphism, uplift and erosion<sup>2</sup>.

The Canterbury Suite comprises two-thirds of the Rangitata Sequence<sup>8</sup> and has an estimated<sup>9</sup> thickness of 30,000 m which is not a true stratigraphical thickness but caused by tectonic stacking or a shifting dopocentre. Derivation from a terrain of granodiorite and minor schistose and metamorphic rock is indicated by the composition of the dominant minerals and rock fragments. In particular Triassic sandstones comprise quartz (40–50%), potash feldspar (10–15%), sodic plagioclase (20%) and minor amounts of muscovite, volcanic rock fragments and chert<sup>1</sup>. These sandstones typically average SiO<sub>2</sub> contents of 67.5% (ref. 10). Tuffs are exceptionally rare. Consistent lithological homogeneity for over 500 km from eastern North Island to Otago (Fig. 1) and in time from Permian to Jurassic indicates the persistence of a continental source capable of supplying a quartzo-feldspathic assemblage for some 100 Myr. Although fossils are generally sparse, those that occur range from late Carboniferous to early Cretaceous<sup>11,12</sup> and biostratigraphic zonation indicates a westward and northward younging of the sediments<sup>2,13</sup>.

Based mainly on the distribution of fossil ages<sup>1</sup> deposition of the Canterbury Suite was remarkably episodic with a small pulse in the late Permian (early Tatarian), a very large pulse in the late early to late Triassic (Ladinian–Norian) and a further large pulse in the late Jurassic (early Kimmeridgian to early Tithonian). The extensive occurrence of a thick Jurassic mélange belt which includes reworked Triassic Canterbury Suite sediments<sup>14</sup>, suggests that much of the Jurassic sedimentation pulse was more related to erosion of the earlier Triassic sediments, as a consequence of uplift associated with the first phase of the Rangitata Orogeny<sup>8</sup>, than to tectonic events in the continental source area.

The distribution of depositional facies, detrital conglomerate, plant fossils and the records of directional sedimentary structures all indicate that sediment transport was in all directions and chiefly to the west and north, with non-marine, marginal marine and shallow marine environments in the east and an ocean basin environment in the west<sup>1,15</sup>. The Canterbury Suite thus seems to have been a huge clastic wedge<sup>8</sup> which prograded westward towards a trench, northward to eastern North Island<sup>16</sup>, and southward to a peripheral euxenic deep-marine

environment at Chatham Island<sup>17</sup>.

The stratigraphical and sedimentological evidence points towards an eastern source for the Canterbury Suite. Based on the persistence of a similar composition for ~100 Myr, the quantity of sediment and the rate of sediment supply, a primary cratonic region rather than a late Precambrian or Palaeozoic orogenic belt is indicated. Furthermore, the sandstone composition together with the rate of sediment supply in the Triassic, implies rapid uplift in the source area with vigorous physical erosion and with rapid transport to the sea. In short, there seems to have been an orogeny in the source area which climaxed in the Triassic. Hence, there are mechanistic requirements for the source area in addition to constraints on its composition.

In contrast, the Wakatipu Suite (Fig. 1), derived from a calc-alkaline terrain, shows a pronounced lithostratigraphic change from early and middle Permian volcanics, volcanogenic sediments and intrusives, to late Permian, Triassic and Jurassic highly volcanogenic, mostly marine and locally richly fossiliferous sediments, with common tuffs, but no flows. The complex stratigraphy of the Wakatipu Suite is interpreted<sup>2,15</sup> as representing the development in the early Permian of a volcanic arc–trench environment followed later by formation of a subduction zone accretionary wedge and mid-slope basin deposits, and finally a regressive frontal arc wedge of upper slope and slope basin, shelf and non-marine sediments.

### Jurassic reconstruction of modern Gondwanaland

A central problem in reconstructing the Jurassic configuration is the age of the recurved arc through New Zealand, delineated by the Ophiolite belt (Fig. 1). One idea<sup>18,19</sup> is that the curve is Cenozoic in age and formed by 500 km of dextral strain associated with movement on the Alpine Fault. Such models show New Zealand as a linear feature in the late Mesozoic<sup>18,20</sup>, or incorporate 1,000 km of Cenozoic dextral displacement, 500 km of which is attributed to distributed dextral strain<sup>21–23</sup>. Although some Cenozoic crustal strain cannot be excluded<sup>24–26</sup>, 500 km of Cenozoic strain requires excessive distortion of the present outline of New Zealand and this has not been substantiated. An alternative idea is that the bending originated mainly in the Rangitata Orogeny (early Jurassic to mid-Cretaceous<sup>8,27,28</sup>). Palaeomagnetic data from South Island<sup>29</sup> and Chatham Island<sup>30</sup> (Fig. 1) seem to preclude significant post-late Cretaceous bending between these localities and may support bending during the Rangitata Orogeny. Furthermore, deformation studies<sup>31</sup> have established the existence of a late Jurassic bend after removing 200 km of Cenozoic dextral strain, an amount which did not excessively distort elements of the land. In the reconstruction to be discussed 200 km of Cenozoic distributed dextral strain is considered to have occurred.

There are two assumptions used in the reconstruction presented as Fig. 2: (1) There has been no major relative movements between Marie Byrd Land and East Antarctica since the late Palaeozoic. (2) There was no relative movement between Marie Byrd Land and the Campbell Plateau in the interval from the late Palaeozoic to the late Cretaceous.

The first assumption is considered to be valid because of the close correspondence in lithologies, ages and structural trends of the Palaeozoic to late Cretaceous geology of North Victoria Land, Marie Byrd Land, New Zealand and Tasmania<sup>32,33</sup>. Each region was affected by a pre-Silurian–late Ordovician metamorphic event and a widespread phase of late Devonian–Early Carboniferous (350–390 Myr BP) plutonism<sup>33</sup>. In Antarctica the trend of the Borchgrevink Orogen extends uninterrupted from the Ford Mountains in western Marie Byrd Land north-northwest through the Ross Sea basement to north-east Victoria Land<sup>34</sup>. Moreover, two Albian to Neocomian (90–142 Myr BP) calc-alkaline magmatic arcs extended from Queensland through New Zealand to Marie Byrd Land before

the late Cretaceous break-up<sup>32</sup>. In addition, there is no palaeomagnetic evidence to support large displacements ( $\sim 10^3$  km) between Marie Byrd Land and East Antarctica after the late Cretaceous–early Cenozoic<sup>22</sup>, nor is there evidence during this time for the closing of an ocean basin<sup>34</sup>.

Concerning the second assumption, there are few independent lines of evidence to test the good morphological fit<sup>35</sup> of Campbell Plateau and Marie Byrd Land. In pre-Late Cretaceous times Campbell Basin was a continuation of a sediment-filled trough underlying the eastern Ross Sea shelf<sup>36</sup>. Such a structure would presumably preclude significant late Palaeozoic to late Cretaceous relative movement between Marie Byrd Land and Campbell Plateau.

Because greater New Zealand did not become a landmass until the Rangitata Orogeny (late Triassic to mid-Cretaceous<sup>8</sup>) it is difficult to establish the relative positions of the Canterbury and Wakatipu Suites before the Jurassic, and hence a later Jurassic reconstruction is presented here (Fig. 2). Although some strike-slip faulting may have occurred between the suites in the time between the late early-to late Triassic pulse of sedimentation (Canterbury Suite) and the later Jurassic, it was probably of a small scale (several hundred kilometres), and of dextral character, based on the nature of Cenozoic strike-slip faulting in the New Zealand region.

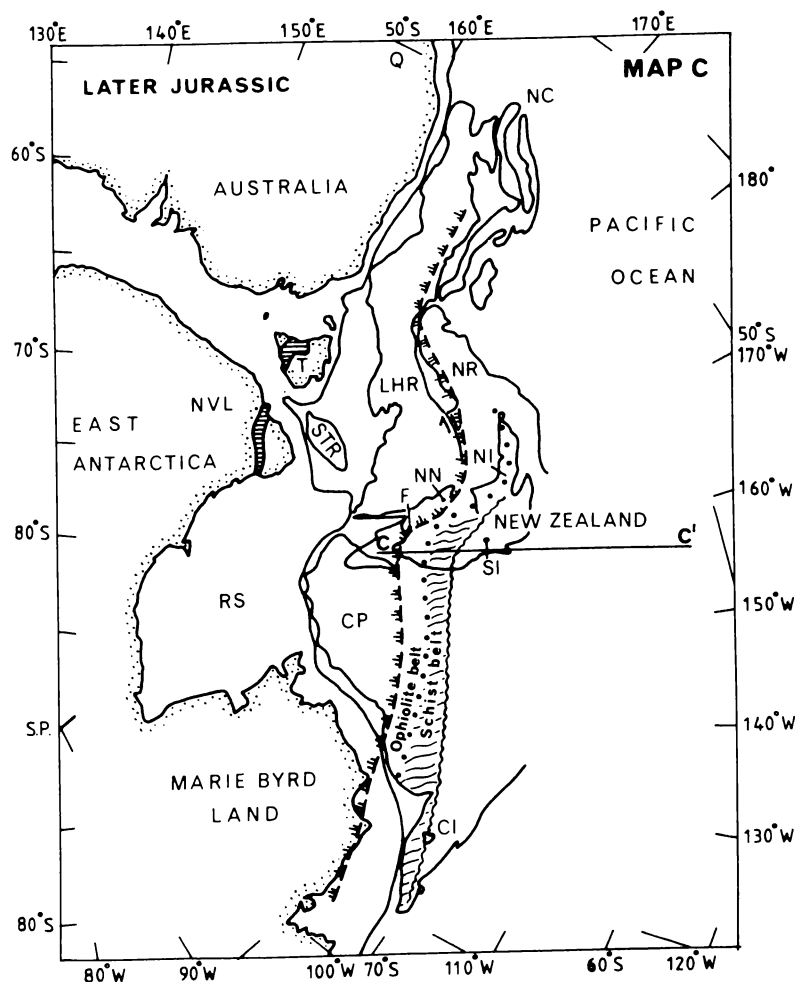
### Source of the Canterbury Suite

The present non-occurrence of a continent east of New Zealand has led to several proposals invoking a source in the west (North Victoria Land–Tasmania–Victoria (Australia)) or in the south-east (Marie Byrd Land). To enable deposition from the west without contamination by volcanoclastic detritus, bypassing mechanisms have been invoked<sup>13</sup>. However, this idea has been largely discredited on the basis of facies properties and sedi-

mentary environments in the Canterbury Suite<sup>1,37</sup>. Transport between basins of Wakatipu Suite deposition has also been proposed as a working hypothesis for sedimentation and tectonics in the New Zealand geosyncline<sup>16</sup>. However, the extent and continuity of the Stokes Magnetic Anomaly System<sup>19</sup> precludes the occurrence of a break in the arc of sufficient size through which the whole of the Canterbury Suite could have been transported without any contamination by volcanoclastic detritus. A development of the western source is the idea that the sediments were derived from an erosional episode in the Carboniferous before the arc–trench environment formed<sup>31</sup>, but such a theory requires an elaborate mechanism to explain the subsequent wholesale reworking westwards back towards the trench.

An eastern source area is now more acceptable although the location has not been specified<sup>1,2,15,38</sup>. In attempts to improve the definition of the eastern source it has been proposed<sup>37</sup> that the Canterbury Suite was formed from sediment derived from Marie Byrd Land and transported north-westwards. However, the Jurassic reconstruction of New Zealand relative to Gondwanaland presented here (Fig. 2) precludes Marie Byrd Land as the source because it lies on the back-arc side of the Canterbury Suite. Moreover, the shape of the clastic wedge comprising the Canterbury Suite is opposite to that expected if Marie Byrd Land were the source; Chatham Island sediments were deposited in a euxenic deep-marine environment yet in a pre-late Cretaceous position (Fig. 2) occur nearer to Marie Byrd Land than the non-marine and shallow marine deposits more distant in South Island.

An alternative idea also involving Marie Byrd Land as the source, but invoking strike-slip faulting of the Canterbury Suite subparallel to the Palaeo Pacific margin of Antarctica has been proposed<sup>39,40</sup>, but not applied to a rigorous Mesozoic recon-



**Fig. 2** A later Jurassic palaeogeographic map of eastern Gondwanaland with Antarctica in its present-day position. The New Zealand subcontinent is reconstructed against Norton and Selater's fit<sup>54</sup> of Australia and Antarctica. Q, Queensland; NC, New Caledonia; T, Tasmania; NVL, North Victoria Land; LHR, Lord Howe Rise; NR, Norfolk Ridge; STR, South Tasman Rise; F, Fiordland; NN, Northwest Nelson; NI, North Island; SI, South Island; RS, Ross Sea; CP, Campbell Plateau; CI, Chatham Island. The continental outlines of New Zealand<sup>55</sup>, Australia<sup>56</sup> and Antarctica<sup>57</sup> are taken as the 2,000-m isobath. The line of 'E-S' indicates the eastern limit of the pre-late Palaeozoic foreland and the line C-C' relates to the cross-section in Fig. 3. This reconstruction was made by initially establishing the extent, shape and position of the foreland, and then attaching to the foreland margin the 'post-orogenic' form<sup>31</sup> of the Rangitata Sequence. The southwestern extent of the pre-late Palaeozoic Lord Howe Rise<sup>58</sup> was taken from borehole data<sup>59</sup>. The margin of the foreland in Campbell Plateau, which has not been mapped, was placed 130 km south of the ophiolite belt<sup>53</sup>; an equivalent position to the corresponding distance immediately on-land in southeastern South Island (Fig. 1). This position of the margin in Campbell Plateau is consistent with the geology of Campbell Island<sup>60</sup> (Fig. 1), and is similar to an earlier estimate of the margin<sup>52</sup>. 480 km of Cenozoic<sup>61,62</sup> dextral transcurrent displacement on the Alpine Fault was reversed. The Waipounami Fault<sup>63</sup> is considered to be the boundary off eastern South Island where foreland rocks and the Rangitata sequence of Campbell Plateau have been brought into juxtaposition by Cenozoic drifting<sup>22</sup> of the New Zealand sub-continent. The late Cretaceous<sup>64,65</sup> Bounty Trough and Cenozoic<sup>66</sup> Waiau Basin–Solander Trough are closed. The fit of Lord Howe Rise against Australia is the conjectural pre-drift position of the Australian margin based on extrapolation of the Australian margin at the time anomaly 33 formed<sup>67</sup> (82 Myr BP). The reconstruction of Campbell Plateau and Antarctica is a morphological fit<sup>35</sup>. New Caledonia and Norfolk Ridge are placed against Lord Howe Rise. About 100 km of dextral transcurrent displacement is involved to bring the southern part of Norfolk Ridge into the best visually determined morphological fit with Lord Howe Rise. In this reconstruction North Island occurs in a position slightly further south and oceanward of its present position relative to Lord Howe Rise.

struction of eastern Gondwanaland and New Zealand. In taking the later Triassic reconstruction presented here (Fig. 3), and noting particularly the extent of the volcanic arc, to avoid transportation through the arc-trench system some 2,000 km of sinistral strike-slip movement would be required to derive the Canterbury Suite from more eastern parts of Marie Byrd Land. Moreover, the bulk of this movement would need to have

occurred between the late early and late Triassic pulse of sedimentation and the first phase of the Rangitata Orogeny (late Triassic-early Jurassic<sup>8</sup>). No mechanism has been proposed and substantiated to account for such rapid movement, and it is in an opposite sense to Cenozoic strike-slip movement in New Zealand. A model invoking strike-slip faulting would be acceptable only if a lesser amount of fault movement were

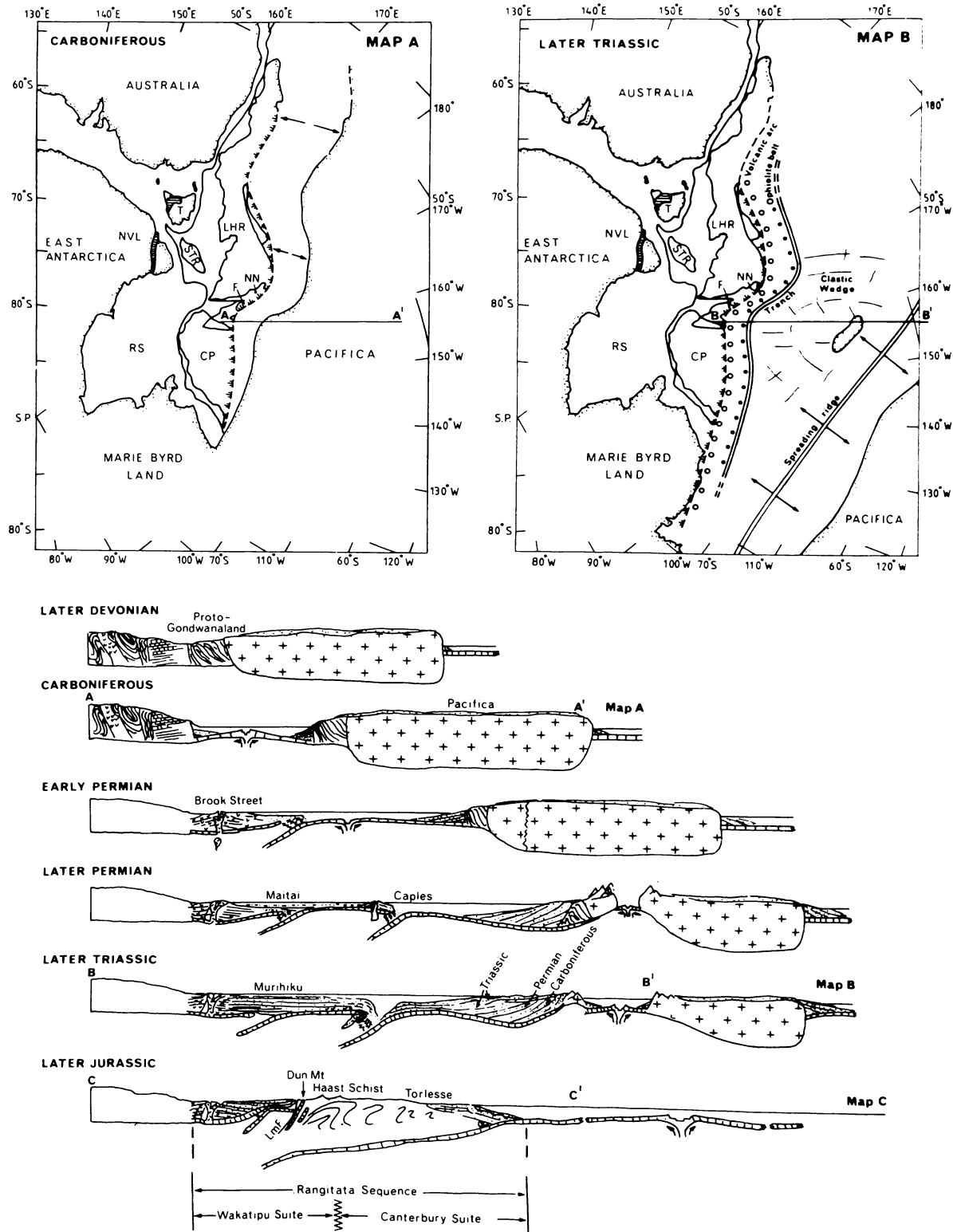


Fig. 3 Palaeogeographic maps and schematic cross-sections illustrating a model of the late Palaeozoic-Mesozoic geological development of New Zealand. These show a relationship of the plate tectonic development of the Wakatipu Suite<sup>2,31</sup> and derivation of the Canterbury Suite, to the drift and fragmentation of Pacifica. The later Jurassic cross-section relates to the section line in Fig. 2. The details of map construction and abbreviations are given in Fig. 2, and the terrain names on the cross-sections (for example, Brook Street) are defined elsewhere<sup>2</sup>.

necessary. This could apparently only be achieved by arbitrarily twisting the Campbell Plateau and Lord Howe Rise into different positions during the Mesozoic, such that until the mid-Jurassic the Canterbury Suite was more proximal to source, yet, by the mid-Cretaceous the Campbell Plateau and Lord Howe Rise were in the pre-breakup late Cretaceous positions. There is no evidence to suggest that before the mid-Cretaceous the Campbell Plateau and Lord Howe Rise had different positions relative to Antarctica and Australia, and hence there is not a substantiated case for Marie Byrd Land as the source of the Canterbury Suite.

## Pacifica and development of New Zealand

Pacifica was a continent hypothesized from geological evidence<sup>3</sup> to have lain off eastern Gondwanaland until the Triassic. It then fragmented and now occurs as exotic blocks of continental crust within the circum-Pacific Cordillera. The recent demonstration<sup>41</sup> that large parts of western North America are allochthonous adds credibility to Pacifica's fragmenting and subsequently contributing to formation of the Pacific Cordillera.

In discussing Lost Pacifica, Nur and Ben Avraham<sup>3</sup> did not use stratigraphical evidence from New Zealand to support their argument. Pacifica may well be the source of the Canterbury Suite<sup>42</sup>. Not only was Pacifica in the correct position at the right time, but its fragmentation also provides the mechanism for deriving huge volumes of Permian and Triassic sandstone.

I largely agree with the plate tectonic interpretations<sup>2,4,31</sup> for the Wakatipu Suite and the subsequent collision of the two suites, but seek to extend these models eastwards by including Pacifica (Fig. 3).

The Rangitata sedimentary–orogenic cycle<sup>43</sup> is postulated to have begun in the late Devonian to early Carboniferous with rifting within the Tuhua Orogen (Fig. 3); fragmentation of supercontinents is believed commonly to occur along old orogenic belts<sup>44</sup>. The spreading centre probably propagated southwards. A reconstruction of New Zealand for the Carboniferous (Fig. 3, map A) shows that the foreland was curved and the corresponding embayment in Pacifica might have promoted delta formation of the Canterbury Suite. By the Early Permian the Wakatipu arc–trench environment had formed and by the mid-Permian an incipient fracture had developed within Pacifica. The fragmenting of Pacifica (Fig. 3) ensured extensive uplift of the continent during the late Permian and Triassic and derivation, by physical erosion, of detritus which preserved a quartzo-feldspathic composition because of the huge volumes involved and the rapid transport to the sea. The spreading ridge which initiated the fragmentation of Pacifica then extended south to Antarctica (Fig. 3, map B), perhaps associated with anticlockwise rotation of Gondwanaland concomitant with transformation from Panagea B to A<sup>45</sup>, and by the end of the Triassic was actively rafting the Canterbury Suite on oceanic crust towards the Wakatipu Suite. The first phase of the Rangitata Orogeny ensued in the late Triassic–early Jurassic<sup>8</sup>, and although most folding occurred in the Canterbury Suite, the wedge impinged on the Wakatipu Suite, consequently restricting Jurassic sedimentation to the areas now represented by the Southland and Kawhia Synclines (Fig. 1). The point collision of the clastic wedge (Fig. 3, map B) caused eversion of the Ophiolite and its progressive convergence westwards with the foreland (Fig. 2). In the Jurassic, Pacifica fragmented further and parts were drifting across the Pacific Ocean.

## Source of the Franciscan assemblage

Attention has been drawn previously to the geological similarity between California and New Zealand: each comprises an inner volcanogenic terrain (Great Valley sequence versus Wakatipu Suite) adjacent to an older crystalline foreland, and an outer rarely fossiliferous quartzo-feldspathic terrain (Franciscan assemblage versus Canterbury Suite)<sup>4</sup>. As in New Zealand, the critical problem is the source of the quartzo-feldspathic assem-

blage which also has a composition close to granodiorite, and was deposited on the Pacific side of the coeval Great Valley sequence. Although the Franciscan assemblage is derived from a continental source, the differences in grain-size and composition between the two sedimentary belts, and the pronounced westward thinning of the Great Valley sequence, are difficult to reconcile with a Sierran–Klamath source for the Franciscan assemblage<sup>4</sup>. This difficulty led to the proposal that a remnant volcanoplutonic arc, possibly a continental fragment, existed between the two sedimentary terrains during the late Jurassic to early Tertiary<sup>46</sup>. Subsequently, the remnant arc was eroded to derive the Franciscan assemblage and its roots subducted so that now no part remains<sup>4</sup>. This remnant arc could well have been a fragment of Pacifica, for such a fragment approached California during the late Jurassic to early Cretaceous<sup>3</sup>. Consistent with this model, the bulk of the Franciscan assemblage was deposited in latest Jurassic to earliest Cretaceous time (Tithonian–Valanginian)<sup>4</sup>, when presumably the continental fragment was rapidly uplifted and eroded due to interaction with the North American Plate.

## Consequences of Gondwanaland rifting

Pacifica is conceived as a large continent not only adjacent to New Zealand but also to Antarctica<sup>3</sup>. The age and distribution of Jurassic tholeiitic dykes and sills and basaltic lavas from Africa across Antarctica to Tasmania show evidence of a period of incipient rifting within Gondwanaland well before the separation of East and West Gondwanaland at 140–160 Myr BP. In Africa these igneous rocks are the Karroo Basalts dated<sup>5</sup> at 150–190 Myr, in Antarctica the 175 ± 5 Myr old Dufek Massif, Ferrar Dolerites and Kirkpatrick Basalts<sup>47</sup>, and in Tasmania, dolerites aged<sup>7</sup> at 170.5 ± 5 Myr. Rather than link these voluminous rocks to the break-up of East and West Antarctica<sup>48</sup>, an abortive separation of India<sup>49</sup>, an initial rifting of East and West Gondwanaland<sup>50</sup>, or incipient rifting of Australia and Antarctica<sup>51</sup>, for all of which the age of rifting post-dates the intrusion and extrusion of these rocks, their origin may be related to contemporary volcanicity and active spreading in the Palaeo Pacific Ocean which caused the breakup and drift of Pacifica away from the Pacific margin of Gondwanaland. The occurrence of the African, Antarctic and Tasmanian Jurassic dolerites and basalts has already been suggested as related to a former coeval spreading axis in the Palaeo Pacific Ocean off Antarctica<sup>44</sup>.

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NATURE AND SIGNIFICANCE OF VOLCANOGENIC DEPOSITS AT THE EOCENE-OLIGOCENE  
BOUNDARY, HOLE 593, CHALLENGER PLATEAU, TASMAN SEA

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ABSTRACT

Hole 593 includes near its base within chalks a spectacular 16.4 m sequence of thinly bedded grayish black, lithified volcanogenic sandstones, mudstones and occasional breccias. Sandstone - mudstone couplets (up to 50cm thick) have sharp basal contacts, are normally graded, and include Bouma A, B, occasional C, and E divisions, while breccia-dominated units are thicker (up to 140cm), massive or inversely graded, and unsorted. The beds were deposited rapidly at bathyal depths, close to the Eocene - Oligocene boundary, from turbidity currents and/or subaqueous pyroclastic flows originating on the slopes of "Lalitha pinnacle", a now-buried ~500m high volcanic shield (av. 6-8° slopes) located only ~3km from Site 593.

The occurrence in the deposits of rare primary augite and olivine crystals, and the abundance of the low Si/Al zeolite phillipsite, as well as certain chemical considerations, support a basaltic parentage. However, as a result of low-temperature oxidative alteration by pore fluids following emplacement, the original basaltic glass fragments which formed the bulk of the deposits have been extensively palagonitized and replaced by phillipsite, smectite and calcite.

"Lalitha pinnacle" is similar to several other (buried) "pinnacles" evident on seismic records from southern Lord Howe Rise, both in its seismic character and structural and age relations to surrounding sediments. This suggests that submarine basaltic volcanism and associated sedimentary re-deposition was widespread in the southeast Tasman Sea region during the late

Eocene to early Oligocene. The activity is viewed as off-rift (western) volcanism related to regional extension and the formation of a major western New Zealand rift system associated with eastwards propagation of the mid-ocean Southeast Indian Ridge into the south Tasman Sea and through the New Zealand subcontinent at this time. Analogous occurrences of submarine Eocene-Oligocene basalts east of the rift system now crop out onland in eastern South Island, New Zealand.