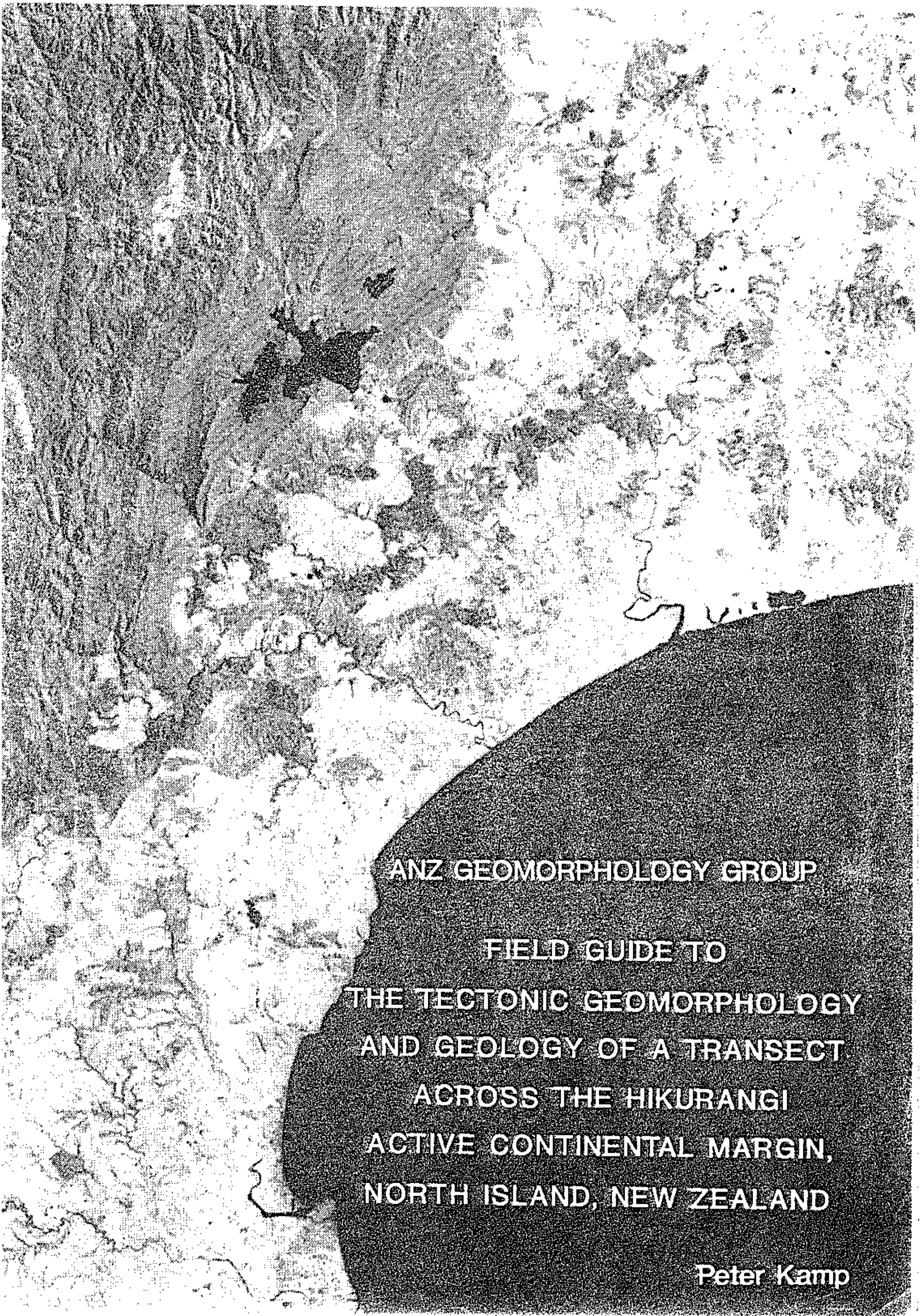

FIELD GUIDE TO THE TECTONIC GEOMORPHOLOGY AND GEOLOGY OF A TRANSECT ACROSS THE HIKURANGI ACTIVE CONTINENTAL MARGIN, NORTH ISLAND, NEW ZEALAND

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Introduction to Excursion

The intention of this field trip is to show participants the major structural, lithological and geomorphological features of a NW-SE transect from the centre of a forearc basin (Heretaunga Plains - Hawke Bay) to the slopes of an active frontal arc, subduction derived, volcano (Mt Ruapehu). The preceeding half-day field trip to Te Mata Peak - Heretaunga Plains compliments this excursion in that the participants viewed part of the thrust-dominated, accretionary borderland that now lies onland to the SE of Napier, and continues offshore to the base of the Hikurangi Trench.

The field trip comprises several stops that give panoramic views of tectonic features, and stratigraphic sections of mainly volcanic deposits. The total distance by road from Napier to Mt Ruapehu is 246 km; this would normally take about 3½ hours driving without stops. Nine stops of about ½ hour duration each are planned. The lunch stop only will be near toilets. One or two brief photo stops may be made if there are features of particular interest to anyone.

This guide comprises two parts. In part A, the concept of active subduction of the Pacific Plate beneath the North Island, and its different geomorphological and geological expressions are developed. In Part B, details relevant to each of the nine stops are presented.

PART A: REVIEW OF THE HIKURANGI MARGIN

The Hikurangi Margin of eastern North Island is a modern active continental margin where oceanic lithosphere of the Pacific Plate is being subducted beneath continental lithosphere of the Australia Plate. The occurrence of active crustal and upper mantle seismicity, dipolar gravity anomalies, an oceanic trench, an active andesitic frontal arc, an asymmetric heat flow pattern, the state of stress of the overriding plate as revealed by geodetic data and focal mechanisms, and structural evidence for thrust deformation, together indicate the existance of an active Hikurangi continental margin. The rates and orientations of seafloor spreading in the Indian and Pacific oceans also indicate that the Pacific and Australia plates are converging; the present day rates and directions of relative plate motion are shown in Fig.1. Figure 2 shows the Hikurangi Margin in the context of the Australia-Pacific plate boundary.

The following subsections review the geophysical evidence for lithospheric subduction at the Hikurangi Margin.

The Waditi-Benioff Zone

The present extent and geometry of the subducting Pacific Plate beneath the North Island and northernmost South Island (Fig.2) is defined by a dipping seismic zone (Hatherton, 1970; Adams and Ware, 1977). The subducted slab originates at the Hikurangi Trench and dips initially at a shallow angle of 5-15° for about 250 km, before it abruptly steepens to a dip of 50° at a depth of 80 km; the plane of the slab generally strikes N45°E and dips to the NW. 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 across the Alpine Fault.

Microearthquake studies (Robinson 1978; Smith, 1979; Arabasz and Lowry, 1980; Reyners, 1980) and seismic reflection-refraction studies (Davey & Smith, 1983; Bennett, in press) have more closely defined the dip of the subducting Pacific Plate in the low angle section beneath eastern North Island and Wellington. A change in the dip occurs at 25 km depth; trenchward of this point the slab dips at about 5° and arcward at about 14° (e.g.Fig. 3). The deeper (80 km) line of marked change in dip corresponds at the surface with the trend of the Taupo Volcanic Zone, and more specifically the line of late Quaternary frontal arc andesite-dacite volcanoes.

Although the North Island Waditi-Benioff Zone has traditionally been viewed as a planar dipping surface, not withstanding the knee-type bends at 25 and 80 km, it now appears that the slab may be discretely fractured at depth by NW-SE trending faults (Reyners, 1983). In addition, or alternately, the slab may be buckled in the plane of subduction (Kamp, 1985), as has recently been demonstrated for other Circum-Pacific subducted slabs (e.g. Cardwell and Isacks, 1978; Ukawa, 1982; Bevis and Isacks, 1984).

Gravity Anomalies

Active plate margins are characterised by major dipolar gravity anomalies (Hatherton, 1969; Yoshii, 1979). Northern New Zealand is broadly characterised by positive gravity values (0-50 mgal) between the Hikurangi Trench and the east coast, a negative belt from East Cape (Waiapu) to Wanganui (Rangitikei) to Cook Strait (up to -150 mgal), and positive values over the northern North and South Islands (Reilly et al., 1977) (Fig. 4). A gravity profile trending NW-SE through Hawke's Bay would show the typical dipolar gravity anomaly pattern; it is uncharacteristic, however, in that the gravity couple is displaced NW of the expected position (Hatherton, 1970). The gravity minimum normally lies over the trench, but it actually lies onshore and 200 km NW of the trench in Hawke's Bay. The gravity maximum is also displaced NW of its usual position over the volcanic arc; it lies instead some 50-100 km NW of the arc over the back-arc region (Fig. 4). Another feature of the gravity pattern that differs from the usual case is the occurrence of a substantial gravity high over southeastern North Island, which lies trenchward of the major negative anomaly (Fig. 4). Although the gravity patterns were originally explained in terms of mass deficiencies within the upper 80 km of the subducted plate, and mass excesses in the depth range 80-250 km (Hatherton, 1970), it has been suggested more recently that they originate from variations in crustal thicknesses and upper mantle inhomogeneities (Stern,1985). Importantly, the belt of negative anomalies coincides with major late Cenozoic sedimentary basins.

Heat Flow

Active plate margins are characterised by major heat flow anomalies. Heat flow values in the forearc region are usually well below the average continental value of 56.6 mW/m^2, and typically double in value in the arc

and back-arc regions to higher than average continental values (Uyeda, 1982).
The North Island distribution of heat flow values reported by Studt and Thompson (1969), Thompson (1977) and Pandey (1981) are shown in Fig. 5, together with the distribution of hydrothermal fields and thermal springs. South and east of the active arc, lower than average continental values occur due to the cooling effect of the cold subducting Pacific Plate, which is at shallow depths below. Northwest of the arc, higher than normal values occur. Interestingly, and predictably, the average continental value (56.6 mW/m^2,) lies only a few km SE of the active frontal arc volcanoes (Fig.5).

The average heat flow of the TVZ (840 mW/m^2) is extremely high, and considerably higher than the average value of continental rifts (80-110 mW/m^2) This heat output is, however, very localised and arrives at the surface via hydrothermal systems that feed numerous small geothermal fields, each of about 20 km^2, where upflowing hot water with temperatures as high as 300°C are found (Fig.6). Between these fields the heat flow is commonly zero, which is due to zero geothermal gradients that result from down flowing meteoric waters which provide the recharge for the geothermal fields (Studt and Thompson, 1969; Thompson, 1977).

The amount of heat output from the TVZ is considered to be a problem (Stern, 1985). According to a quantitative model by Stern, the heat output requires two-thirds of the 13 km (15 km less 2 km of superficial pyroclastic cover) thick crust of the TVZ to consist of cooling intruded rock. The basement of the TVZ has traditionally been considered, however, to consist of Mesozoic greywacke, the material from which the voluminous Quaternary rhyolites were probably derived (Reid, 1983).

Short term state of stress of the overriding (Australia) plate.

The crustal structure and tectonic geomorphology of the overriding plate between the Trench and the back-arc region are a manifestation of the long term (1 x 10^6 yr) state of stress induced by the convergence of the Australia and Pacific plates. Walcott (1984) has shown for New Zealand that the average long term deformation can be directly related to strain derived from short term (1 x 10^2 yr) geodetic data.

Geodetic data

The geodetically determined azimuths of the principal axis of compression and the rates of maximum shear strain of different parts of N.Z. are shown in Fig. 7a after Walcott (1984). Points of interest to the field traverse are that (1) the TVZ and back-arc region of northern North Island show short term extension normal to the plate boundary, (2) SW of the TVZ in the Wanganui Basin, there is compression normal to the plate boundary, (3) extension presently occurs in the forearc region over the southern part of eastern North Island. Walcott (1978b) has attributed the spatial difference in the state of stress in eastern North Island to alternate locking (which causes compression in the overriding plate) and unlocking (giving extension) of the subduction thrust.

Focal mechanism

The short term (in this case present day) state of stress may also be determined from earthquake focal mechanism solutions. Figure 7b after Reyners (1980) summarises the published composite focal mechanisms of crustal earthquakes in the overiding plate.

Mechanisms A - I (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 in 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 by Walcott (1984), the present state of stress in region 2 is probably unrepresentative of the long term state.

Mechanism P, from a source beneath the Wanganui Basin, is a pure thrust solution with a WNW oriented P-axis. Mechanism M represents about equal components of thrust and strike-slip motion. 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 indicates NE-SW thrusting.

Geological and Geomorphological character of the active Hikurangi Margin

Hikurangi "Trench"

The Hikurangi "Trench" in pre-plate tectonic times was initially described as a shallow (3 km below sea level) southwest continuation of the Kermadec Trench at the base of the continental slope east of the North Island (Brodie and Hatherton, 1958). Because it does not strictly have a trench morphology that distinguishes it from the seafloor bathymetry further east, it has been termed a trough (Eade and Carter, 1975). The fact that it is underlain by nearly flat-lying strata up to several km thick has also tended to downplay its structural importance, and Katz (1974) considered it to be a downwarped intra-continental basin. The evidence on marine seismic reflection profiles of thrust faulting and under-stuffing of sediment at the lower continental slope, however, clearly indicates that the Hikurangi trough is effectively a structural trench and marks the position where the Pacific Plate starts to subduct.

At its northern end, the Hikurangi Trench is slightly offset to the west of the Kermadec Trench (Fig. 1). This transition is confused by volcanic knolls in the axis of the trough (Katz and Wood, 1980). At its southern end, the trench is transformed offshore and onshore in Marlborough into a series of transform basins (Carter and Carter, 1982; Lewis and Bennett, 1985).

Continental shelf and slope : a subduction complex

The continental shelf and slope off eastern North Island (Figs 8 and 9) comprises a series of synclinal sedimentary basins and anticlinal ridges oriented NE-SW parallel to the Hikurangi Trench (Lewis 1980; Lewis and Bennett, 1985). The basins are typically 5 to 30 km wide (NW - SE) and 10 to 60 km long. Most of the anticlines, better described as antiforms, comprise thrust faulted ridges with internally sheared lithologies that have been uplifted to dam accretionary slope basins, which typically contain landward dipping turbidite sequences. Foraminiferal data suggests that the ridges progressively increase in age from mid-Quaternary ages near the lower trench slope to Mid-Miocene and possibly Cretaceous ages at the shelf edge (Fig. 8) (Lewis and Bennett, 1985). These dates also show that the ridges on the upper slope have been uplifted from lower slope depths during the Plio-Pleistocene; minimum estimates of post-depositional uplift range from 700 m to 1600 m (Lewis, 1974).

High rates of deformation and Quaternary oscillations in sea level have combined to produce conspicuous unconformity-bound sequences beneath the continental shelf and slope (Fig. 10)(Lewis, 1971 and 1973). Adjacent to the ridges, the glacial age unconformaties have been folded. From the inferred ages of some of the sequences, the difference between the rate of uplift of the truncated shelf ridge crests and the rate of subsidence of the basin axes, is estimated to be 3 m/1000 years (Lewis, 1971).

High quality marine seismic profiles (see Lewis and Bennett, 1985, Figs 5 - 19), indicate clearly that the structure of the middle to lower continental slope offshore from Hawke's Bay and Wairarapa originated by the process of subduction accretion, as envisaged by Seely (1979) and Scholl *et al.* (1980). The occurrence of older lithologies (Cretaceous) at the surface of some of the ridges beneath the continental shelf and upper slope, however, suggests that the whole of the subduction complex may not have originated from the scraping of sediment off the subducting plate; the inner part of the complex may represent the subduction kneading of a wedge of late Cretaceous - lower Tertiary rocks that accumulated earlier as passive margin deposits.

Coastal ranges of Southern Hawke's Bay: the inboard margin of a subduction complex

Figure 11, from Pettinga (1982), shows the generalised geology of the coastal ranges of southern Hawke's Bay. This area consists of three narrow (< 4km) NE-SW trending zones of extremely complexly folded and thrust faulted Cretaceous to Miocene "basement" which is exposed between basinal "cover" strata of Miocene-Pliocene age. Deformation in the structural highs, in particular the Coastal High, was dominated by thrust faulting. Many of the sequences are clearly allochthonous and have suffered a multiphased deformation history - see Pettinga (1982) for further details. The Elsthorpe Anticline is actually a splinter fault zone of the Coastal High, and developed after (Plio-Pleistiocene) the Coastal High formed (late Oligocene- late Miocene) (Fig. 12).

A major sedimentary basin, named the Makara Basin, lies between the Inland and Coastal highs. Late in the Miocene history of this basin, it was inverted and divided into eastern and western asymmetrical synclines by thrust formation of the Elsthorpe Anticline (van der Lingen and Pettinga, 1980) (Fig. 12). Basin sediments consist of flysch strata, pebbly mudstones, tuff beds and hemi-pelagic mudstones, up to 2200 m thick. These sediments are considered to have been ponded between thrust ridges (the structural highs) at slope depths; the modern lower slope basins offshore from Hawke's Bay are viewed as modern analogues to the Makara Basin (van der Lingen and Pettinga, 1980). Moreover, the structural highs formed by imbricate thrust faulting and deformation near the leading edge of the upper plate. The later formation of the Elsthorpe Anticline and uplift of the whole coastal ranges was caused by imbricate thrusting on the inboard margin of the subduction complex, while this whole prism was building outward (seaward).

The onland exposure in southern Hawke's Bay of the inboard part of such a young, imbricate thrust dominated, subduction complex is unusual and important. It allows us to study the style of deformation, at a macroscopic and mesoscopic scale, of an intact, actively forming orogenic belt that we normally only "see" with seismic reflection profiles; it has also aided structural interpretations of offshore seismic profiles.

East Coast depression : the forearc basin

A major topographic and structural depression that can be broadly classified as a forearc basin extends through inland eastern North Island(Figs. 1 and 13). By comparison with the coastal hills, the structure is generally simple; this is typified by the broad Wairoa Basin in northern Hawke's Bay that may contain as much as 10 km of Miocene-Pliocene shelf sands and mudstones (Grindley, 1960). South of Wairoa, only the western limb of this basin occurs onland (as the Hawke's Bay Monocline, Fig 13); the maritime Hawke Bay forms its eastern limb. It is pertinent to add here that the inboard margin of the subduction complex, represented by the coastal hills, passes offshore north of Cape Kidnappers only to appear briefly onland again at Mahia Peninsula.

South of Napier, the East Coast depression narrows from 20 km wide near Hastings to 12 km wide near Woodville. It also becomes increasingly disrupted by faults (Fig.13). The deposits infilling the basin are also younger. Outcrop and drillhole data show that mid-Pliocene and Pleistocene mudstones, limestones and conglomerates overlie Mesozoic basement. The dip of these deposits invariably increases southward within the basin, and adjacent to the Ruahine Range middle Pleistocene beds locally stand on end. The more usual dips of 5° to 20° can be explained by the growth of force-folds in cover beds over reverse-faulted greywacke basement at depth. Southward, the forearc basin takes on characteristics more akin to those of transform basins; it is also difficult to justify the term 'forearc' as the volcanic arc ends near the latitude of Napier.

The Plio-Pleistocene paleogeographic development of the East Coast depression is a classic example of an interplay between tectonism and sea level oscillations. As a consequence of subduction and the associated compression, virtually the whole of southern North Island has been uplifted from the marine realm since early Pliocene times. Differential faulting uplifted initially the axial ranges and coastal hills (Fig. 14, and see Fig. 13.4 of Kamp and Vucetich, 1982). This was followed by the progressive withdrawal of the sea from the inland seaway of the East Coast depression to about the current shoreline of Hawke Bay. Detailed mapping by the writer has shown, however, that between 1.7 My B.P. and about 0.8 My B.P. this regional regression was characterised by smaller scale advances and retreats that are attributed to glaciation driven sea level changes. Since about 0.8 My B.P., the shoreline has repeatedly moved in and out of Hawke's Bay in response to northern Hemisphere glaciations; a stratigraphic record of this is preserved in the small accretionary Kidnappers Basin (Kamp, 1978).

Axial ranges : the Arc Massif

The NE-SW trending axial ranges of the North Island, which range in elevation from 1000-1700 m above sea level, are a major landform and component of the Hikurangi margin. They consist of largely unfossiliferous alternating sandstones and argillites of Triassic and Jurassic age (Kingma, 1959), which are now highly deformed and overturned to the NW (Sporli and Bell, 1976). Few detailed studies have been undertaken on these rocks, but regional considerations suggest that they formed at the Pacific margin of Gondwanaland as part of a subduction complex. Thus, since the Miocene, a new orogenic belt has formed partly upon and east of an earlier orogenic belt, which is now indurated and highly eroded. Further geomorphic and geologic details of the axial ranges are described by Kamp (1982) and Kamp and Vucetich (1982).

In an active margin context, the axial ranges can be regarded as constituting the Arc Massif. This classification may, however, mask the major tectonic differences between the ranges to the north and south of the latitude of Napier. Briefly, south of Napier, the Ruahine and Tararua ranges are bounded and internally divided by oblique-slip faults - the uplift is clearly due to reverse thrusting; north of Napier, however, late Cenozoic strata lap onto basement and uplift of the ranges appears to be associated with normal faulting.

The White Island - Ruapehu volcanic line : the frontal volcanic arc.

Nine late Quaternary andesite-dacite volcanoes form a frontal volcanic arc from the Tongariro Volcanic Centre to White Island (Fig. 15). Ninety-five percent of all exposed andesites in the TVZ occur in the Tongariro Volcanic Centre, where they are distributed amongst four major andesite massifs: Kakaramea, Pihanga, Tongariro and Ruapehu (Fig. 16) (Cole, 1978). These massifs are all younger than 0.25 My B.P., and most of the lavas are two-pyroxene andesites; the olivine andesites are all younger than 50 000 years and were erupted on the Tongariro Massif only(Cole, 1978). Chemically, the andesites are all normal to low-Si calc-alkaline rocks. The andesites differ chemically from those associated with island arcs such as the Tonga-Kermadec Arc. In particular, the Tongariro andesites are enriched in alkalis (Na_2O, K_2O) and associated trace elements, and have higher strontium and lead isotope values. This suggests crustal involvement in their genesis, considered by Cole (1978) to be caused by the assimilation of minor amounts of Mesozoic greywacke - argillite or Cenozoic sediments with oceanic crust during subduction.

North of the Tongariro Volcanic Centre, a series of acid andesite-dacite volcanoes lie in a line along the eastern margin of the TVZ (Fig.15). Together they form about $5km^3$ of lava (Cole, 1979), and details of their form are described in Duncan (1970). Their petrography and petrology are described in Reid and Cole (1983). The petrogenesis of the lavas of each volcanic cone appears to be very individual. White Island dacite can be modelled by fractional crystallisation of basic magma. Maungaongaonga resulted from partial melting of greywacke basement, and Tauhara by partial melting of greywacke together with minor mixing with a more basic magma.

Taupo Volcanic Zone: a marginal basin within continental lithosphere?

The TVZ is a narrow (<50km), complex volcano-tectonic depression extending about 250 km southwest from White Island in the Bay of Plenty to Mt Ruapehu (Fig.15). The TVZ has erupted voluminous quantities ($>10^4$ km^3) of mainly rhyolitic material (i.e. SiO_2 >67 wt%) in the form of steep-sided domes of lava, thick sheets of ignimbrite (welded or nonwelded pyroclastic flow deposits), and widely dispersed airfall tephra (Healy, 1982). Most of these lavas and pyroclastic rocks have derived from six large, multivent calderas (volcanic centres) that are defined geophysically by significant basement depressions containing clustering of known or inferred vent sites (Fig.17) (Wilson et al., 1984).

The Mangakino and Kapenga calderas are probably extinct, Rotorua and Maroa may be active, and Okataina and Taupo are very active (Fig. 18). Major welded ignimbrite eruptions in the TVZ have a mean recurrence interval of 25 000 - 30 000 years since C. 1.1 million years ago; the latest (Mamaku Ignimbrite) erupted from the Rotorua caldera c. 140 000 years ago. Since then, major nonwelded ignimbrites were erupted c. 50 000 years ago (Rotoiti Breccia) from Okataina, and c.20 000 years ago (Kawakawa Ignimbrite) from Taupo; the most recent one (Taupo Ignimbrite) was erupted from Taupo Caldera 1800 years ago (186 A.D.).

Over the last 20 k y about 25 major plinian tephra eruptions (Fig.19), mainly from Taupo and Okataina, have erupted at a mean rate of one every 800 years. Consequently, much of the central North Island landscape is mantled with thick sequences of tephras, frequently with buried paleosols (Pullar et.al. 1973; McCraw, 1975). No part of New Zealand has escaped occasional dustings of thin, fallout tephras (e.g. Pullar et al, 1977; Kohn, 1979; Lowe et al., 1980).

Petrologic modelling has shown that the TVZ rhyolites originated by partial melting of the Mesozoic greywacke basement (Reid, 1983); a conclusion that may be anticipated by the extreme heat flow values (Fig.5). While this explains the collapse origin of the major calderas, the calderas themselves occur within a major topographic depression aligned NE-SW (Figs 15 & 17), which has a crustal thickness of only 15 km (Stern, 1985). This depression is highly fractured by steeply dipping NE-SW trending normal faults (Grindley, 1959, 1960, 1965; Healy et al., 1964). These faults invariably bound horsts and grabens and differentially uplifted tilt blocks. They commonly display variable throw along their traces and Grindley (1965) has documented evidence of repeated displacements on several of the major faults. This pattern of faulting indicates NW-SE extension, and is characteristic of continental rifting. Because it lies behind an active arc, however, it has been viewed as a marginal basin within continental lithosphere (Stern, 1985).

The Back-arc Region

The region of northern North Island NW of (behind) the frontal arc and the TVZ is characterised by a basin-and-range topography involving Mesozoic greywacke basement, and basic Quaternary volcanics.

Back-arc volcanism

Back-arc alkalic and tholeiitic suites lie between 140 and 400 km behind the current frontal arc. They are distributed within five main volcanic fields; Alexandra (near Hamilton) (Briggs, 1983; Briggs and Goles, 1984), South Auckland (Rafferty and Heming, 1979), Auckland (Searle, 1960; 1961), Whangarei and Kaikohe-Bay of Islands (Northland)(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 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.

The lavas from each of these fields, except Auckland, can be divided on petrographic and geochemical grounds into two groups: (see refs above) an early alkaline suite, and a subsequent dominantly tholeiitic suite. The former suite originated from varying degrees of partial melting of a garnet peridotite within the upper mantle (75-100 km). These rocks contain no evidence of fractional crystallisation, contain ultrabasic xenoliths and xenocrysts, and are associated with surface normal faults. These properties indicate rapid magma ascent rates and no residence time in magma chambers, features consistent with crustal extension. By contrast, the more voluminous tholeiitic suite was derived by partial melting of a much shallower (45-60 km) source (Iherzolite), and suffered some fractional crystallisation. This indicates much slower ascent rates and the formation of short-lived magma chambers.

Back-arc basin-and-range- topography.

The back-arc region of Auckland, south Auckland and Waikato is dominated by a system of NW-SE, N-S and NE-SW bearing faults (Kear, 1960, 1966; Schofield, 1967; Healy et al., 1964). The faults are all normal, show scissors displacements (Hochstein and Nunns, 1976), and have dips of 70°-80°, but occasionally as low as 60°. The present relief on these faults is commonly 300m; gravity surveys in the South Waikato basin (Kear and Schofield, 1978) and Hauraki basin (Hochstein and Nixon, 1979) show that throws of up to 3.5 km occur.

As a result of vertical movement on these faults, the region has been segmented into rectilinear blocks that have commonly been tilted, and basins. The amount of tilting is often only a few degrees and usually less than 10° and the blocks dip in all directions, except to the SE. The occurrence of these differentially uplifted blocks and the character of the faults that bound them are primary evidence of crustal extension. The variations in tilt direction of the blocks imply NW-SE and E-W, as well as NE-SW directions of extension. The triangulation survey data also indicates variable directions of extension (Fig.7A).

The age of the faulting is difficult to establish exactly. Initial differential vertical movement probably started first in the Auckland district (mid-Miocene) and then progressively moved southeastward into the TVZ in the early to mid-Pleistocene. There have been substantial vertical movements, however, over the whole of the back-arc region during the Quaternary.

Evolution of the Hikurangi Margin

The geological and geomorphological character of the Hikurangi Margin has really only been widely appreciated and understood since about 1980, when the volume of papers on oblique-slip mobile zones, edited by Ballance and Reading, was published. Consequently, we have a long way to go before fully understanding the evolution of this margin.

There are at least three major tectonic questions: the age of initiation of subduction; the nature and location, north of the Alpine Fault, of the relative plate motion evident as 480 km of displacement on the Alpine Fault; and the way in which the subducted plate was emplaced beneath northern New Zealand.

Age of the Hikurangi Margin

The biostratigraphic age of the initiation of thrust faulting, which formed the structural highs and the Makara basin in coastal Hawke's Bay, indicates that subduction beneath parts of eastern North Island was occurring during the early Miocene (Pettinga, 1982). The occurrence of early Miocene (21-18 My B.P.) calc-alkaline subduction-derived, arc volcanics in Northland (Brothers and Delaloye, 1982) indicates that subduction had started by at least the early Miocene. From the late Cenozoic relative rates of Australia-Pacific plate motion, Walcott (1978a) calculated that it took at least 15 My for the present extent of the subducted slab to be emplaced.

As the Hikurangi Margin is part of the Australia-Pacific plate boundary, evidence for the age of other parts of the plate boundary, for example the Alpine Fault sector, may also age the Hikurangi Margin sector. The age of the Alpine Fault has, however, been a persistent problem. Four different ages have been proposed so far: early Cretaceous (Suggate, 1963; Grindley, 1974), late Eocene-early Oligocene (Molnar et al., 1975; Norris and Carter, 1982), early Miocene (Wellman and Wilson, 1964), and late Miocene (Wellman, 1970). The recent identification of a mid-Eocene to early Miocene continental rift system through western New Zealand precludes pre-Miocene Alpine Fault displacement; an earliest Miocene age, about 23 My B.P. has been proposed from the age and pattern of disruption of the rift, which is attributed to formation of the Alpine Fault (Kamp, 1986a,b).

Nature and location of the relative plate motion north of the Alpine Fault and through the Hikurangi Margin

Another persistent conceptual problem has been the nature and location, north of the Alpine Fault (which ends in northern Marlborough), of the 480 km of dextral displacement evident on the Alpine Fault. Figure 20 illustrates six recent treatments of this problem in regional tectonic analyses; successive writers have assumed that the relative plate motion is expressed as fault displacement, that this displacement generally occurred on a simple extension of the Alpine Fault, and that the displacement occurred through eastern North Island.

There are geological difficulties with all of these models (Kamp, in prep.) For example, the present distribution of basement terraces would be further complicated, rather than simplified, if any one of these pre-plate boundary outlines was adopted. Furthermore, it is difficult to identify sensible patterns in the Paleogene disposition of sedimentary basins, source areas and paleoshorelines in the North Island with the outlines in Fig.2. The notion of a single Alpine Fault extension through Marlborough and eastern North Island is not consistent with the late Cenozoic pattern of deformation. The faulting is infact distributed across a 100 km wide zone, and at present within this zone about half of the deformation is taken up as distributed anelastic strain (Lensen, 1975; Walcott 1978a,b; Bibby, 1981).

Figure 21 is a new model from Kamp (in prep.) of the evolution of New Zealand's shape that attempts to integrate all of the published geological and geophysical (geodetic and paleomagnetic) data. The starting shape, at 25 My B.P., is from Walcott and Mumme (1982). In this model, the 480 km of relative plate motion is expressed in Marlborough and eastern North Island as the formation of a mega, brittle-ductile, shear zone that formed as a result of distributed fault displacement and anelastic strain. This shear zone, or Eastern Arc of Fig. 21, is essentially the plate boundary zone, and importantly, it developed in the overriding (Australia) plate. Hence, there have been two types of relative plate motion in eastern North Island. One type was expressed within the leading margin of the overriding plate as the formation of a shear zone, and the other was expressed as a subduction thrust beneath the shear zone.

Emplacement of the Subducted slab

Although the extent and geometry of the present slab are defined geophysically, the former extent and geometry of the slab can only be established from geological evidence, and then chiefly from the distribution, age and composition of subduction-derived volcanic rocks.

Such rocks of Miocene-Pliocene age are widely dispersed over the North Island north of the TVZ. There has been, however, a long history of controversy about the orientation of the former frontal arcs; some have inferred NW-SE to N-S orientations (Ballance, 1976; Hayward, 1979; Cole, and Lewis, 1981; Ballance et al, 1982, 1985), while others have inferred a NE-SW orientation parallel to the modern frontal arc (Challis, 1978; Kamp, 1984; Brothers, 1984) (Fig.22).

By arguing the latter interpretation of the age pattern of the orogenic andesites, and applying the geochemical K_2O-h parameter of depth of magma generation, the changing extent and geometry of the subducted slab has been established (Kamp, 1984) (Fig. 23). During the late Cenozoic, 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°. This caused the volcanic front to migrate trenchward at an average rate of 20 km/My.

PART B. : Details to accompany field sites

See Fig. 24 for a map of the route from Napier to Mt Ruapehu and the locations of the field sites.

Scinde Island - Napier City

The hill upon which the older part of Napier City was built was originally an island, separated from the rest of Hawke's Bay by the Ahuriri Lagoon to the NW and the flood plain of the Tutaekuri River to the southeast.

The sedimentary lithologies that underlie the hill, and are best exposed at Bluff Hill opposite the Port of Napier, are lower Nukumaruan (late Pliocene) in age. Three formations occur; a lower cross-bedded calcareous sandstone that contains limestone pods, a middle sandy siltstone and an upper sandy limestone. The lower and upper formations probably accumulated in mid to inner shelf environments, and the middle formation, in a mid to outer shelf setting. The occurrence of more calcareous lithologies on Scinde Island, compared with equivalent age rocks to the west, probably explains its preservation as an erosional outlier.
Thick loess sections, probably of middle to late Pleistocene age and named the Brick Yard Clays (Kingma, 1971), unconformably overlie the marine rocks, especially on the western side of the "island". The airfall tephras of the 20 000 yr Kawakawa eruption mantle the island.

Ahuriri Lagoon - Napier Earthquake - Photo Stop.

The M 7.8 February 3rd, 1931 Napier Earthquake was associated with up to 2.4 m of uplift near Napier (Fig.25). Approximately 1300 hectares of lagoon, into which the Esk River (to North) and Tutaekuri River (to south) formerly flowed, was uplifted co-seismically. Since then a further 1700 hectares have been artificially drained.

Stop 1: Panoramic view of the forearc basin (East Coast depression

Location: Napier-Taupo Highway, Te Pohue, Map reference N114/128727 NZMS 1 Series)

Note the following:

1. To left of centre (East), Darkies Spur-Devil's Elbow block of Nukumaruan (late Pliocene-early Pleistocene) strata that gently dip at 5° - 10° SE into Hawke Bay and comprise the NW limb of the forearc basin. These

strata are part of the Hawke's Bay monocline in Fig.13, and represent the youngest beds deposited in the forearc basin (Fig.1) north of Napier. A composite stratigraphy of these strata from Beu and Edwards(1984), is illustrated in Fig. 26.

2. Hawke Bay. This bay represents the remnants of a seaway that formerly stretched between here and Cook Strait. It withdrew to this position about 0.8 My ago - see Fig 14 for paleogeographic details. All the country in the foreground (forested) and to the centre-right (south) are Nukumaruan rocks deposited in this seaway.

3. Coastal Hills. The hilly country in the far distance south of Hawke Bay is the uplifted inboard margin of the thrust-dominated subduction complex. (Figs. 11 & 12). The Kidnappers Group, which accumulated in a small coastal plain accretionary basin at the northern end of the coastal hills, can be seen on the southern side of the bay.

4. Te Aute limestones. To the extreme right, and left there are exposures of,and dip slopes on, the Pliocene Te Aute Limestone Facies. See Fig. 27 from Beu et al (1980) for the stratigraphy of these beds, which dip at 15° SE.

Stop 2: Panoramic view of the eroded margin of the forearc basin.
Location : Napier-Taupo Highway, Te Haroto, Map reference N 114/043816

Note the following.

1. We are standing on late Miocene (Tongaporutuan) blue-grey mudstones, with late-middle Miocene sandstones and thin limestones in the slopes immediately below, which lap up onto Mesozoic basement and generally dip to the SE at 15° - 40°. One is looking across the Mohaka Valley(river flowing right to left) at the eroded margin of the forearc basin. The beds strike parallel to the valley and dip away from us; the vertical relief (700 m) is therefore a true indication of straigraphic thickness - in this case mainly of late Miocene strata, with a capping of Pliocene mudstone and limestone.

2. Active faults that lie north of the Mohaka Fault have been mapped in the valley and the slopes to the east (Grindley, 1960). Several workers view these faults as the northeastern continuation of the Alpine Fault, and detach the whole of eastern North Island on them and shunt it 480 km to the north or northeast (see Fig. 20 and contrast it with Fig. 21).

Stop 3 : Landslides and associated engineering problems.
Location : Napier-Taupo Highway, Waipunga River, Tarawera,

On Friday 8 March, 1985, a heavy rainstorm swept through inland areas of Hawke's Bay. Five hundred mm (20 inches) of rain fell within a 24 hour period creating severe damage along a narrow path through the axial ranges. A preliminary estimate of flood damage to roads was $1 million. We stop to view repairs to a hillside above the main road, which was the source of a major landslide that completely blocked the road. Note also small scale landslips in scrub/bush country, many of which occurred in the Taupo Ignimbrite.

Stop 4 : Mesozoic basement of Axial Ranges (Arc Massif), Te Whaiti Ignimbrite, Taupo Pumice Formation.
Location : Napier-Taupo Highway, Waipunga Falls, Map reference N 104/967047

Note the following.

1. Kaweka and Urewera Greywacke. A fairly typical exposure of redeposited sandstone and dark grey argillite of the axial ranges, which is very rarely fossiliferous. The exposure beside the road is mapped as Kaweka Greywacke (late Triassic - early Jurassic)(Grindley, 1960). The Wheao Fault has upthrown this block with respect to the younger Urewera Greywacke (late Jurassic- early Cretaceous), which occurs on the other side of the valley (to the north). This section consists mainly of sandstone, with some packets of alternating sandstone and argillite, which are sheared on all scales. Major vertical and subvertical shear zones are evident, but also note the bedding-plane shearing; shearing also typically occurs at a microscopic scale. These rocks were probably deposited and deformed within a subduction complex.
2. Te Whaiti Ignimbrite. Grey to brown quartzose ignimbrite, otherwise described as a dark grey lenticulite. This is one of the most highly welded of the numerous Pleistocene ignimbrites to have been erupted from the Taupo Volcanic Zone, and it tends to show a middle layer of horizontal cooling columns. It has a Fission track age of about 0.33 My B.P.(Kohn, 1973). It appears to have flowed into a pre-existing valley and filled it up - note the terrace on the opposite side of the valley. Note also how it flowed up and thinned onto the basement hill.
3. Taupo Pumice Formation. The Taupo eruption of 186 A.D. was one of the largest explosive eruptions in the world within the last 7000 years (Wilson

and Walker, 1985). It generated a great variety of pyroclastic deposits: two plinian pumice falls, three phreatomagmatic ashes and several ignimbrite flow units. The vent was located within a large lake (Taupo) and magma-water interaction determined the style of parts of the eruption. Figure 28 gives a summary of the stratigraphy and volumes of the Taupo eruption products, and Fig.29 illustrates many of the field relations. The participants are referred to review papers by Wilson and Walker (1985) and Wilson (1985) for further details. The western end of the road cutting shows very well the valley facies of the Taupo Ignimbrite (on right handside, northside) versus the veneer facies on the lefthand side where the ignimbrite climbed up onto the Te Whaiti Ignimbrite. The Taupo Pumice Formation will be examined at the small cutting on the north side of the road. Older eruptives of the Taupo Subgroup are exposed on the southside and at the western end of the road cutting.

Stop 5: De Brett's section - Taupo subgroup

Location : Napier-Taupo Highway, opposite De Brett's Hotel, Map reference N94/572355

This is the classic section of Vucetich and Pullar (1973). A description of the section is given in Fig.30. It comprises mainly <15 000 year old rhyolite tephras from the Taupo Caldera (Taupo Subgroup), but also interbedded rhyolite tephras from the Okataina and Maroa calderas, and andesite tephras from the Tongariro Volcanic Centre (compare Figs 19 and 30). The radiocarbon ages and erupted volumes of the Taupo tephras are summarised in Fig. 31A. Figure 31B illustrates schematically the broader nomenclature of the rhyolite tephras; note that the more widespread Kawakawa Formation derived from the Taupo Caldera, and the Rotoiti Breccia Formation from the Okataina Caldera.

Note the dacite volcanic cone of Mt. Tauhara, aged 31 000 y B.P. which is one of the frontal arc volcanoes(Fig.15).

Stop 6 : Views of Lake Taupo (caldera), Tongariro Volcanic Centre

Location : State Highway 1, (Taupo-Turangi), rest area opposite entrance to Taupo Airport, Map reference N 94/543312

This stop is included mainly to discuss and obtain photographic slides of Lake Taupo and the Taupo Caldera (Fig.17), the Tongariro Volcanic Centre andesite cones (Fig.16), the thick proximal early flow unit outcrops near Waitahanui township, and geomorphic evidence (benches) of higher lake levels.

Stop 7 : Proximal Taupo Pumice Formation

Location : State Highway 1, Waitahanui Deviation, Map ref. N103/548238.

A new road cut has exposed the Taupo erution products very close to their source, which was probably the Horomatangi Reefs in Lake Taupo. From the northern (down hill) end of the cutting to the southern end one sees in order the Hatepe Tephra, very thick Rotongaio Ash (4m), eroded remnants of Taupo Lapilli, and a succession of ignimbrites and airfall lapilli. Near the top of the section is a distinctive lithic-rich layer which underlies the major and most widespread ignimbrite unit.

Stop 8: Views of the Taupo Volcanic Zone, a marginal basin

Location: Scenic lookout, Te Ponanga Saddle Rd., Map Ref. N102/250008

This stop is included mainly to discuss and obtain photographic slides of the southern part of the Taupo Volcanic Zone, and to discuss recent sedimentation patterns (Tongariro River delta) at the southern end of Lake Taupo.

Note the following :

1. Titiraupenga, left (NW) and distance, an early Pleistocene deeply eroded andesite volcano (K-Ar total rock age of 1.89 + 0.02 My B.P; Stipp, 1968). It formed part of an earlier frontal arc parallel to, but 40 km northwest of, the present arc. It consists of low-Si andesites.

2. Western Ignimbrite Plateau (Fig.15), in the foreground of Titiraupenga, comprises the NW flank of the TVZ. It has been built up by successive ignimbrite sheets, especially the Whakamaru Ignimbrite (0.33 My B.P., Kohn, 1973).

3. Taupo Volcanic Zone (Fig.6,15,17) - a normal faulted zone of extension that comprises tilt blocks, horsts and grabens that generally trend NE-SW. The Taupo Caldera (foreground) is one of six major rhyolitic volcanic centres within the TVZ. See also the earlier discussion on the TVZ.

4. Kaingaroa Plateau, centre-right (NE) and distance, is the SE flank of the TVZ. It consists of several ignimbrite sheets up to several hundred metres thick that overlie fault-bounded block of Mesozoic basement.

5. Kawakawa Ignimbrite, right, age 20 000 y B.P. underlies the grassy-forested hills around the southeast margin of Lake Taupo.

6. Kaimanawa Range, right distance, consists of early Triassic basement (sandstones, argillites and schistose rocks) similar to those seen at Stop 4.

7. Pihanga Massif, behind right, is a little disected andesite volcano with a K-Ar date of 0.12+0.003 My.B.P. (Stipp, 1968). Kakaramea Massif, behind left, is another composite volcano; lava flows have been K-Ar dated at 0.222 + 0.001 My B.P. and 0.192 + o,023 My B.P. (Stipp, 1968).

Stop 9 : Te Ponanga Saddle tephra (Andesitic) section - Tongariro Subgroup

Location : Te Ponanga Saddle Road, Map reference N112/224983

The stratigraphy and chronology of tephraa from Tongariro and Ruapehu have been recorded by Topping (1973) who has identified six formations that account for 4 km^3 of andesite tephra erupted between 13 800 y B.P. and the present day. A summary of the main tephra units is given in Fig. 19. Rhyolite tephras from the Okataina, Maroa and Taupo centres are interbedded with the andesite tephras and have provided stratigraphic control. Topping and Kohn (1973) have identified 13 rhyolite tephras; the most widespread and important of these is the Kawakawa Fm (Taupo Centre, 20 000 y B.P.), the Rotorua Ash (Okataina Centre, 12 500 y B.P.) and the Taupo Pumice (Taupo Centre, 186 A.D.) (Fig.32).

Figure 33 is a description from Topping and Kohn (1973) of the Te Ponanga Saddle section. The youngest deposit is the Ngauruhoe Tephra Fm, erupted (mainly from Ruapehu) since the Taupo eruption. Below the Taupo Pumice, the Mangatawai Tephra Fm records the building of the bulk of Ngauruhoe over 700 years from 2 500 y B.P., and is characteristically a paleosol. Intense volcanic activity between 9 700 and 9 780 y B.P. formed the Mangamate Tephra Fm with units from Tama lakes, Blue lake and North Crater. Many ash and lapilli beds were erupted from Ruapehu from 14 000 and 10 000 y B.P. The Rotoaira Lapilli, erupted from lower Te Mari Crater at 13 800 y B.P., forms the base of the Tongariro Subgroup.

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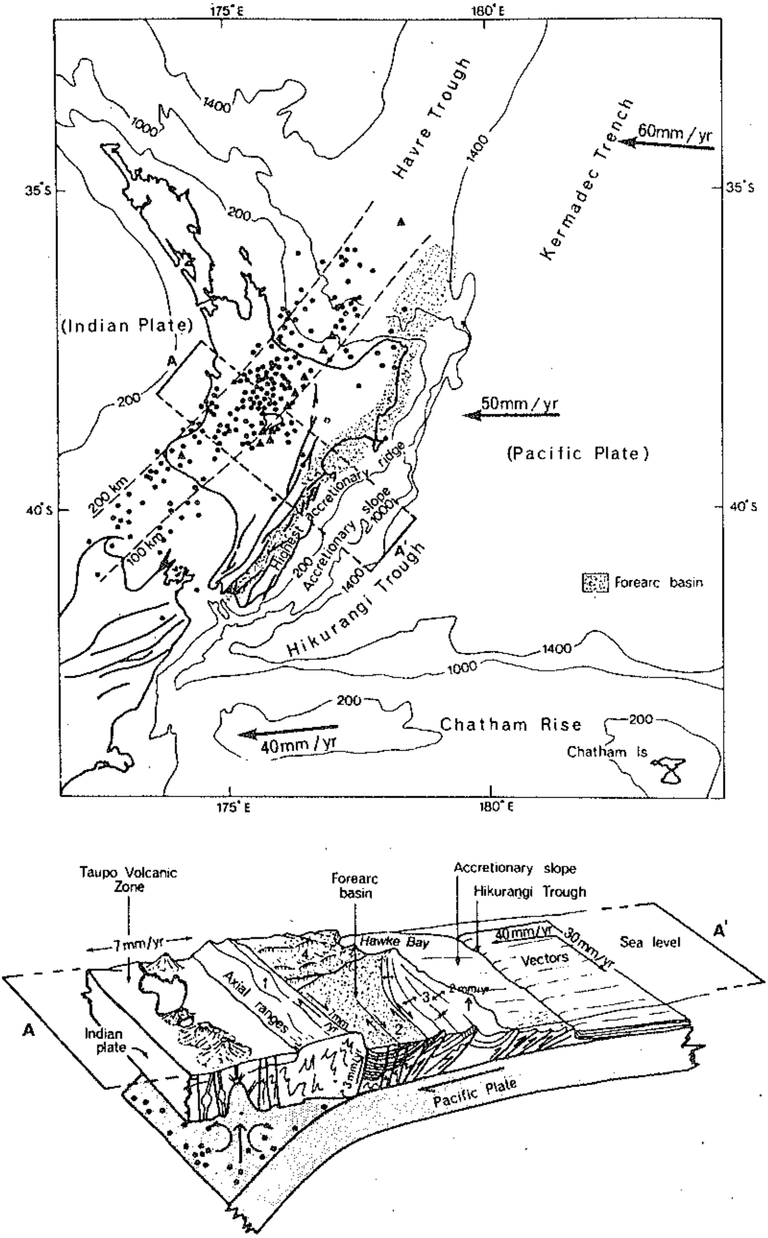


Figure 1. A map and block diagram illustrating a plate tectonic interpretation of the structure and landforms Hawke's Bay. The black dots on the map are earthquake epicentres believed to originate from the subducting plate (they are schematically positioned on the cross-section). The black triangles represent volcanoe The bathymetric units are fathoms. The numbers 1,2,3,4 refer to the landform terrains. The map is modified fro Walcott (1978a) and the cross-section is modified from Walcott (1978b) and Lewis (1980). (From Kamp, 1982, F 12·4).

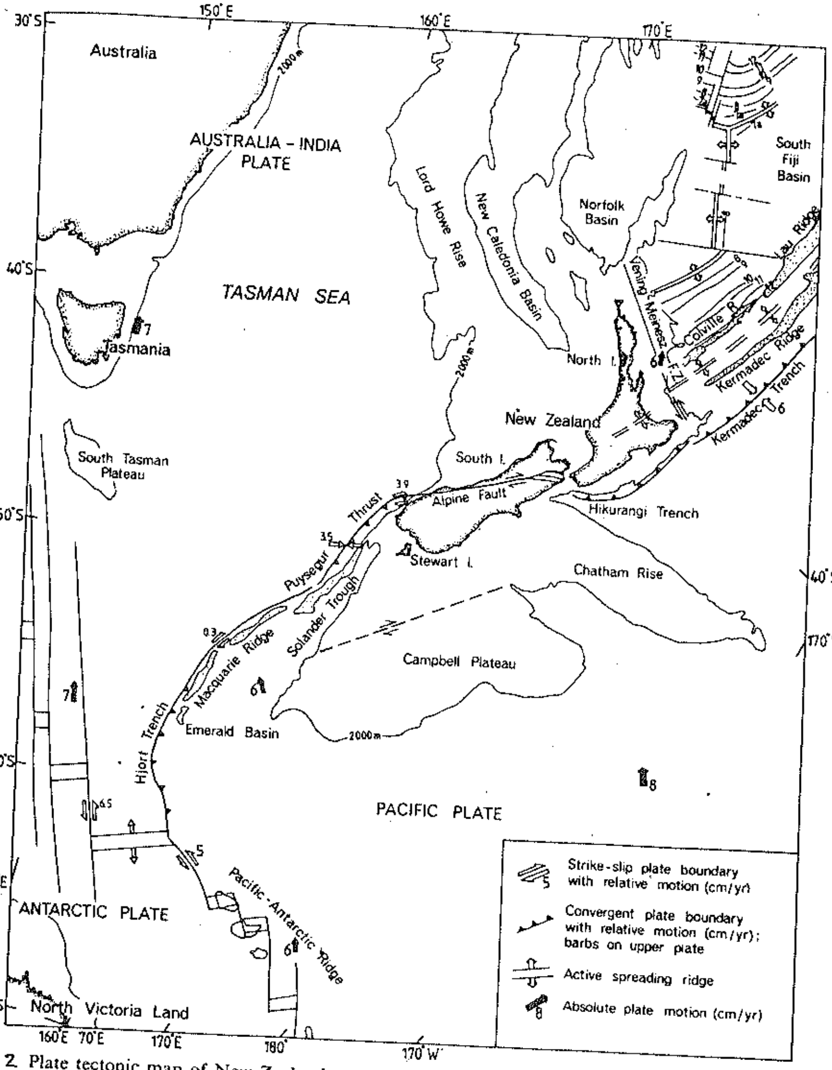


Fig. 2. Plate tectonic map of New Zealand and the southwest Pacific showing the surface location and character of the Australia–Pacific plate boundary. Reproduced from the Plate Tectonic Map of the Circum-Pacific Region—Southwest Quadrant (the American Association of Petroleum Geologists, Tulsa, U.S.A.). Seafloor magnetic anomalies 7a–12 in the South Fiji Basin have been added from Malahoff et al. (1982). (From Kamp, 1984).

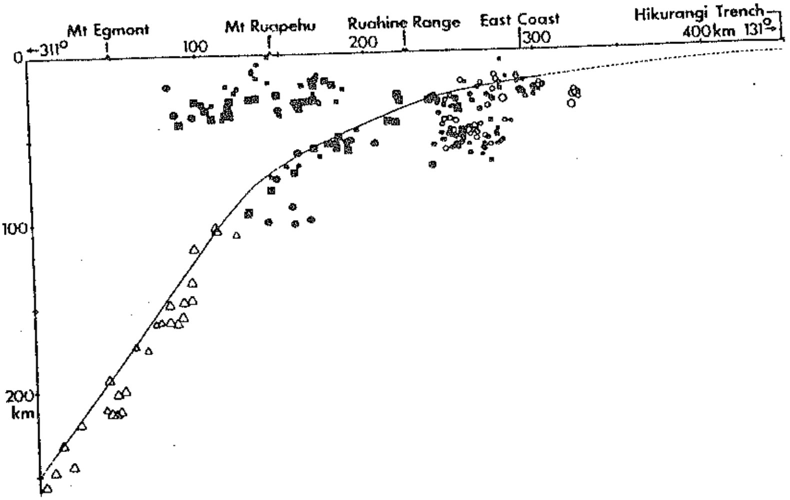


Fig. 3 A vertical cross-section across the Hikurangi margin from southern Hawke's Bay to Mt. Ruapehu (see Fig. 5) showing well-determined earthquakes and micro earthquakes and the inferred geometry of the subducted Pacific plate. (From Reyners, 1980)

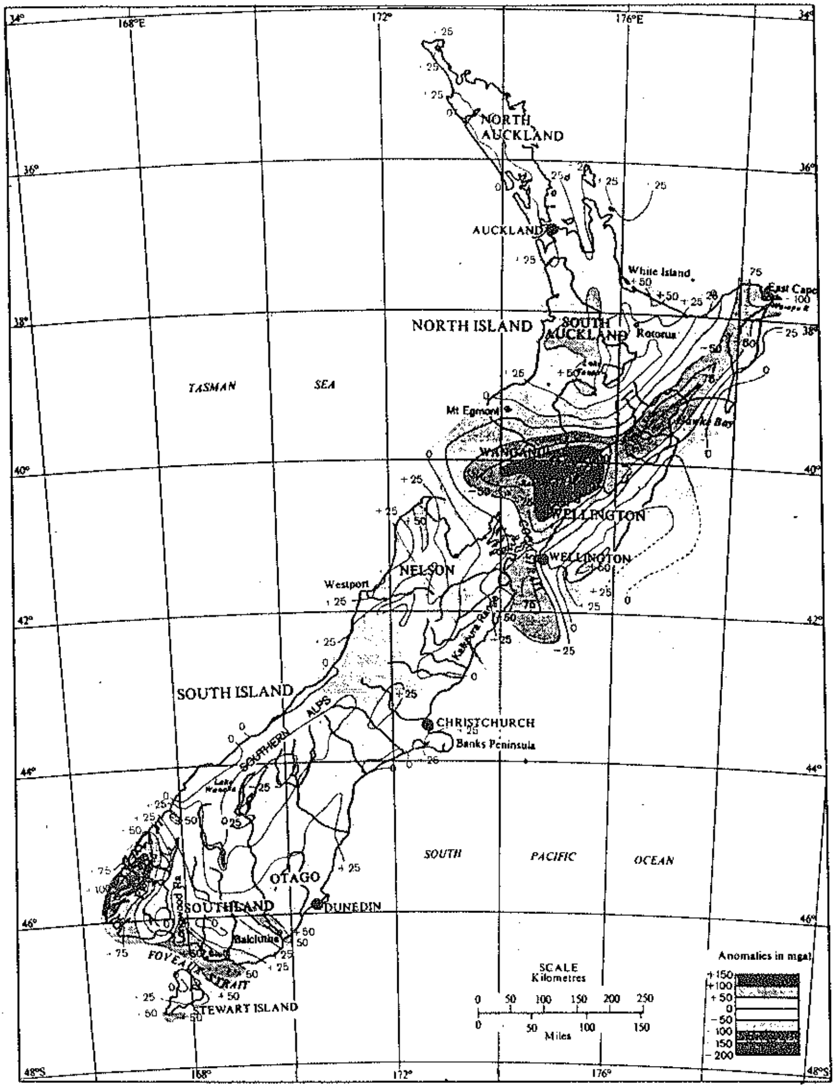


FIGURE 4 *Gravity map of New Zealand. Isostatic anomalies. (Airy–Heiskanen, normal thickness of crust 30 km.)*

(From Reilly et al. 1977)

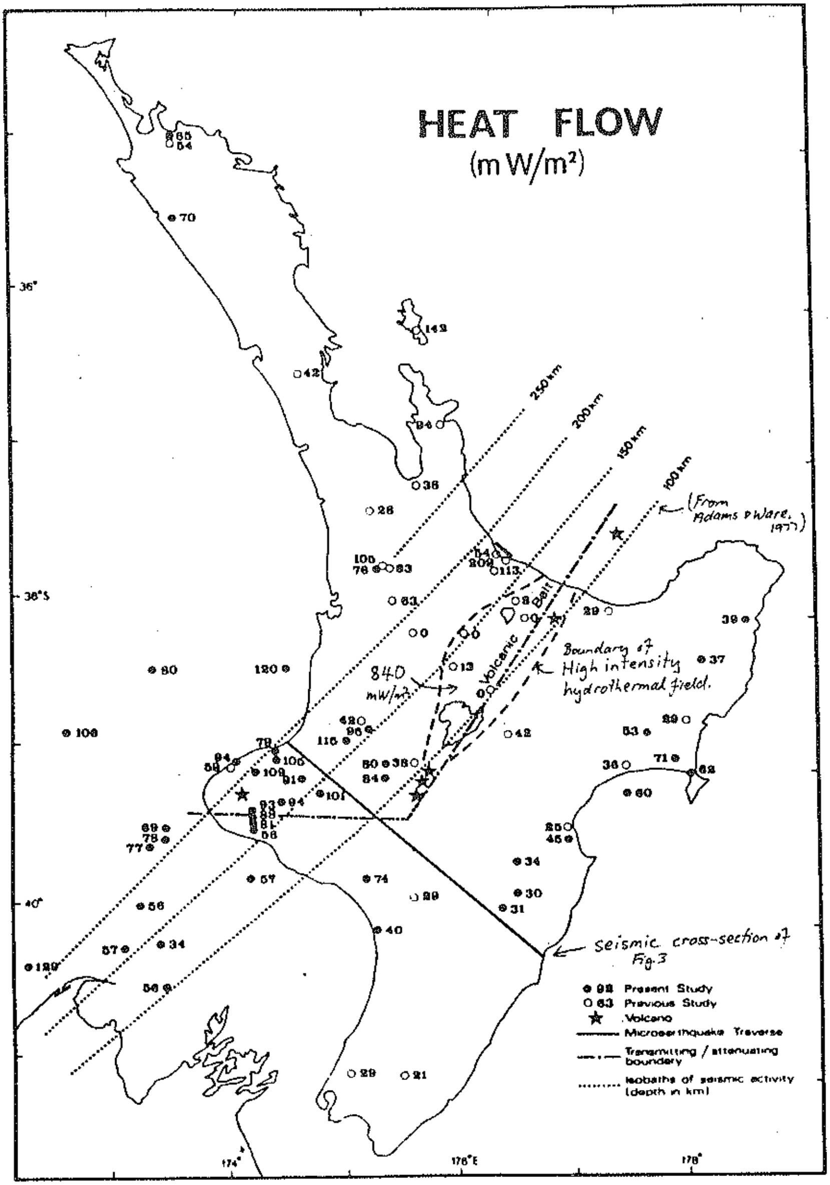


Fig. 5. Regional distribution of terrestrial heat flow in the North Island of New Zealand. Locations of active volcanoes, the high-frequency transmitting/attenuating boundary, microearthquake traverse (Fig. 2) and isobaths of seismic activity are also shown.

(From Pandey, 1981).

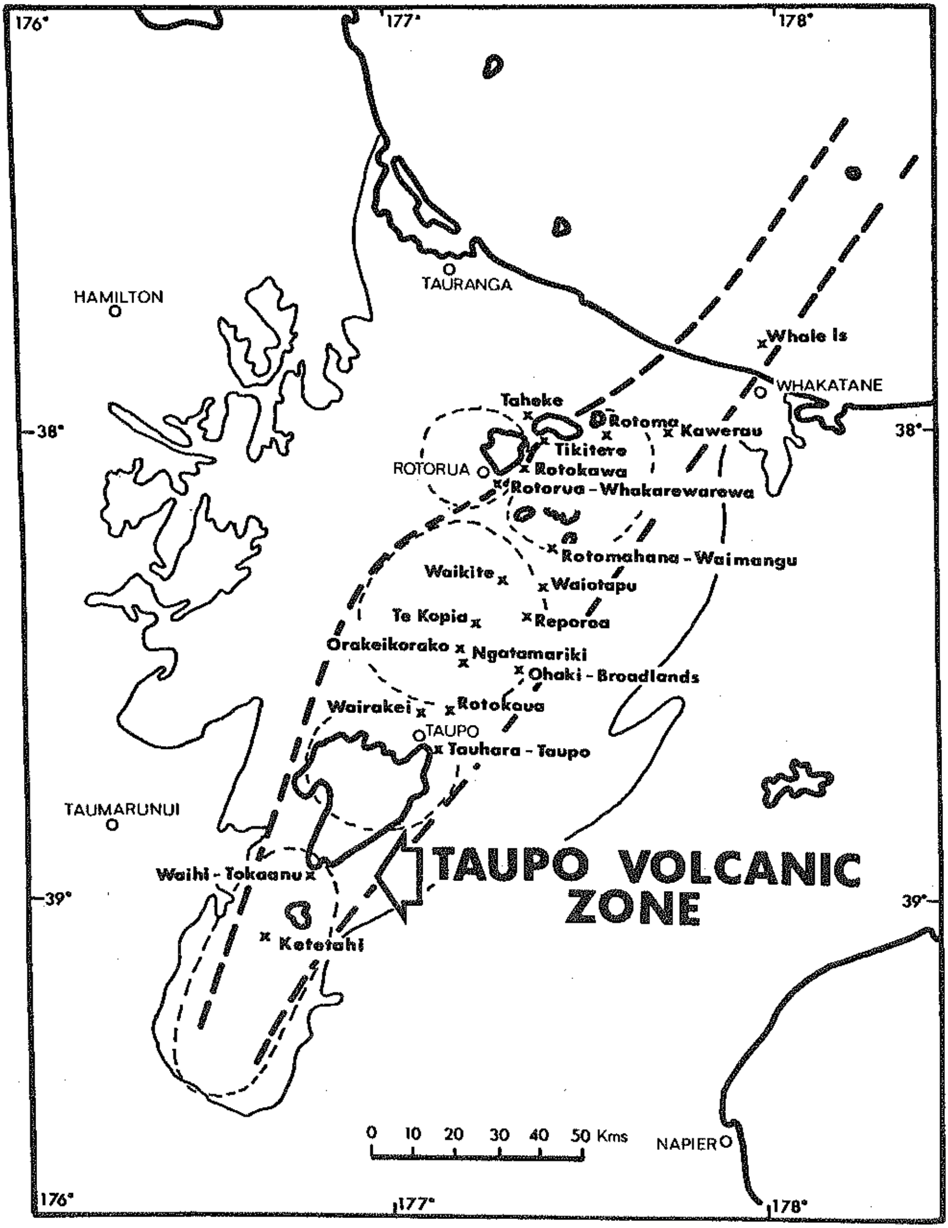


Fig. 6 Distribution of high temperature hydrothermal fields (x) within the Taupo Volcanic Zone. (From Cole and Nairn 1975, p. 13.)

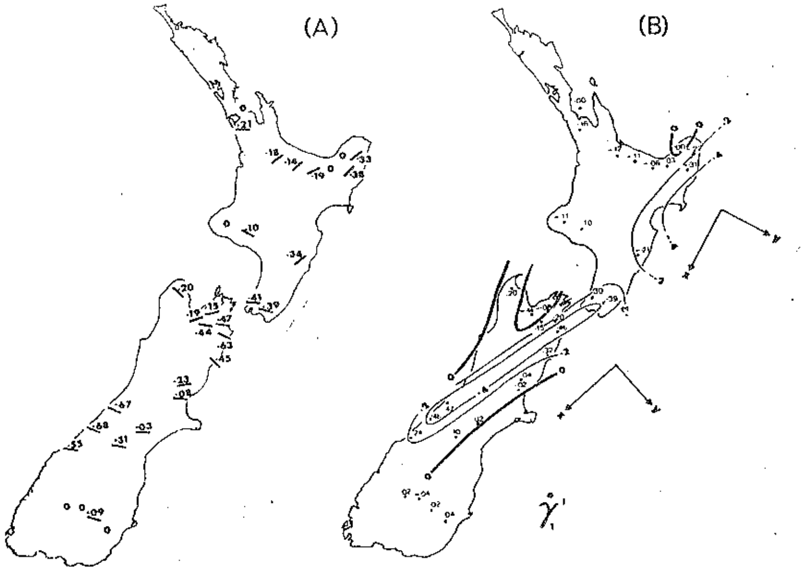


Figure 7A Map (A) shows the aximuth of the principal axis of compression and the shear strain rates for selected areas of northern New Zealand, and map (B) shows the shear strain rates component $\dot{\gamma}'$ resolved normal to the plate boundary; negative values indicate extension and positive values compression. (A) after Walcott (1984: Figure 2b) and (B) modified from Figure 3 of the same paper.

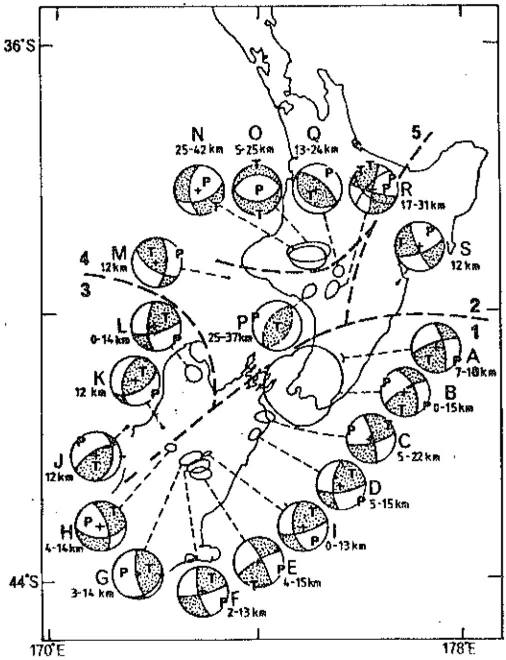


Fig. 7B
Focal mechanisms for shallow earthquakes in the Indian Plate. All diagrams are equal-area projections of the upper focal hemisphere with the compressional quadrants shaded. Solutions are from many sources and were compiled by Reyners (1980, Figure 11).

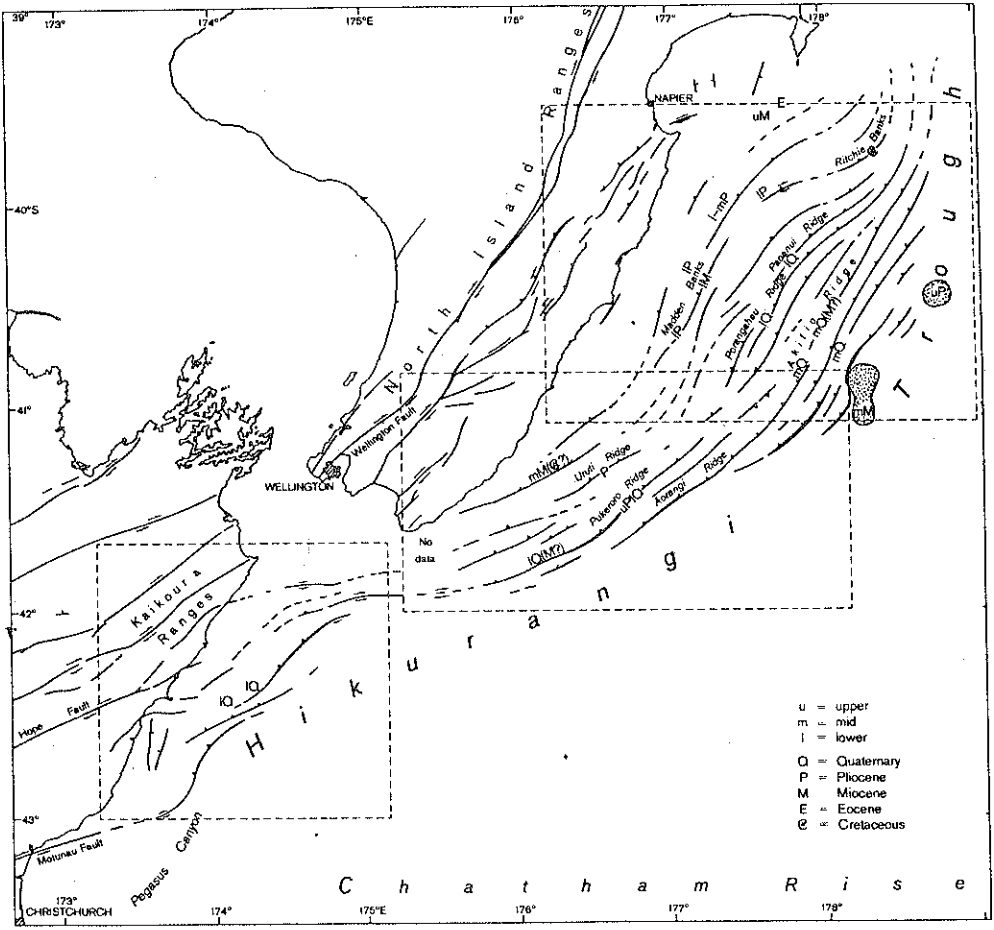


Fig. 8. Map of structural trends along the Hikurangi Margin from Hawke Bay to near Christchurch. Faults on land are from Lensen (1977). Letters refer to the ages of rock samples. C = Cretaceous, E = Eocene, M = Miocene, P = Pliocene, Q = Quaternary, l = lower, m = middle, u = upper. (From Lewis + Bennett, 1985, Fig. 20).

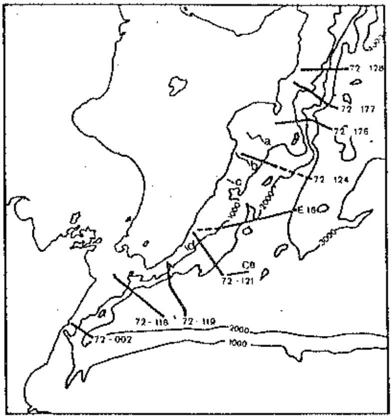


Fig. 9A
(From Lewis, 1980, Fig. 4).

Fig. 9A Positions of seismic profiles illustrated in Figs 5, 6 and 8. Depth contours in metres.

Fig 9B
(From Lewis, 1980, Fig. 5)

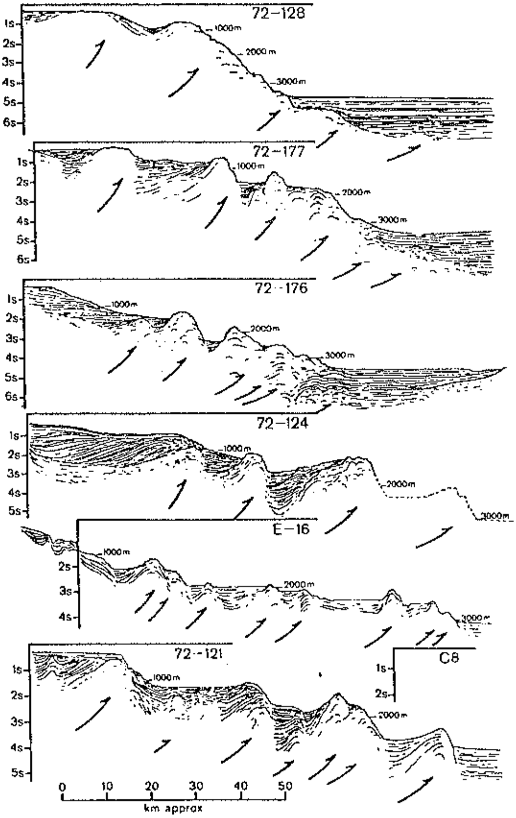


Fig. 9B Tracings of seismic profiles from the Hikurangi Oblique-subduction Margin, continental shelf (left) to Hikurangi Trough (right). Arrows represent probable position of thrust faults. At left, two-way travel time in seconds. On slope, depth to seabed in metres. Horizontal scale approximate only. A line sloping at 45° on the profiles represents a surface with a dip of about 6° in the line of the profile. Note underthrust toe of slope in 72-176 and 72-177. Basin-fill sediments mainly Quaternary in age. Ridge-crest strata range from Quaternary to Early Tertiary but are mainly Late Tertiary.

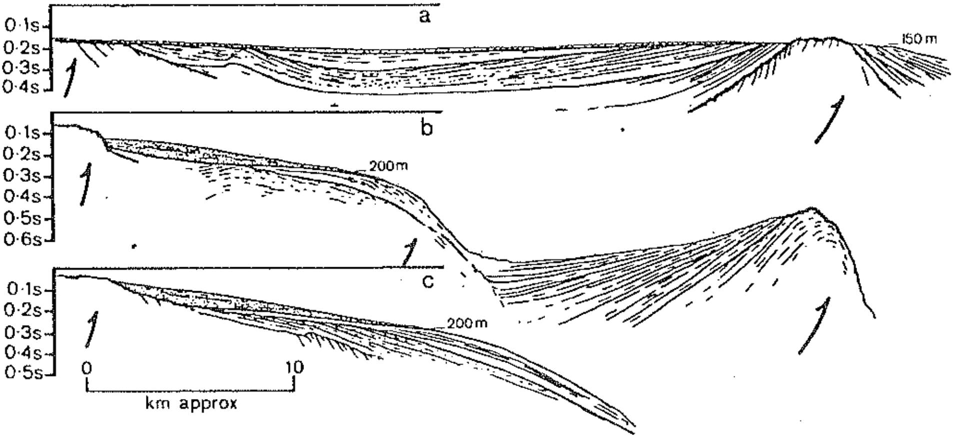


Fig.10 High-resolution profiles of the continental shelf and upper slope illustrating development of continental shelf in continually folding basins during Quaternary oscillations of sea level. Stippling denotes post-20 000 year old sediments. Below this sediments of the Last Glacial Age overlie an Early Last Glacial Age unconformity and are themselves truncated at a 20 000 year old unconformity. Deeper still are Last Interglacial Age sediments. At left two-way travel time in seconds. On profile, depth to seabed in metres. Horizontal scale approximate only. A line sloping at 45° on the profiles represents a reflective surface dipping at 5° (modified from Lewis, 1973a). (From Lewis, 1980, Fig.8)

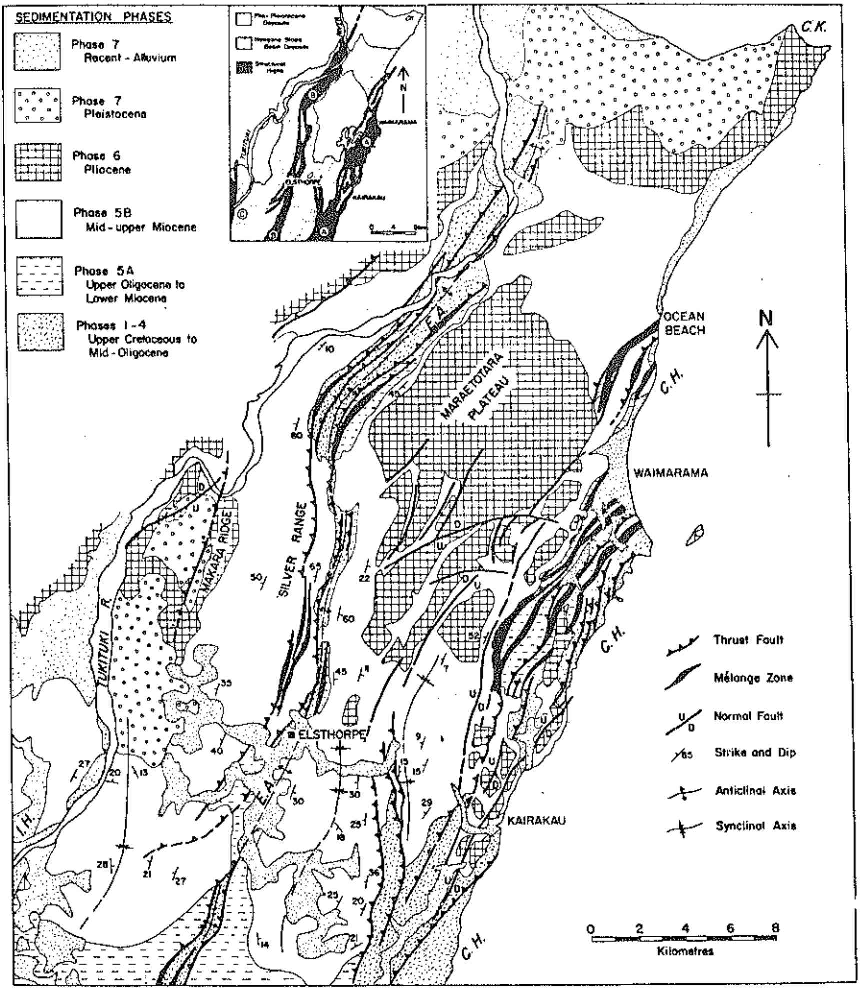


Fig. 11 Generalised geological map of the area studied. For brief description of sedimentation phases (1–7) refer to text. *Inset*: generalised structural entities (highs) and upper Cenozoic sediment groupings. C.H. (A, inset) = Coastal High; E.A. (B, inset) = Elsthorpe Anticline; I.H. (C, inset) = Inland High.

Fig. 11 (From Pettinga, 1982, Fig 3).

g. 12 Schematic sequential developmental his-
ry, Coastal High and Makara Basin, Southern
awke's Bay.

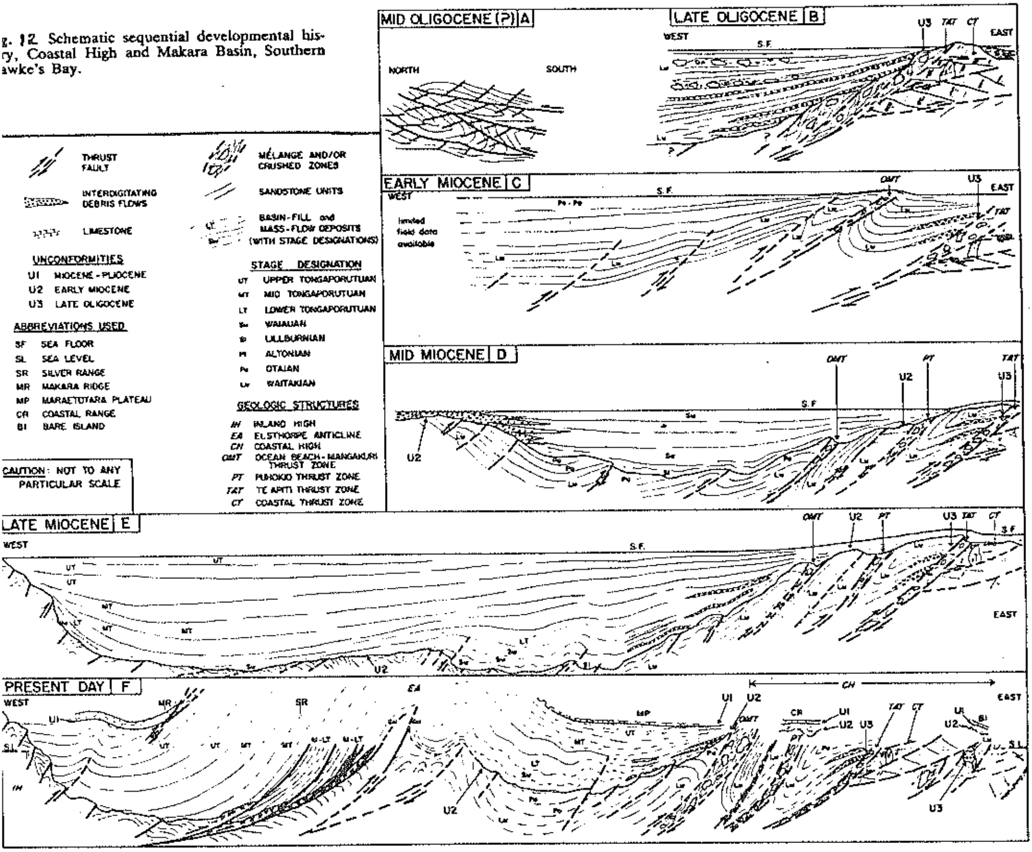


Fig. 12 (From Pettinga, 1982, Fig. 31).

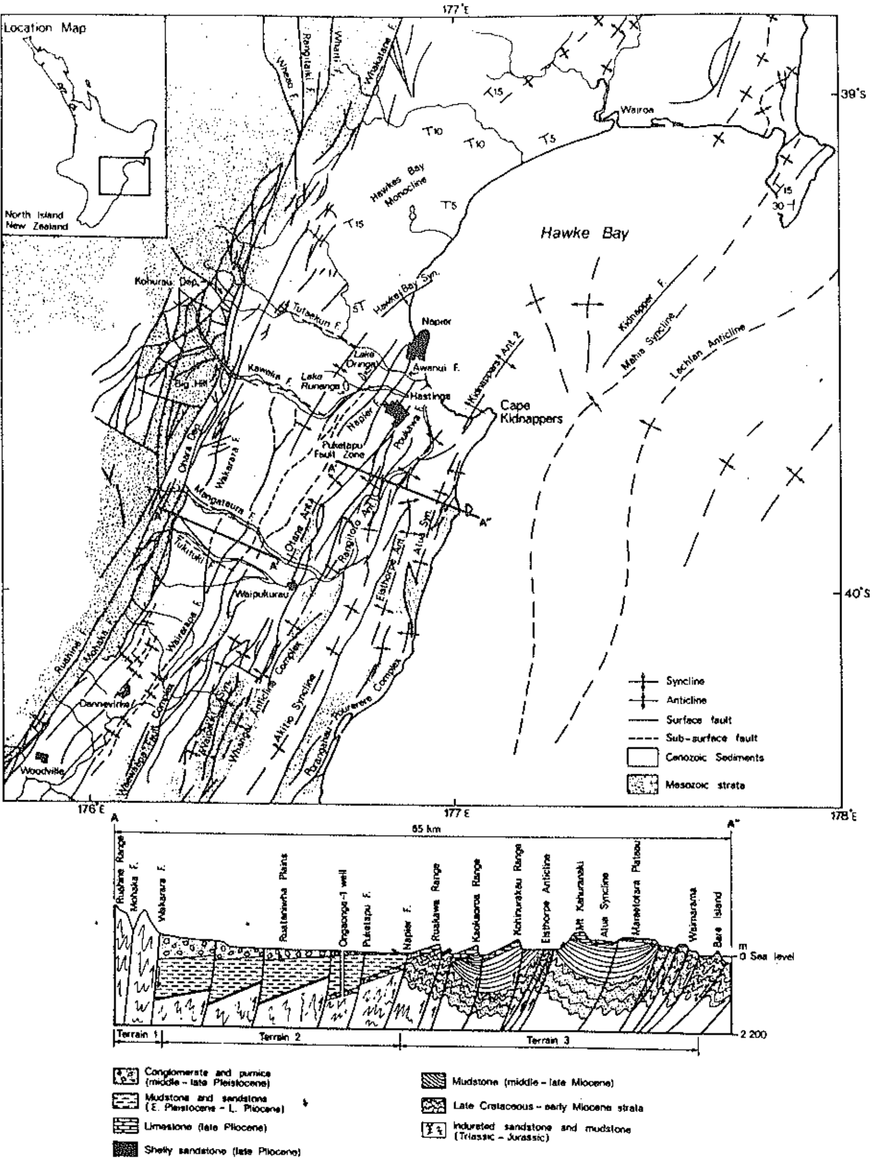
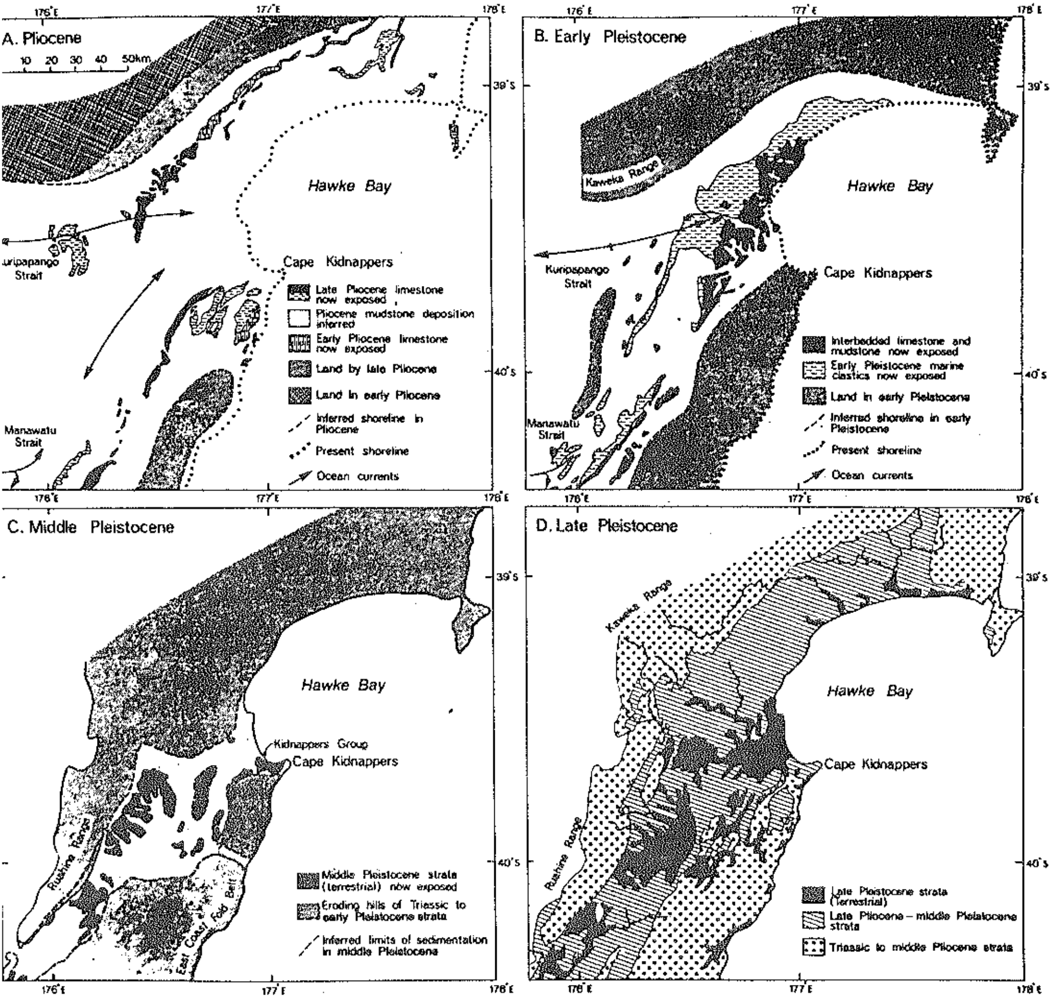


Figure 13. A map of Hawke's Bay structure and a generalised cross-section (not to the same scale). The map shows the pronounced NE-SW regional structural trends onshore and offshore in central and southern Hawke's B This contrasts with the Hawke's Bay monocline further to the north-east, and the rectangular to rhombic pattern 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 dra from data in the following sources: Lillie, 1953; Grindley, 1960; Kingma, 1962; Leslie and Hollingsworth, 1972; B and Grant-Taylor, 1975; Clark, 1976; Lensen, 1977; Kamp, 1978; van der Lingen and Pettinga, 1980.

(From Kamp, 1982, Fig 12·3)



gure 14. A sequence of Pliocene and Pleistocene paleogeographic maps showing the development of Hawke's .y landforms. Map A is modified from Beu *et al.* (1980). The distribution of early, middle, and late Pleistocene diments is taken from New Zealand Geological Survey (1973). (From Kamp, 1982, Fig 12·5).

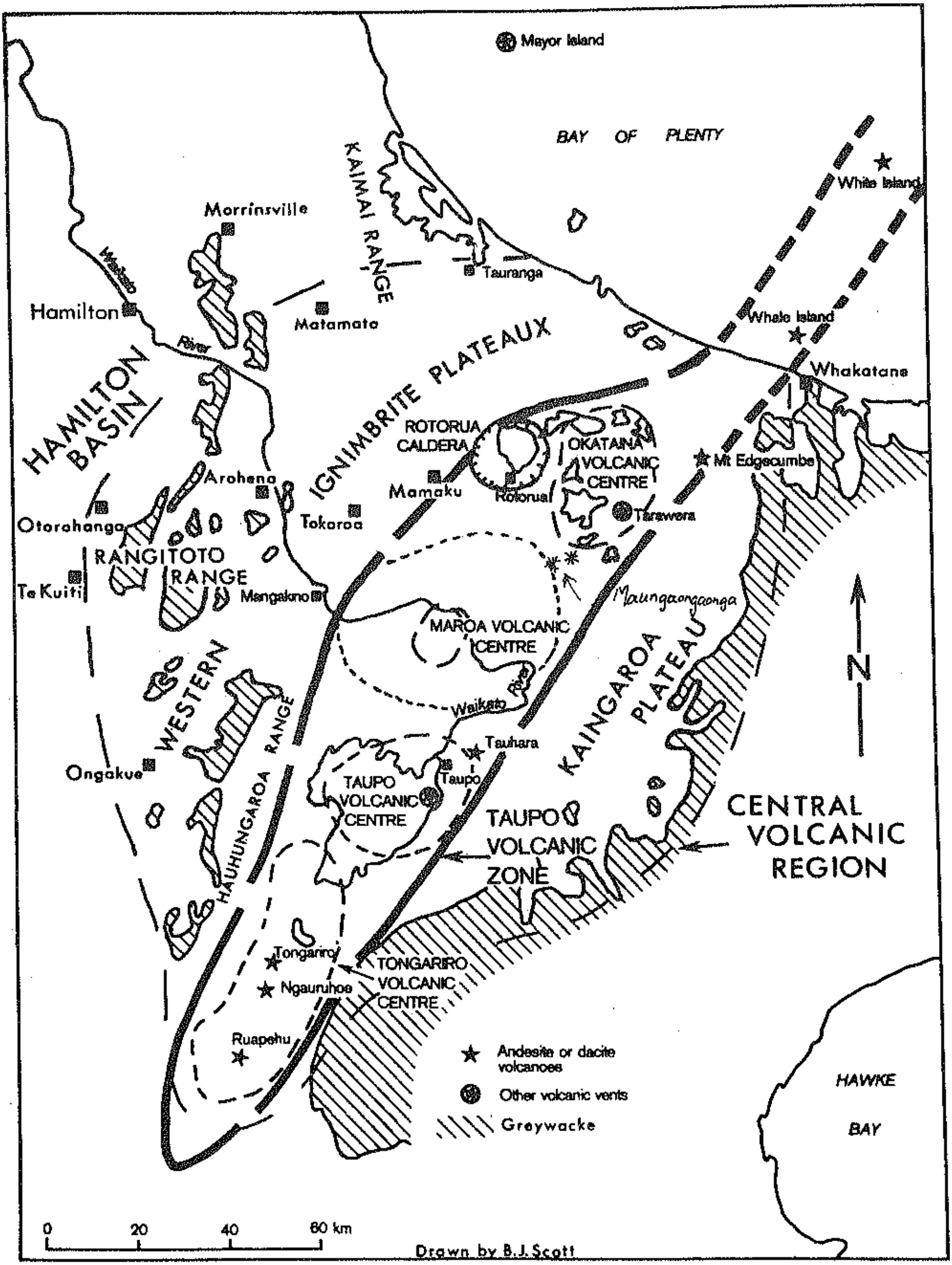


Fig. 15 Map of the Taupo Volcanic Zone and the central volcanic region, North Island, showing principal physiographic and structural divisions. (After Healy 1982, p. 161.)

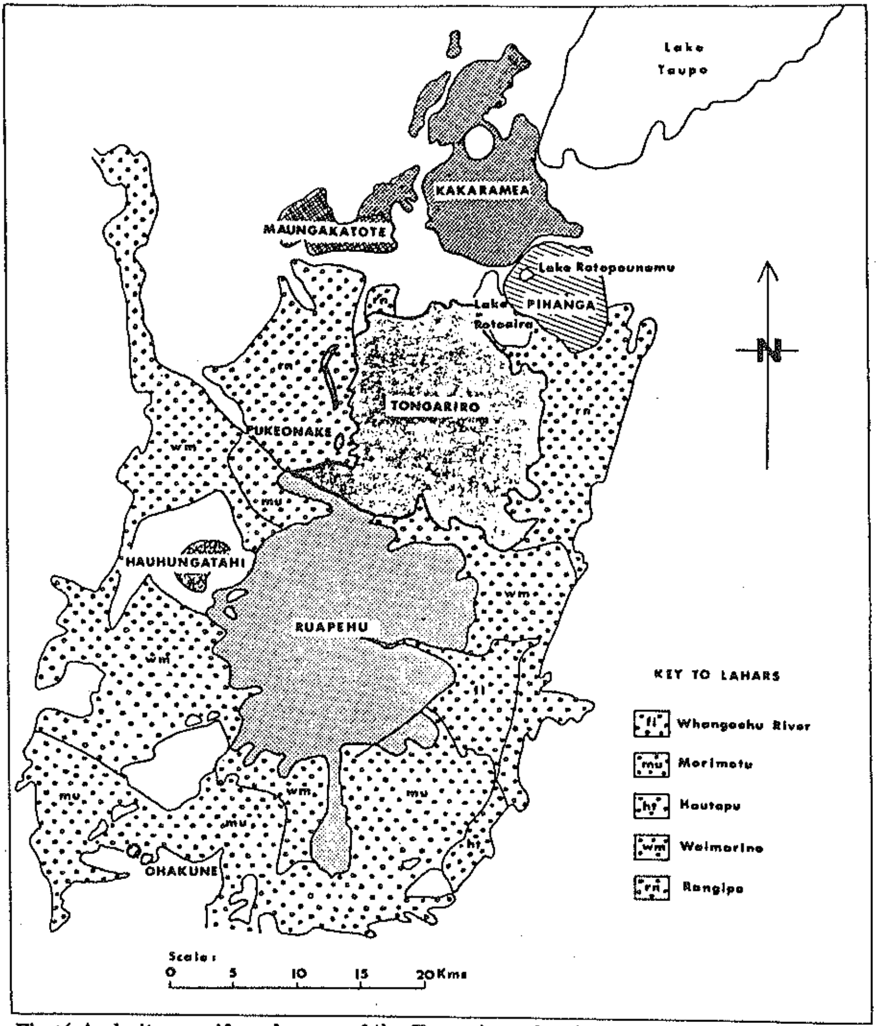


Fig.16 Andesite massifs and cones of the Tongariro volcanic centre. Terminology of lahar ring plain surrounding andesitic lavas after Grindley (1960). (From Cole 1978, Fig 2).

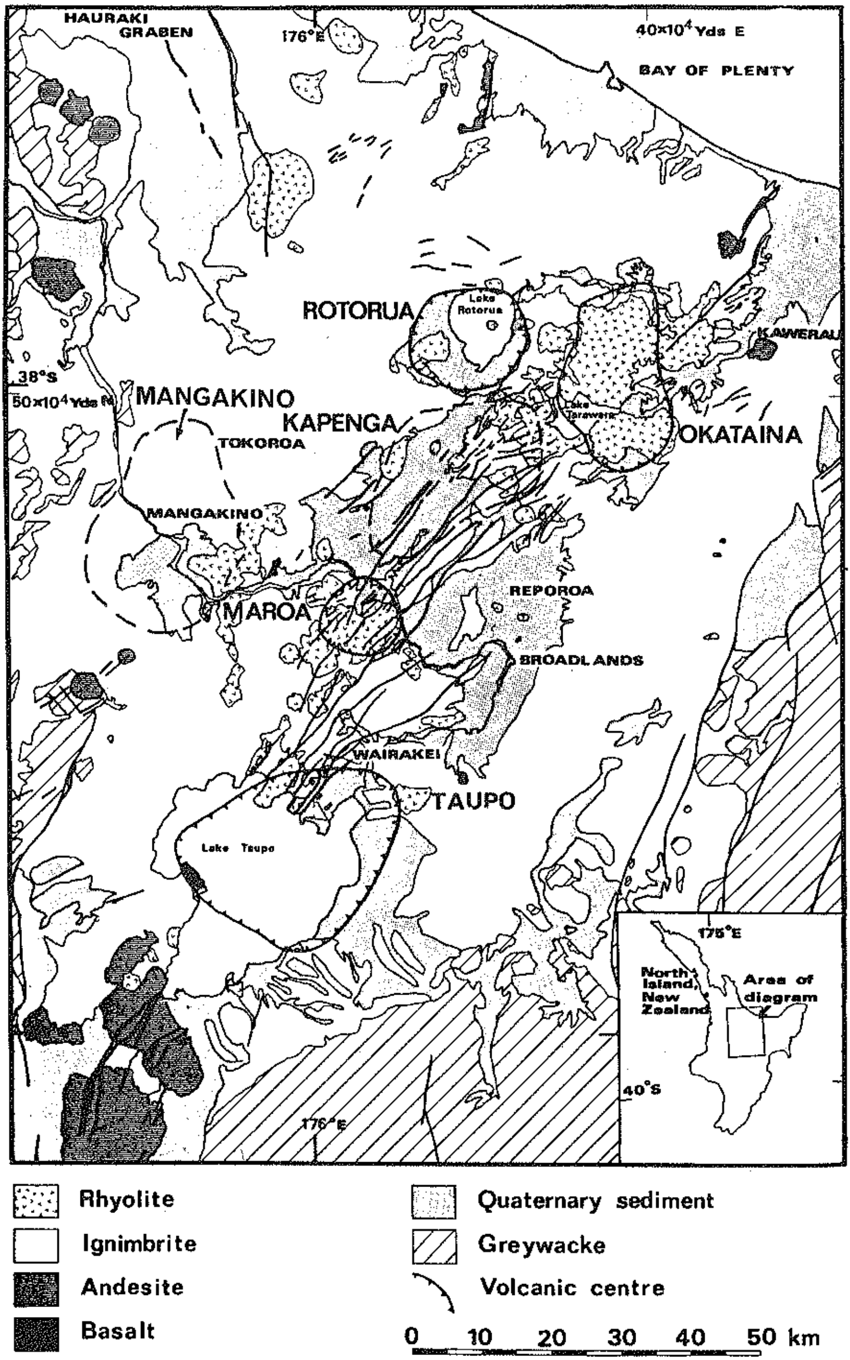


Fig. *17* Simplified geology of the Taupo Volcanic Zone and central volcanic region, showing the volcanic centres/caldera collapse structures delineated by geophysical models and known or inferred vent sites (TAUPO, MAROA, MANGAKINO, KAPENGA, ROTORUA, OKATAINA). Gravity and magnetic models have also located depressions (basins) beneath the Wairakei, Broadlands-Reporoa, and Kawerau geothermal fields (Rogan (1982). (After Rogan 1982, p. 4074 and Wilson et al. 1984, p. 8464.)

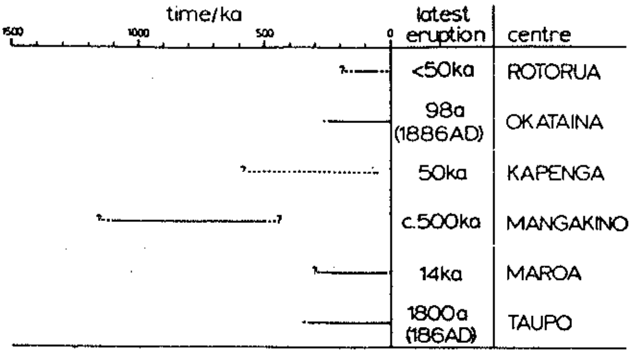


Fig. *18* Summary of the time spans occupied by eruptive activity at the central TVZ caldera volcanoes. (From Wilson et al. 1984, p. 8480.)

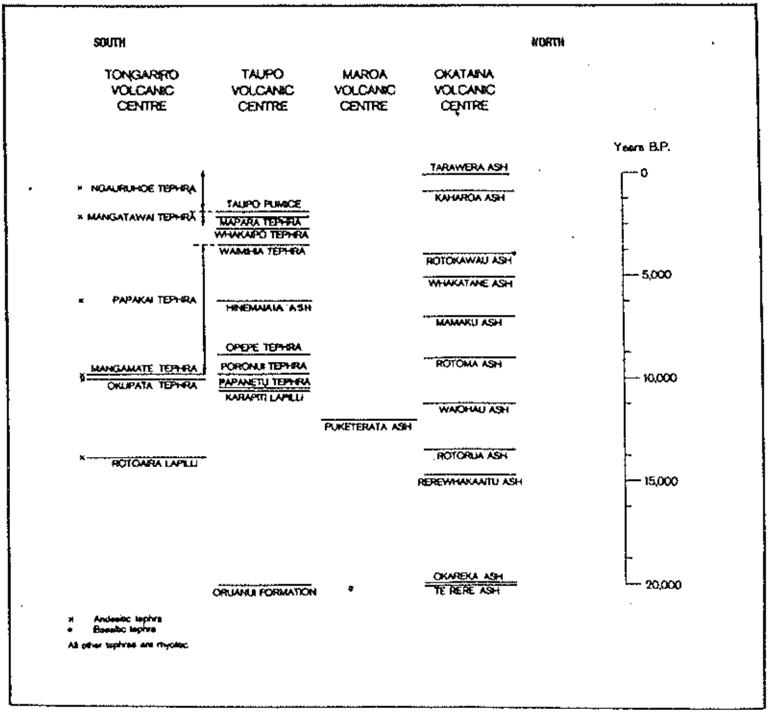


Fig 19 Sequence of major tephras within the Taupo Volcanic Zone. (From Nathan 1976, p. 12.)

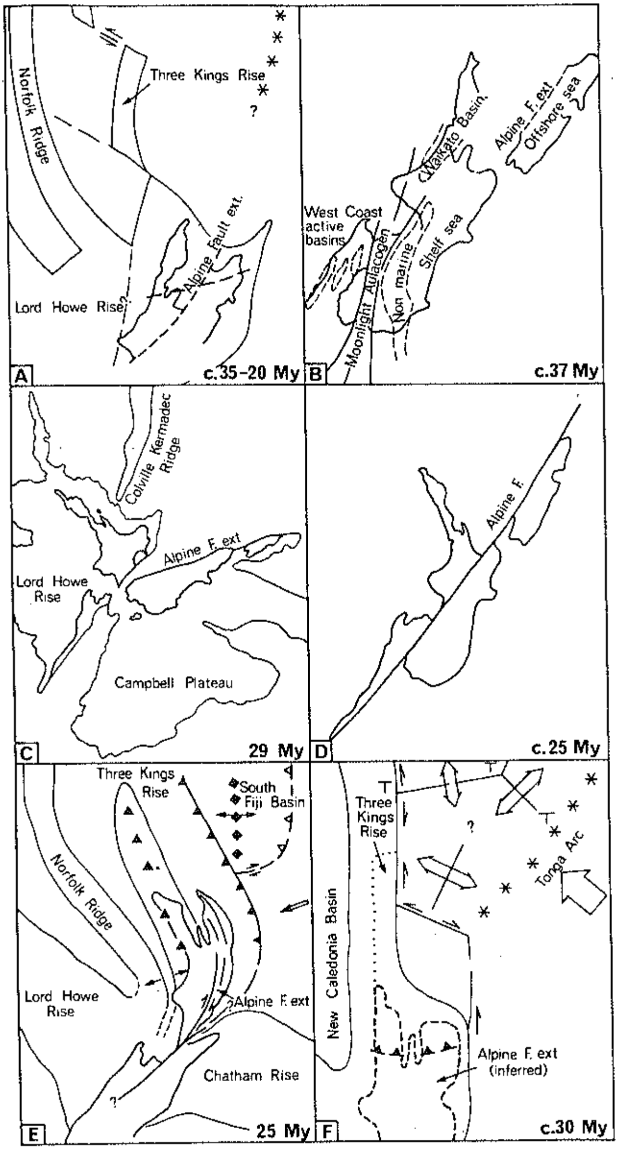


Fig.20 Middle Cenozoic reconstructions of New Zealand by previous workers showing the inferred nature and location north of the Alpine Fault proper of the relative plate motion evident as dextral displacement on the Alpine Fault. A from Ballance (1976); B, Carter and Norris (1976); C, Crook and Belbin (1978); D, Stevens and Suggate (1978); E, Cole and Lewis (1981); F, Ballance *et al.* (1982). From Kamp (in prep.).

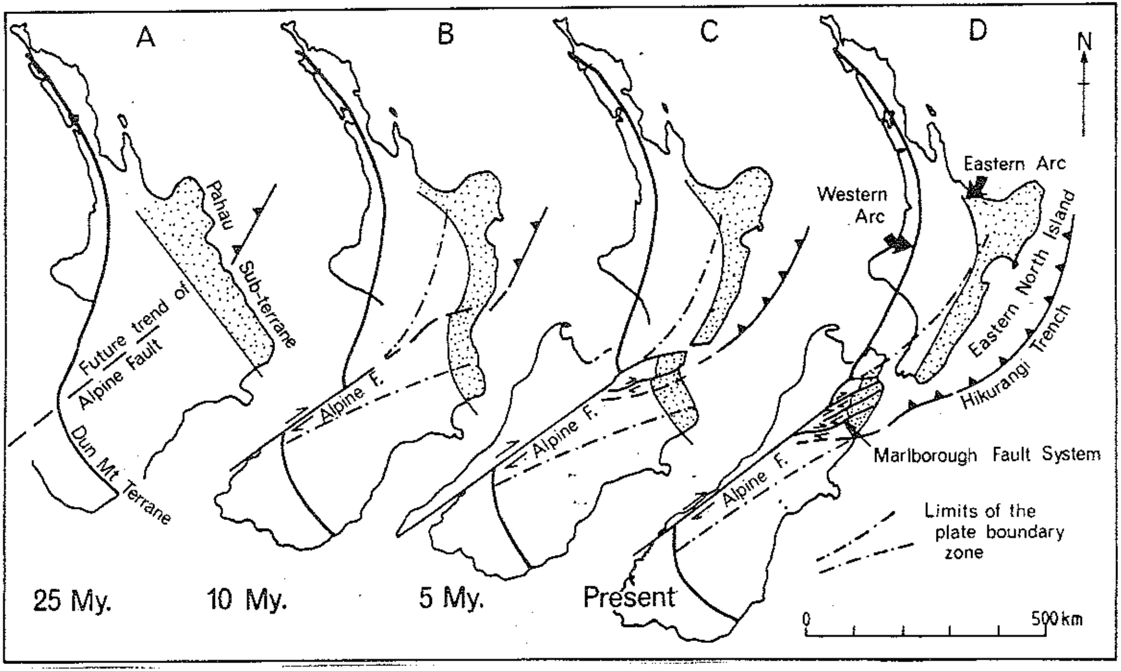


Fig.21. A model showing as a series of sketches the postulated age and origin of the New Zealand recurved arcs in relation to movement on the Australia-Pacific plate boundary including the Alpine Fault sector. The limits of the plate boundary zone in D are from Walcott (1978a). The changes in the former extent of the plate boundary zone are inferred in A-C. (From Kamp, in prep)

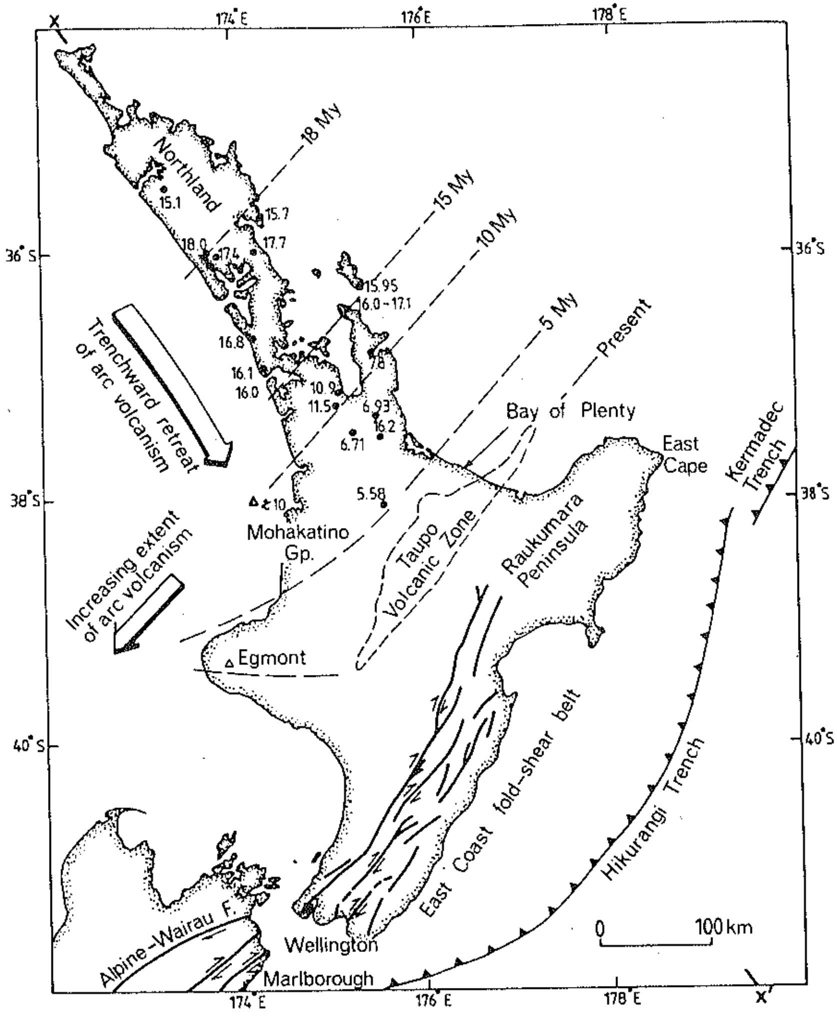
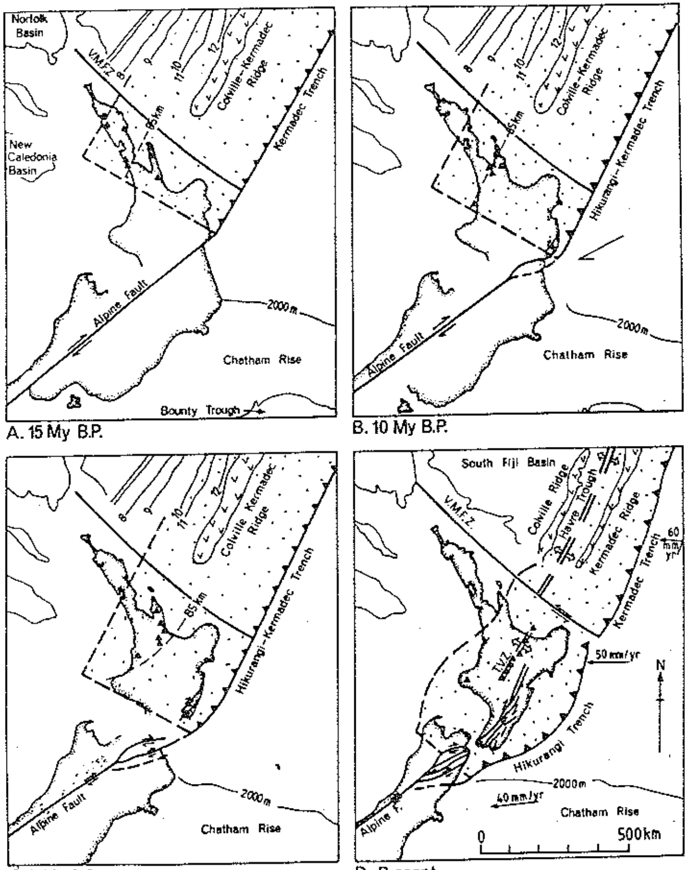


Fig. 22 Distribution of published (sources in text) radiometric ages of orogenic andesites with interpreted isolines showing both a trenchward retreat and an increasing southwestward extent of arc volcanism with time. While the 18.0 My B.P. age is the oldest published date, it should not be strictly 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. (From Kamp, 1984).



A. 15 My B.P.

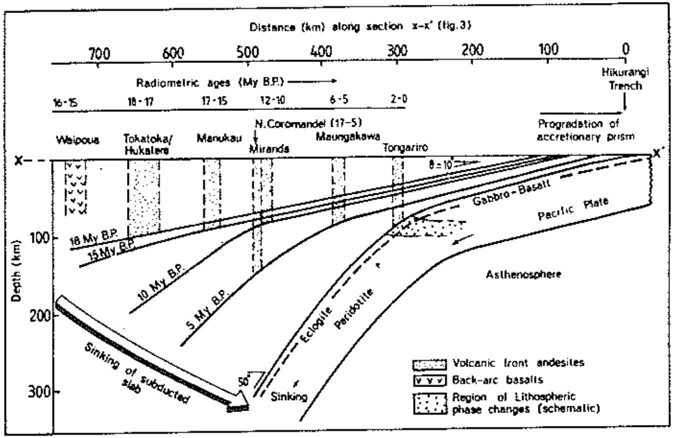
B. 10 My B.P.

C. 5 My B.P.

D. Present

. 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).

Fig. 23A (From Kamp, 1984)



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).

Fig 23B (From Kamp, 1984).

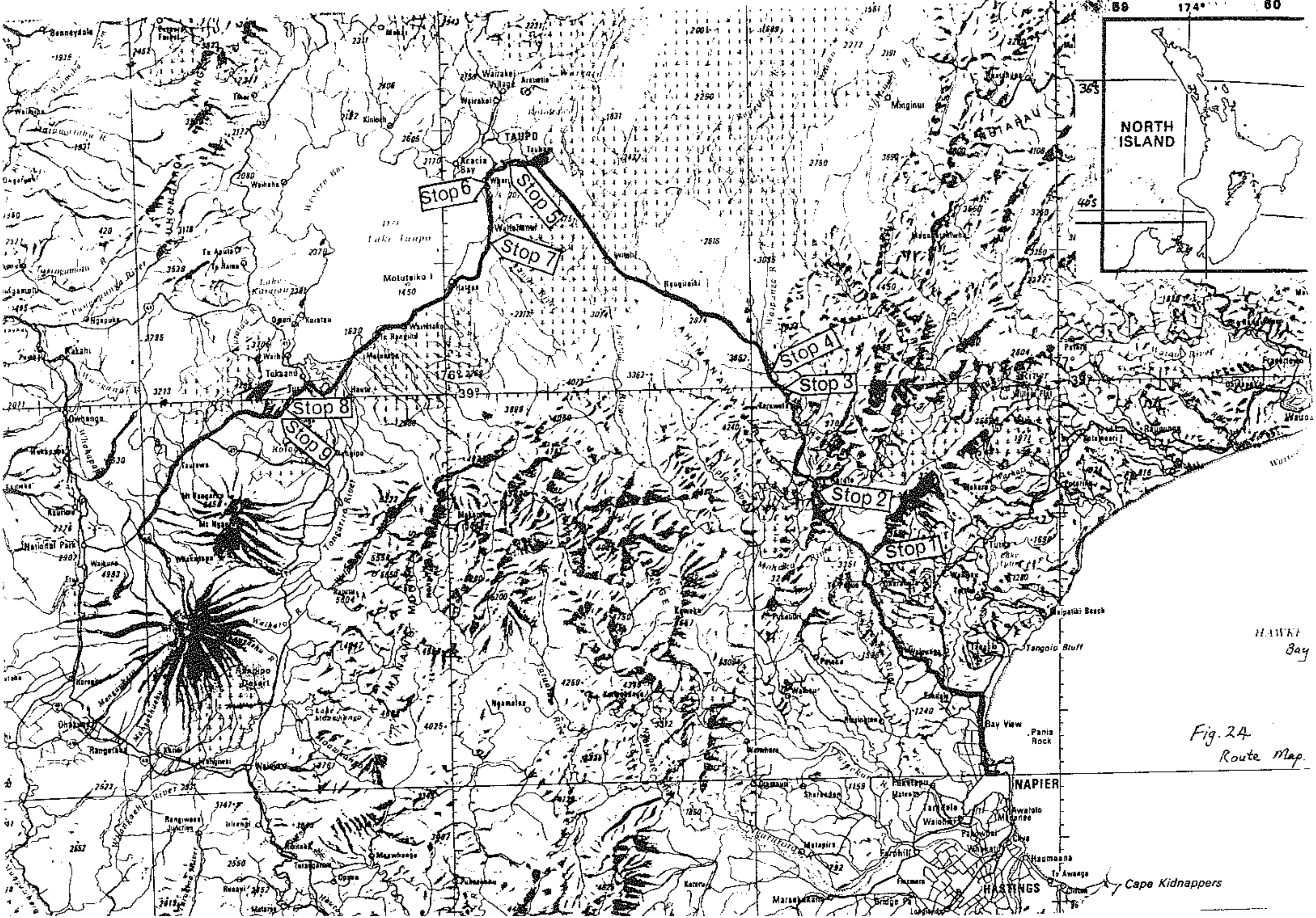


Fig. 24
Route Map.

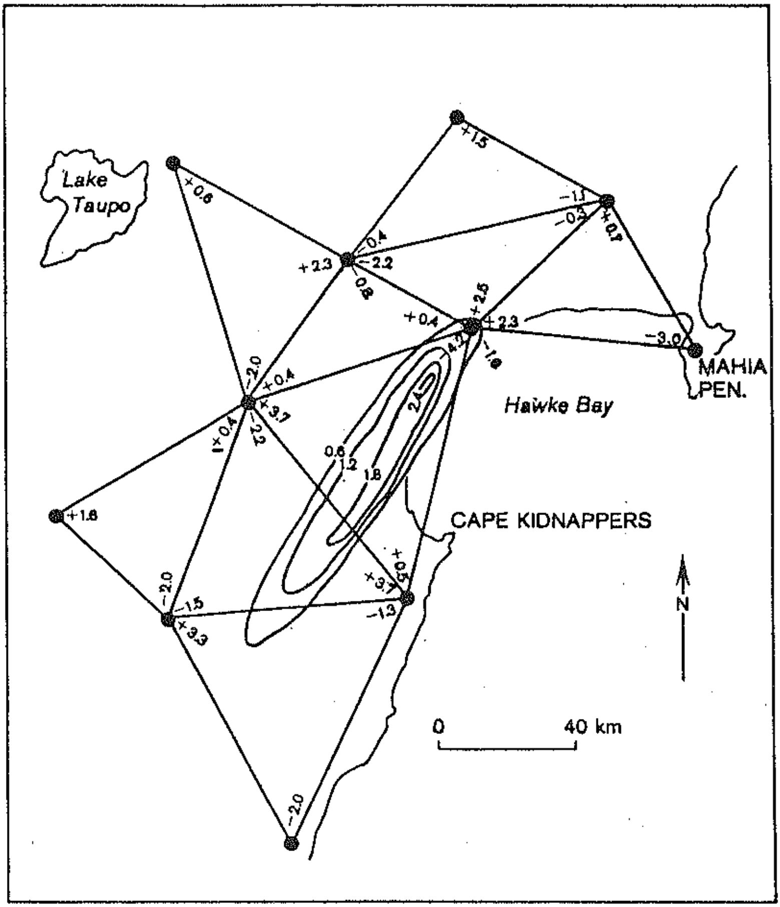


Fig. 25. - Map showing the triangulation network in the Hawkes Bay area surveyed in 1927-29 and again in 1932 following the M 7.8 Hawkes Bay Earthquake of 1931. Angle changes are shown in the corner of triangles. The axis of shortening can be seen by the systematic increase in angles (numbers are seconds of arc) oriented east-west and decrease in angles oriented north-south. In the southern Hawkes Bay area this shortening is consistent with the uplift contours (in metres) shown west of Cape Kidnappers. In Northern Hawkes Bay there is a change in the orientation of the axis of shortening suggestive of extension and downwarping in the Wairoa area. The triangulation network shows changes in angles over a much larger area than surface deformation has currently been recognised (adapted from Wellman 1970). (From Berryman and Hull, 1984).

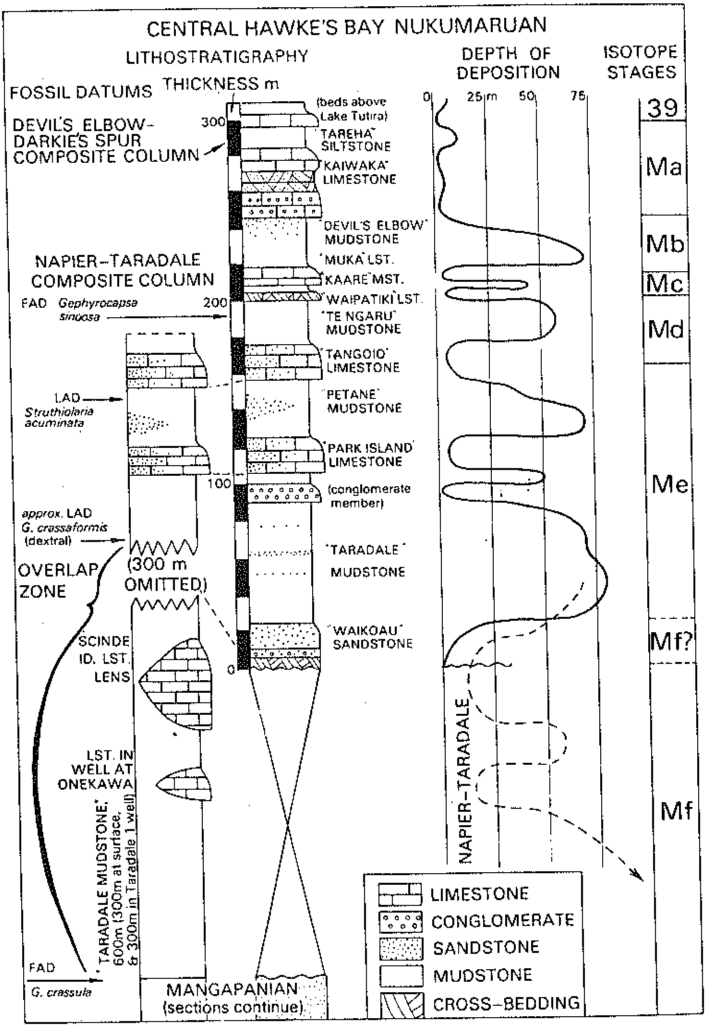
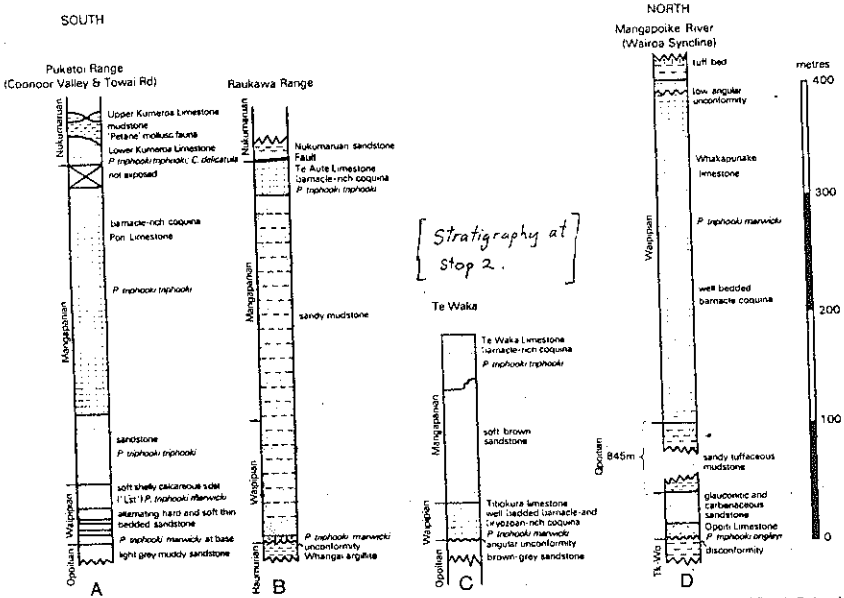


Fig.26 Composite stratigraphic columns of the Nukumaruan sequence of central Hawke's Bay, showing fossil datums (Edwards, 1976; Hornibrook, 1981; Beu, new data), lithostratigraphy (Hornibrook, 1969; N.Z. Geological Survey, unpublished columns; Beu and Edwards, new data; most names are informal), our interpretation of depths of deposition, and correlations with isotope stages. Correlation of lithologies below Park Island limestone is schematic. (From Beu & Edwards, 1984, Fig. 6)

Fig. 26



[Stratigraphy at
Stop 2.]

A Stratigraphic column of Pliocene and early Pleistocene rocks in the valley between Coonoor and Waitahora, and on Towai Road, Puketoi Range.
B Stratigraphic column of Pliocene rocks at Onepu & Argyll Roads, Raukawa Range (composite).
C Stratigraphic column of Pliocene rocks at Te Waka trig station, Te Waka Range.
D Stratigraphic column of the Pliocene rocks of Mangapoike River, Wairoa Syncline.

Fig 27A (from Beu et al., 1980)

ZONE NAME	SYMBOL	ZONAL INDEX MOLLUSCA; TIME RANGES	STAGE	EPOCH
Struthiolaria convexa Zone	*spc*	*Struthiolaria (Pelicaria) convexa*, *Struthiolaria (Pelicaria) acuminata*, *Chlamys (Zygochlamys) delicatula*	NUKUMARUAN	PLEISTO-CENE (early)
Chlamys (Phialopecten) triphooki triphooki Zone	*ptt*	*Chlamys (Phialopecten) triphooki triphooki*; last appearance of *Polinices* and *Maoricardium*	MANGAPANIAN	PLIOCENE
Chlamys (Phialopecten) triphooki marwicki Zone	*ptm*	*Chlamys (Phialopecten) triphooki marwicki*, *Mesopeplum crawfordi*	WAIPIPIAN	
Chlamys (Phialopecten) triphooki ongleyi Zone	*pto*	*Chlamys (Phialopecten) triphooki ongleyi*	OPOITIAN	
Sectipecten wollastoni Zone	*Tk*	*Sectipecten wollastoni*, *Austrofusus coerulescens*	KAPITEAN	MIOCENE (late)

Fig.27B Molluscan zonation of Pliocene and early Pleistocene rocks of Hawke's Bay.
(From Beu et al. 1980)

SUMMARY OF STRATIGRAPHY AND VOLUMES OF THE TAUPO ERUPTION PRODUCTS

(Compiled from data in Walker (1980, 1981*b*, *c*), this paper and Paper II. Magma volumes assume a density of 2.3 g cm^{-3} and lithic-debris volumes a density of 2.6 g cm^{-3}. The Taupo Ignimbrite of Froggatt (1981) is divided into Lower, Middle and Upper units and a 'lithic lag layer', which correspond with our interpretations thus:

Lower unit	early ignimbrite flow units, plus layer 1 of the Taupo ignimbrite (in part);
lithic lag layer	ground layer (part of layer 1) of the Taupo ignimbrite;
Middle unit	layer 1 (in part) and layer 2 (in part) of the Taupo ignimbrite.
Upper unit	layer 2 (in part) of the Taupo ignimbrite, plus secondary deposits.)

Healy (1964)	Froggatt (1981)	this paper	volume *in situ*/km^3	volume, magma/km^3	volume, lithics/km^3
(Taupo Pumice Alluvium)	—	secondary deposits	—	—	—
	—	floated giant pumices	?	?	—
	Taupo Ignimbrite	secondary deposits	—	—	—
Upper Taupo Pumice Rhyolite Block Bed (members 1 and 2)		Taupo ignimbrite	31	10	2.1
Taupo Lapilli (member 3)	Taupo Lapilli	Taupo plinian pumice +	23	5.1	0.73
		early ignimbrite flow units	1.5	0.5	0.05
Rotongaio Ash (member 4)	Rotongaio Ash	Rotongaio phreatoplinian ash	1.3	0.7	0.09
'putty-coloured ash' (member 5)	Hatepe Tephra	Hatepe phreatoplinian ash	2.5	1.0	0.12
Hatepe Lapilli (members 6–8)		Hatepe plinian pumice	6	1.4	0.18
		initial phreatomagmatic ash	0.015	0.005	negl.
Paleosol developed on older deposits			*subtotal ca.* 65	18.7	3.27
		layer 3 deposits of ignimbrite phases	up to *ca.* 20	up to *ca.* 7	negl.
		primary material now under Lake Taupo	20–60	8–20	?
			total ≥ 105	≥ 35	> 3.27

Fig 28 (from Wilson and Walker, 1985)

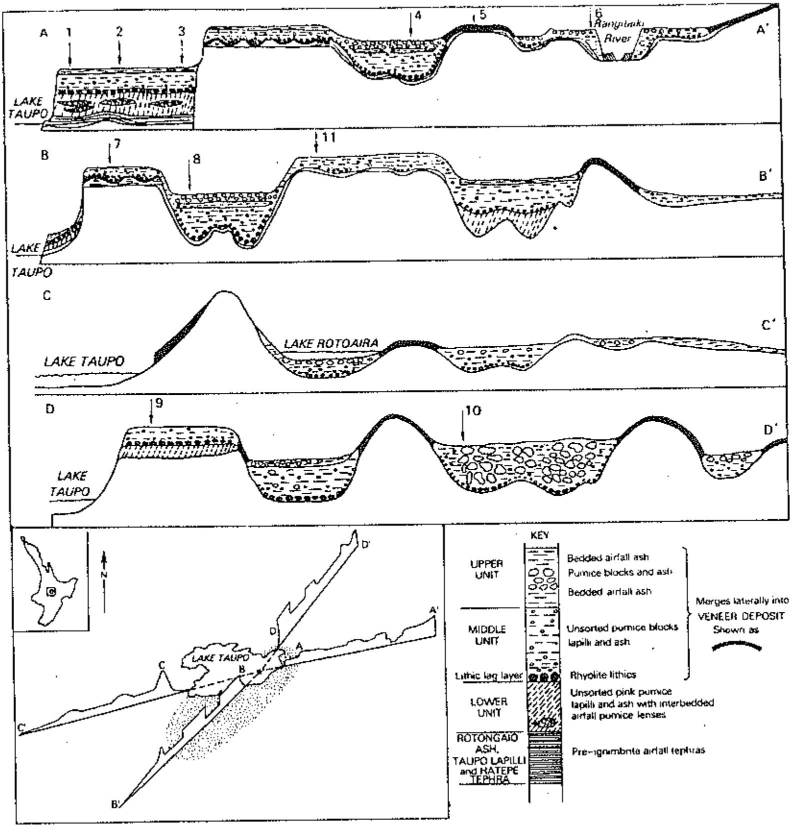


Fig.29 Schematic cross-sections (not to scale) through Taupo Pumice Formation to show the relationship and distribution of each unit and facies of Taupo Ignimbrite as shown in the key. Thickness of Taupo Ignimbrite is largely topographically controlled with thick sequences in the valleys and thin "veneer deposits" on the ridges. Restricted occurrence of pumice alluvium is shown in the Rangitaiki River, Profile A. Stippled area on location map (upper right) indicates the approximate extent of the Lower unit. The numbered arrows refer to sections figured in the text or described in Appendix 1. (From Froggatt, 1981)

Fig. 29

Stop 5

(Stratigraphy in cm)

1. De Brett Thermal Hotel, Taupo; deep road cutting on Taupo–Napier Highway; N94/573353 (1969). The section description commences near the eastern end of the cutting and progresses, with the formation contacts at eye level, westwards towards Taupo; see Fig. 3, 4, 5, 11, 14.

Taupo Pumice (Tp)

210	Upper Taupo Pumice
15	Rhyolite Block Member
60	Taupo Lapilli
15	Rotongaio Ash
15	"Putty ash" Member
45	Hatepe Lapilli
360 cm	

Mapara Tephra (Mp)

15	ash (paleosol, dark greyish brown 10YR 4/2 silty sand; charcoal fragments)
10	olive brown ash and lapilli
32	light grey lapilli and coarse ash with darker rhyolite fragments common; layers of indurated fine ash alternating with layers of loose, coarse ash; indurated layers form conspicuous ribs in a weathered section
5	light grey coarse ash; loose; distinct lower contact
62 cm	

Whakaipo Tephra (Wo)

10	ash (paleosol, dark yellowish brown 10YR 3/4 silty sand); charcoal fragments
28	grey coarse ash and lapilli; shower-bedded; massive; 40% rhyolite lithics; indistinct but regular contact
38 cm	

Waimihia Formation (Wm)

5	ash (paleosol, very pale brown 10YR 7/4 sandy loam) fine ash (paleosol, white 5YR 8/1 loamy fine sand, "bleached" layer)
10	yellow fine ash
12	very pale brown ash
143	grey to white bedded ash and lapilli incorporating one 30-cm-thick massive ash layer with charcoal fragments (flow unit)
20	pale grey lapilli and blocks; loose; sharp wavy lower contact
195 cm	

Hinemaiaia Ash (Hm)

2	fine ash with charcoal fragments (paleosol, very dark brown 10YR 2/2 fine sandy loam); this layer is not positively identified as Whakatane ash
13	ash (paleosol, greyish brown 10YR 5/2 sandy loam)
20	pale olive medium and coarse ash (and fine lapilli); massive with fine charcoal fragments (flow unit)
10	pale grey coarse and medium ash; loose indistinct lower contact
45 cm	

Rotoma Ash (Rm)

15	ash (paleosol, greyish brown 2·5YR 5/2 sandy loam), charcoal fragments
15	olive grey fine ash; massive
30 cm	

Opepe Tephra (Op)

35	reddish yellow soft, highly vesicular, pumice blocks, lapilli and ash; blocks have reddish yellow coating and pale grey to white interior; charcoal fragments in middle of layer; (paleosol; rubbly sandy loam, 23 cm thick, incorporates andesitic ashes)
80	yellow coarse ash and pumice lapilli; shower bedded
40	yellow pumice lapilli and blocks; abundant coarse rhyolite ash; weakly shower bedded
155 cm	

Poronui Tephra (Po)

20	ash (paleosol, brownish yellow 10YR 6/6 sandy loam; upper 5 cm incorporates "specked andesitic ash" containing 2% Extr. Al. by Tamms Oxalate extractant
20	yellow ash and coarse ash; distinct lower contact
40 cm	

Karapiti Lapilli (Kp)

15	coarse ash weakly developed (paleosol, brown 10YR 4/3 coarse sandy loam; yellowish brown veins, contains negligible andesitic ash; 0·4% Extr. Al. by Tamms Oxalate)
78	brown lapilli and coarse ash; conspicuous interbedded rhyolite ash
12	pale yellow coarse ash; poorly bedded; distinct lower contact
105 cm	

62 cm	yellowish brown (10YR 5/8) fine sandy loam (0·45% Extr. Al. Tamms Oxalate) . . . tephric loess
300 cm	olive sands passing to cross-bedded fluvial deposits on

Fig. 30 (from Vucetich and Pullar, 1973).

Oruanui Formation

(section described at this site by Vucetich & Pullar 1969, pp. 799–800)

TEPHRA FORMATION			YEARS B.P. (T½ OLD)	C-14 No.	SAMPLE	ERUPTED VOLUME (km³)
TAUPO ~~TEPHRA~~ Pumice FORMATION	TAUPO IGNIMBRITE					70
	TAUPO LAPILLI					14
	ROTONGAIO ASH		1820 ± 20 (mean)			2
	HATEPE TEPHRA ash					2
	HATEPE TEPHRA lapilli					2
	MAPARA TEPHRA	ssssss	↖2010 ± 60	1068	P	6
			↙2150 ± 48	1069	P	
	WHAKAIPO TEPHRA	ssssss	←2670±50	1070	P	6
			←2730-60	1071	P	
	WAIMIHIA TEPHRA Ignimbrite	ssssss	↖3130 ± 65	1062	P	5
			↖3170±80	504	P	
	WAIMIHIA TEPHRA Lapilli		↖3280±110	3947	P	12
			←3150±90	180	C	
			←3440±80	2	C	
			↙3270±65	1061	P	
			↙3440±80	505	P	
	HINEMAIAIA TEPHRA	ssssss	↖4650±80	4574	C	3
			↙5680±130	3950	P	
	MOTUTERE TEPHRA	ssssss	↙5370±90	3951	P	
			↙5370±90	4846	C	1
	OPEPE TEPHRA	ssssss	↙8850±1000	185	C	12
	PORONUI TEPHRA	ssssss	←9740*			7
	KARAPITI TEPHRA	ssssss	↖9780±170	1372	W	6
			←9910±130	4847	C	
		ssssss				

sss Paleosol

P = PEAT

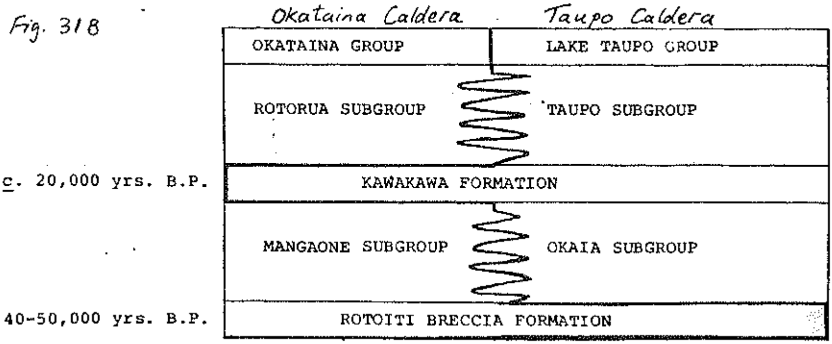
C = CHARCOAL

W = WOOD

* Extrapolated by Topping (1973).

Fig. 31A Stratigraphy, relevant C-14 dates and erupted volumes of Taupo Holocene tephras. *(From Froggatt, 1980).*

Fig. 31B



(From Howorth et al. 1980)

—Stratigraphic column showing the relationship, in the Tongariro area, of andesitic tephras of the Tongariro Sub-group with interbedded rhyolitic tephras from the Okataina, Maroa and Taupo Volcanic Centres.

FORMATION	NAMED MEMBERS	UNNAMED BEDS	SYMBOLS	VOLCANIC CENTRE (SOURCE)	INFERRED STRATIGRAPHIC AGE (NOT ^{14}C-DATED)	^{14}C AGES IN YEARS BEFORE 1950	NZ ^{14}C NUMBER
[1]Ngauruhoe Tephra			ng	Tongariro			
[2]Taupo Pumice	Upper Taupo Pumice		tp 1	Taupo		1,819 ± 17	Averaged from many dates (Healy 1964)
	Taupo Lapilli		tp 3				
	Rotongaio Ash		tp 4				
	'Putty Ash'		tp 5				
[3]Mangatawai Tephra			mg	Tongariro		2,500 ± 200 (basal 80 mm)	NZ186
		Andesitic tephra					
[4]Whakaipo Tephra			wo	Taupo		2,670 ± 50 (above ash) 2,730 ± 60 (below ash)	NZ1070 NZ1071
		Andesitic tephra					
[2]Waimihia	Waimihia Lapilli		wm	Taupo		3,170 ± 80 (above ash) 3,440 ± 80 (below ash)	NZ504 NZ505
[5]Papakai Tephra			pp	Tongariro			
[4]Hinemaiaia Ash			hm	Taupo		6,390 ± 120 (above ash) 6,190 ± 70 (below ash)	NZ1137 NZ1247
[5]Papakai Tephra			pp	Tongariro			
[6]Rotoma Ash			rm	Okataina		7,330 ± 235	NZ1199
[5]Papakai Tephra			pp	Tongariro			
[4]Opepe Tephra			op	Taupo		8,850 ± 1000	NZ185
[5]Papakai Tephra			pp	Tongariro			
[5]Mangamate Tephra	Poutu Lapilli		pt	Tongariro	9,700		
		Andesitic tephra		Tongariro			
[4]Poronui Tephra			po	Taupo	9,740		
[5]Mangamate Tephra		Andesitic tephra		Tongariro			
	Te Rato Lapilli		tt	Tongariro		9,700 ± 200 (below lapilli) 9,780 ± 170 (" ")	NZ1373 NZ1372
Papanetu Tephra			pa	Taupo	9,785		
[4]Karapiti Lapilli			kp	Taupo	9,790		
[5]Okupata Tephra		Unnamed ash Basal lapilli	oa	Tongariro		9,790 ± 160 (above ash)	NZ1374
		Andesitic tephra		Tongariro			
[6]? Rotorua Ash			rr	Okataina	12,500	12,350 ± 220 (above ash) 13,150 ± 300 (below ash)	NZ1187 NZ1186
		Andesitic tephra		Tongariro			
[7]? Puketarata Ash			pk	Maroa	13,500		
		Andesitic tephra		Tongariro			
[5]Rotoaira Lapilli			rt	Tongariro		13,800 ± 300 (below lapilli)	NZ1559
		Andesitic tephra		Tongariro			
[6]Rerewhakaaitu Ash			rk	Okataina		14,700 ± 200 (below ash)	NZ716
		Andesitic tephra		Tongariro			
[8]Oruanui Formation	Oruanui Breccia		ou	? Maroa			
	Oruanui Ash					20,670 ± 300 (within ash) 19,850 ± 310 (below ash)	NZ12 NZ1056

1 Named by Grange & Hurst (1929)
2 " " Baumgart (1954)
3 " " Gregg (1960)
4 " " Vucetich & Pullar (1973)
5 Named by Topping (1973)
6 " " Vucetich & Pullar (1964)
7 " " Lloyd (1972)
8 " " Vucetich & Pullar (1969)

Fig. 32 (From Topping and Kohn, 1973)

Stop 9

Te Ponanga Saddle: a cutting on the eastern side of Te Ponanga Saddle Road near the summit, and to the north of Lake Rotopounamu, N112/224983. Type section for Papanetu Tephra.

Ngauruhoe Tephra	0·15 m	dark brown grey fine ash
Taupo Pumice	0·95 m	pale yellow rhyolitic ash, lapilli and blocks
Mangatawai Tephra	0·34 m	dark brown grey ash
Waimihia Lapilli	0·13 m	pale yellow rhyolitic ash
Papakai Tephra	0·43 m	yellow brown fine ash with interspersed grey and strong brown lapilli; paleosol
Poutu Lapilli	0·65 m	grey and strong brown coarse ash and lapilli
		(erosion)
Poronui Tephra	60 mm	grey ash with a trace of light yellowish brown fine rhyolitic ash
Te Rato Lapilli	0·3 m	dark greenish grey lapilli and coarse ash and pale yellow lapilli
	20 mm	yellowish brown ash and coarse grey lithic ash
Papanetu Tephra	0–20 mm	pale yellow ash with coarse clear obsidian and grey lithic ash
	0·85 m	andesitic tephra
		(?Rotorua Ash in other Te Ponanga Road sections is about halfway down these units)
?Puketarata Ash	30 mm	isolated pocket of yellow rhyolitic ash
	0·16 m	yellowish brown ash
Unnamed rhyolitic ash	20 mm	isolated pocket of yellow rhyolitic ash
	0·12 m	yellowish brown ash
Rotoaira Lapilli	85 mm	20 mm yellowish red coarse ash and lapilli; 5 mm dark grey ash; 60 mm coarse strong brown ash and lapilli
	0·30 m	yellowish brown ash
Rerewhakaaitu Ash	60 mm	white fine rhyolitic ash
	0·60 m	slightly gravelly sand, yellowish brown silts with minor cobbles and boulders
Oruanui Ash	0·30 m	shower bedded pale brown ash, coarse ash and chalazoidites
	1·5 + m	alluvium; angular andesitic boulders and cobbles in pale brown to grey brown silty matrix

Fig. 33. Tephra section, Te Ponanga Saddle, Tongariro Subgroup. (From Topping and Kohn, 1973).