GOLEBY

Seismix2003

Seismix2003

Post Conference Field Trip Guide Across an Active Plate Boundary, North Island, New Zealand

11-14 January 2003

Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

10th International Symposium of Deep Seismic Profiling of the Continents and their Margins

BIBLIOGRAPHIC REFERENCE

Stagpoole, V., Nicol, A., Henrys, S. (comp) 2002. Across and Active Plate Boundary, North Island, New Zealand. The 10th International Symposium on Deep Seismic Profiling of the Continents and their Margins, Post-symposium Fieldtrip Guide, New Zealand, 11-14 January 2002. *Institute of Geological and Nuclear Sciences information series* 54, 62p.

Vaughan Stagpoole, Institute of Geological and Nuclear Sciences Ltd
Andy Nicol, Institute of Geological and Nuclear Sciences Ltd
Stuart Henrys, Institute of Geological and Nuclear Sciences Ltd

ISSN 1172-0298
ISBN 0-478-09786-7

Seismix 2003 Post Conference Field Trip

Day One				Duration	Time
Depart Taupo		Saturday	11-Jan-03		9:00 leave
Travel	Taupo to Orakeikorako			0:45	9:45 arrive
Stop	**View geothermal area**			2:00	11:45 leave
Travel	Orakeikorako to Ngakuru			0:45	12:30 arrive
Optional stop	Waiotapu view				
Stop	**Lunch**			0:30	13:00
avtivity	**View faulting**			0:30	13:30 leave
Travel	Ngakuru to Whakamaru			0:40	14:10 arrive
Stop	Whakamaru			0:30	14:40 leave
Travel	Whakamaru to Pouakani			0:20	15:00 arrive
Activity	**Bush walk and view giant totara**			0:45	15:45 leave
Travel	Pouakani to Waitomo Caves			1:15	17:00 arrive
	Prepare for caves			0:30	17:30
Stop	**View Waitomo Caves**			0:45	18:15 leave
Travel	Waitomo Caves to Motel			0:15	18:30 arrive
Activity	**Dinner**				19:00
Day Two		Sunday	12-Jan-03		
Activity	**Breakfast - Waitomo**				8:00
	Depart Waitomo				9:00 leave
Travel	Waitomo to Awakino Gorge			1:15	10:15 arrive
Stop	**View tited strata and gorge**			0:40	10:55 leave
Optional stop	Minotis fossil hunting				
Travel	Awakino Gorge to Mokau			0:20	11:15 arrive
Stop	**Mokau**			0:20	11:35 leave
Travel	Mokau to Tongaporutu			0:20	11:55 arrive
Stop	**Lunch**			0:30	12:25
avtivity	**View and discuss coastal section**			1:00	13:25 leave
Travel	Tongaporutu to Hawera			1:45	15:10 arrive
Optional stop	New Plymouth				
Stop	**Dariylands**			0:45	15:55 leave
Travel	Hawera to Kai-iwi			1:00	16:55 arrive
Optional stop	**View and discuss coastal outcrops**			0:50	17:45 leave
Travel	Kai-iwi to Wanganui			0:15	18:00 arrive
Activity	**Dinner**				19:00

Day Three

Activity	**Breakfast - Wanganui**	Monday	13-Jan-03		8:00
	Depart Wanganui				9:00 leave
Travel	Wanganui to Mt Stewart			0:40	9:40 arrive
Stop	**View anticline and ranges**			0:40	10:20 leave
Travel	Mt Stewart to Saddle Rd			0:30	10:50 arrive
Stop	**View forearc and discuss deformation**			0:40	11:30 leave
Travel	Saddle Rd to Daniverke			0:30	12:00 arrive
Stop	**Daniverke**			0:20	12:20 leave
Travel	Daniverke to Norsewood			0:15	12:35 arrive
Stop	**Lunch**			0:45	13:20 leave
Travel	Norsewood to Lake Poukawa			1:00	14:20 arrive
Stop	**View lake and discuss**			0:45	15:05 leave
Optional stop	**View old river meander**			0:20	15:25 leave
Travel	Lake Poukawa to Te Mata			0:15	15:40 arrive
Activity	**Visit Winery**			1:00	16:40 leave
Optional stop	**Te Mata Peak and view**			0:45	17:25 leave
Travel	Te Mata to Napier hotel			0:20	17:45 arrive
Travel	Napier to Brookfields			0:20	18:40 leave
Activity	**Dinner**				19:00 arrive

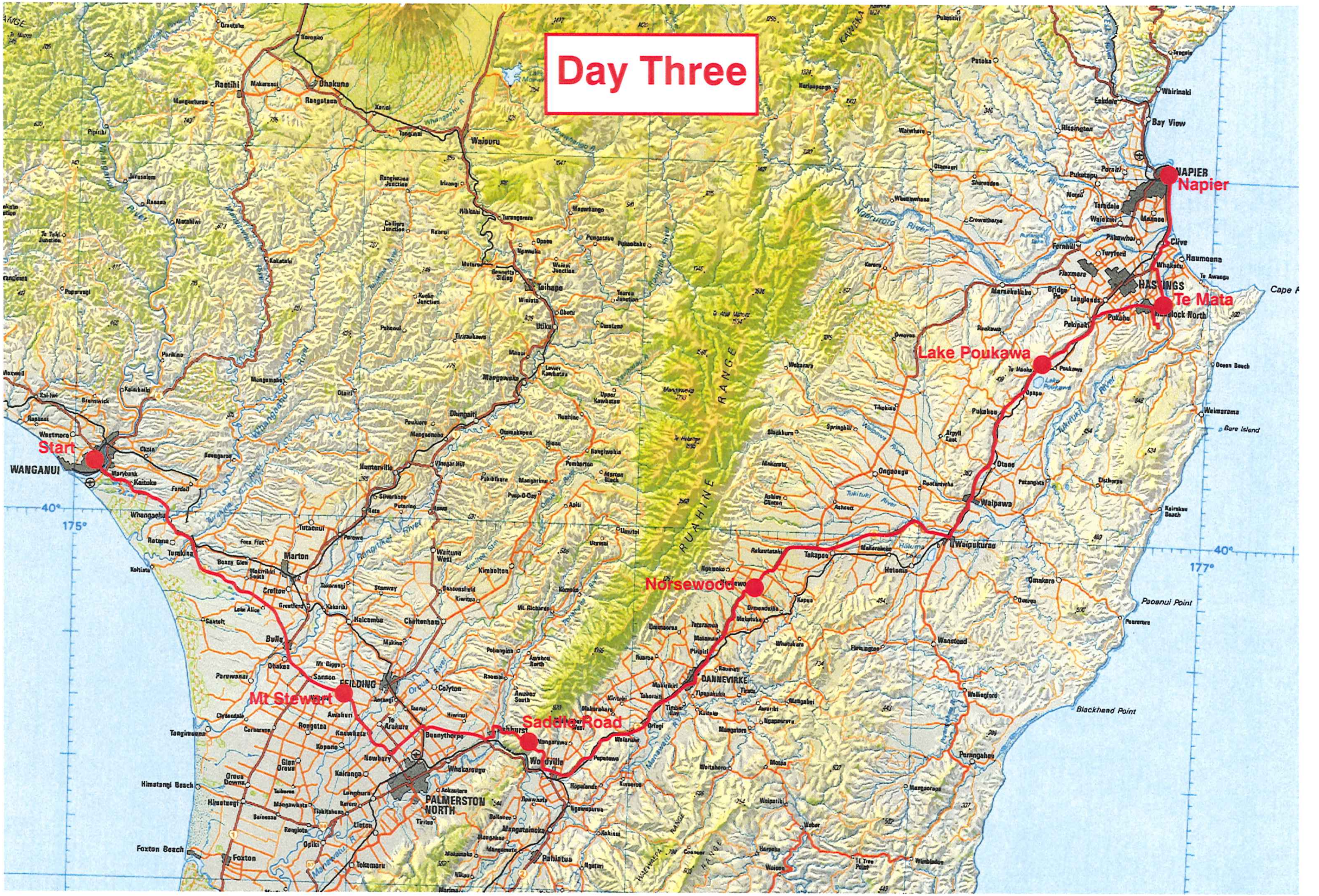
Day Four

Activity	**Breakfast - Napier**	Tuesday	14-Jan-03		8:00
	Depart Napier				9:00 leave
Travel	Napier to Te Pahoe			0:45	9:45 arrive
Stop	**View anticlie and ranges**			0:40	10:25 leave
Travel	Te Pahoe to Waipunga Falls			0:45	11:10 arrive
Stop	**View falls and field trip summary**			0:40	11:50 leave
Travel	Waipunga Falls to Taupo			0:45	12:35 arrive
	Finish				13:00

Day One

Topographic data sourced from Land Information New Zealand (Crown Copyright Reserved).

Topographic data sourced from Land Information New Zealand (Crown Copyright Reserved).



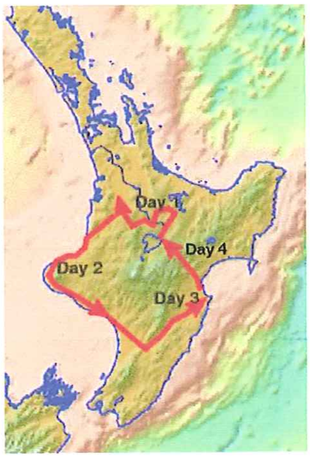
Topographic data sourced from Land Information New Zealand (Crown Copyright Reserved).

Topographic data sourced from Land Information New Zealand (Crown Copyright Reserved).

Across an Active Plate Boundary, North Island New Zealand

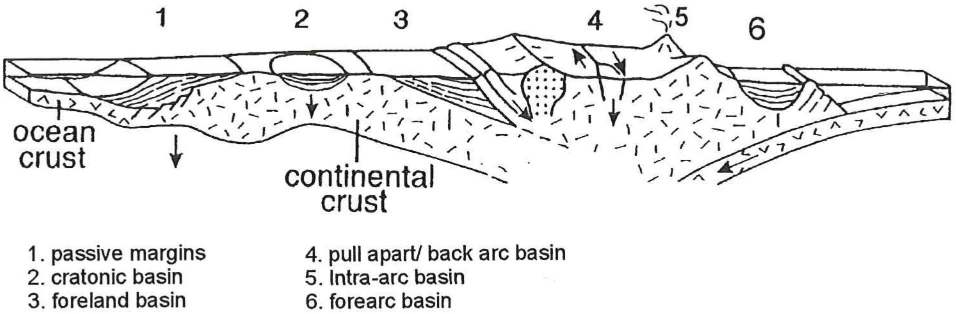
Compiled by Vaughan Stagpoole, Andy Nicol and Stuart Henrys

Introduction



The fieldtrip leaves Taupo at 9.00 Saturday, 11 January 2003, returning at about 13.00 on Tuesday, 14 January 2003. During the trip we will complete a circuit across the central North Island traversing the active plate boundary where the Pacific Plate is being subducted beneath the Australian Plate.

The North Island of New Zealand is an ideal place to view plate boundary tectonism. The geological history of the region over the last 80 million years includes both passive margin and convergent margin evolutionary phases. The younger convergent margin phase is characterised by foreland basin, back-arc basin, intra-arc volcanism and forearc development. Many of the features associated with this tectonic development are seen on this field trip.



Tectonic settings for basin formation. East Coast, was (1) and is currently (6), Taupo Volcanic Zone (5), Taranaki Basin was (1) and (3) and is currently (4).

On the first day of the field trip we view the Taupo Volcanic Zone (TVZ) and travel west toward the back-arc Taranaki Basin. Features seen on this day include geothermal activity and volcanism, active faulting and limestone caves. Day Two focuses on the Taranaki Basin, where we will view fault controlled sediment deposition and beach exposures that exhibit eustatically controlled sedimentary cycles. On Day Three we travel from west to east towards the subduction thrust which intersects the seabed in the Hikurangi Trough. In the East Coast forearc region we will view young (< 5 Myrs) deformation, actively growing structures and faulting. Day Four sees us completing the circuit with travel from the active forearc westward, back to the TVZ.

Other activities planned for the field trip include visits to an East Coast winery, a native bush walk and viewing the effects of recent earthquakes.

Tectonic development of New Zealand

The New Zealand sub-continent comprises large areas of submerged continental crust and a much smaller area of exposed islands. The North Island lies at the centre of the sub-continent and is floored entirely by continental crust. Plate tectonic reconstructions indicate that the New Zealand continent was joined to south-east Australia and east Antarctica prior to the Cretaceous break-up of Gondwanaland (Stock and Molnar, 1982). Spreading in the Tasman sea commenced in the Late Cretaceous just prior to anomaly 33 time (80 Ma) and continued until anomaly 24 time (55 Ma). A period of quiescence and subsidence followed Tasman Sea spreading and by the end of the Eocene most of the New Zealand continent was beneath the sea.

The modern segment of the Australia-Pacific Plate boundary began to propagate through New Zealand in the Late Eocene. This was manifested by subduction of the Pacific Plate beneath the Australia Plate in northern New Zealand and strike-slip in the south. Reconstructions of the plate boundary for the last 40 Myr indicate a clear distinction between the Hikurangi subduction zone, where the Hikurangi Plateau (a large igneous province) is being subducted under the North Island, and the Kermadec subduction zone to the north. The Kermadec trench appears to have translated eastward while the Hikurangi subduction zone has rotated clockwise nearly 90°. Presumably they are separated by a tear in the Pacific Plate. More than 1000 km of lithosphere has been subducted in the northern parts of the Hikurangi margin but little or none has been subducted in the south where the subduction complex terminates (Walcott, 1987). Plate reconstructions of this complex margin are equivocal. A recent summary is found in King (2000) and an animation of Kings (2000) reconstructions can be found on the GNS website (www.gns.cri.nz)

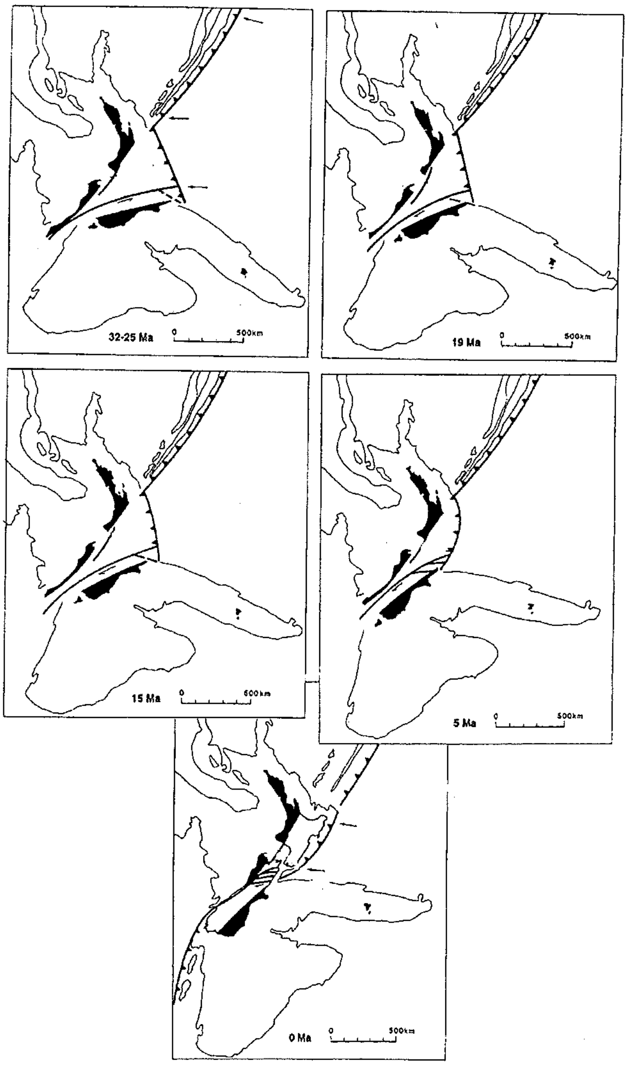
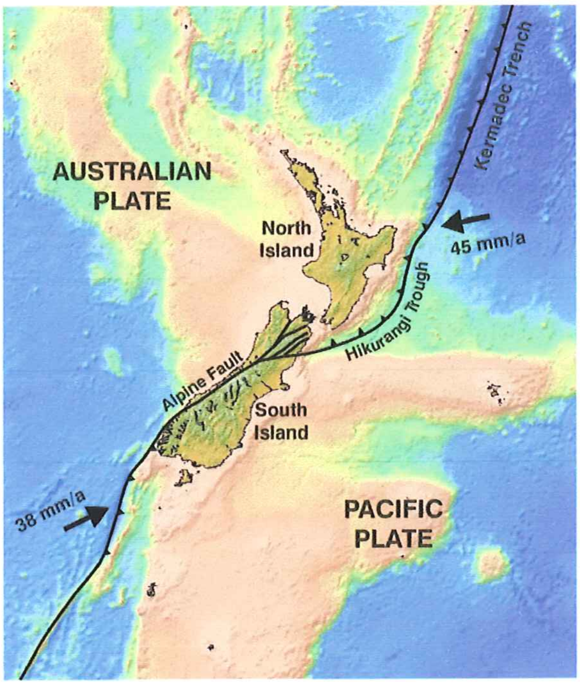


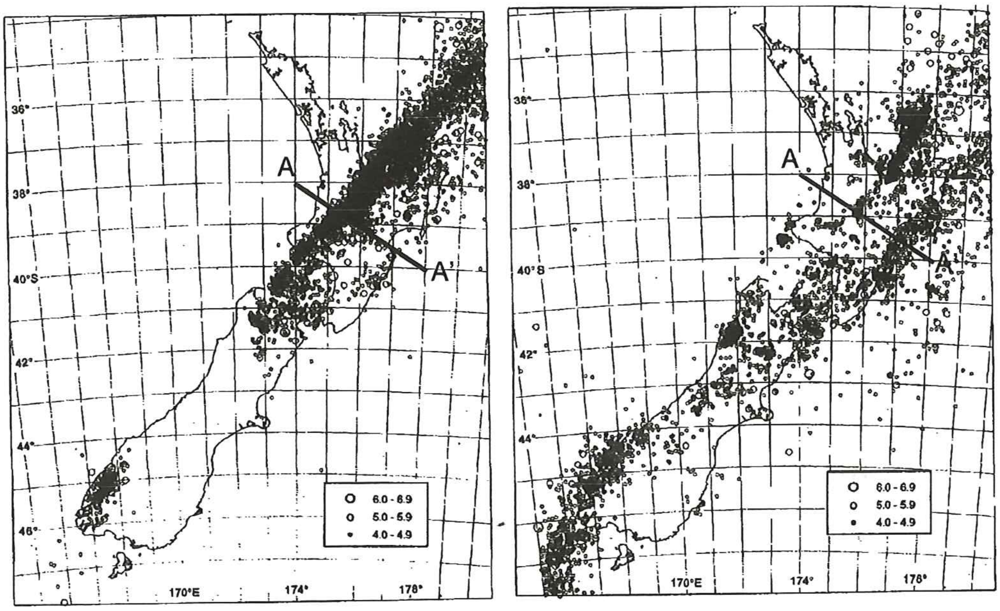
Plate reconstruction for the Neogene (after Walcott, 1987; Holt & Stern 1994) derived from finite rotation parameters of Stock and Molnar (1982).

Present day structure, seismicity and tectonics of New Zealand

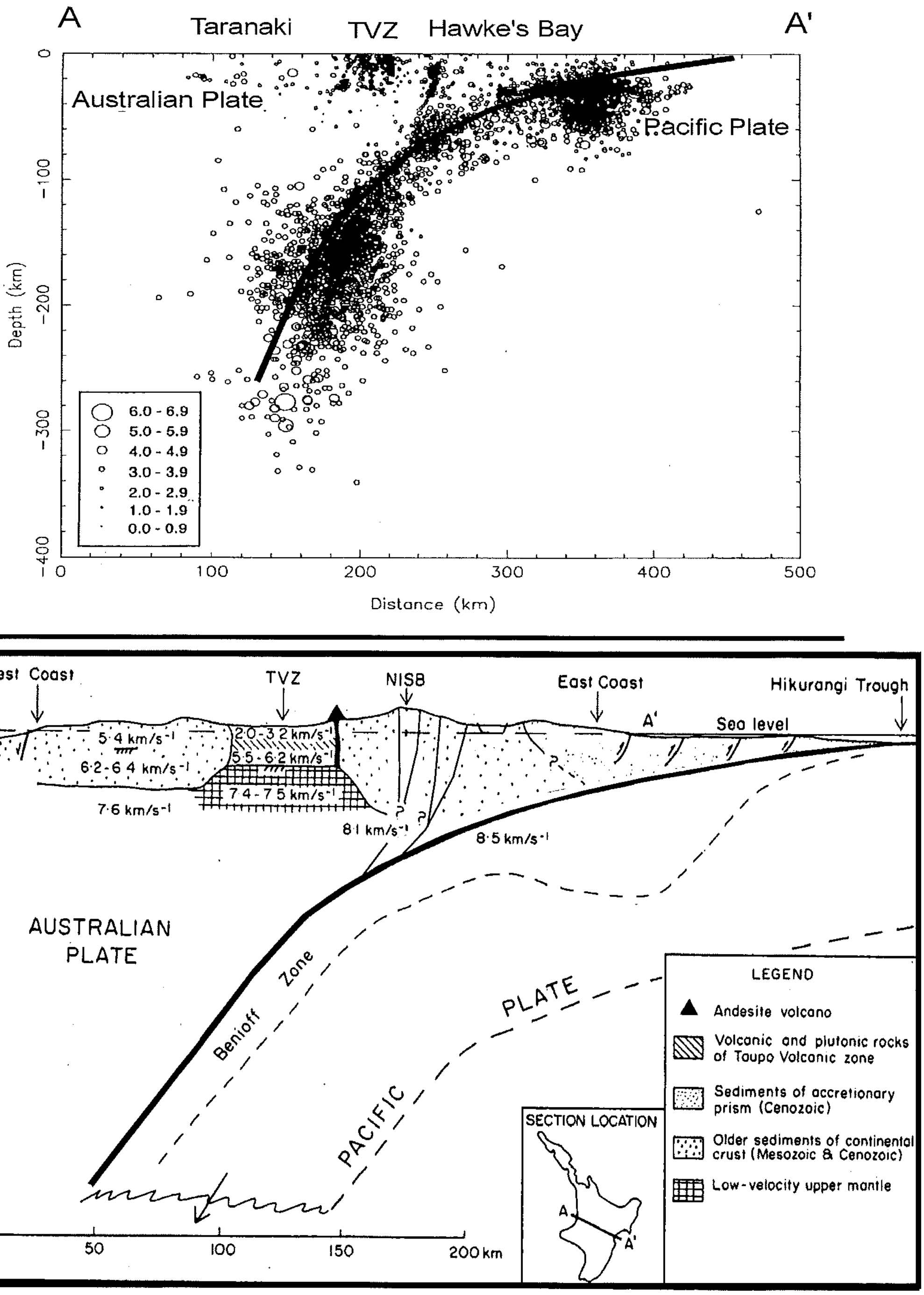


New Zealand is part of an otherwise largely submerged continental block that straddles the Australian and Pacific plate boundary. Although most subdivisions of geological time since the Cambrian (c. 600 Myr) are represented in the rocks of New Zealand, the present land area owes its existence largely to displacements and rotations of continental crust and subduction of oceanic lithosphere that have accompanied oblique convergence across the plate boundary during the last 3-5 Myrs (eg Walcott, 1978, 1987).

Relative motion between the Pacific and Australian plates is currently 30-50 mm/yr through New Zealand. Beneath the North Island and the southwestern South Island, seismicity delineates active subduction of the Pacific plate. The Benioff zone initially dips 3-5° westward from the Hikurangi Trough (Ansell & Bannister, 1996) and eastwards beneath the SW South Island. Shallow seismicity occurs in a broad swath parallel to the plate boundary through New Zealand, but the highest rate of activity, and the majority of large historic earthquakes, has been located where the dip of the subducted plate is shallow. High rates of very shallow seismicity accompany the arc volcanism and active spreading that is occurring at a rate of between 5 and 20 mm/yr across the volcanic arc and back-arc basin of the Taupo Volcanic Zone in central North Island.

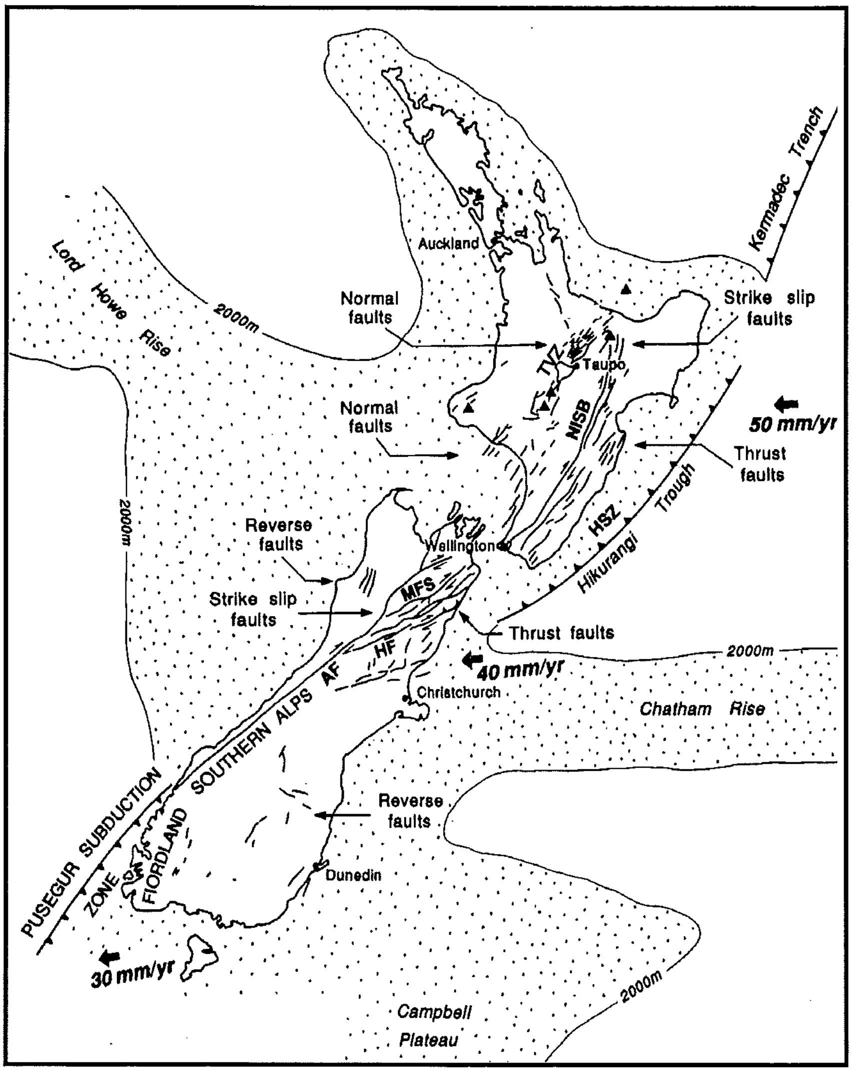


Earthquakes deeper than 40 km (left) and earthquakes shallower than 40 km (right), recorded by the National Seismograph network between 1964 and 1995 (A-A' marks the profile in subsequent figures).



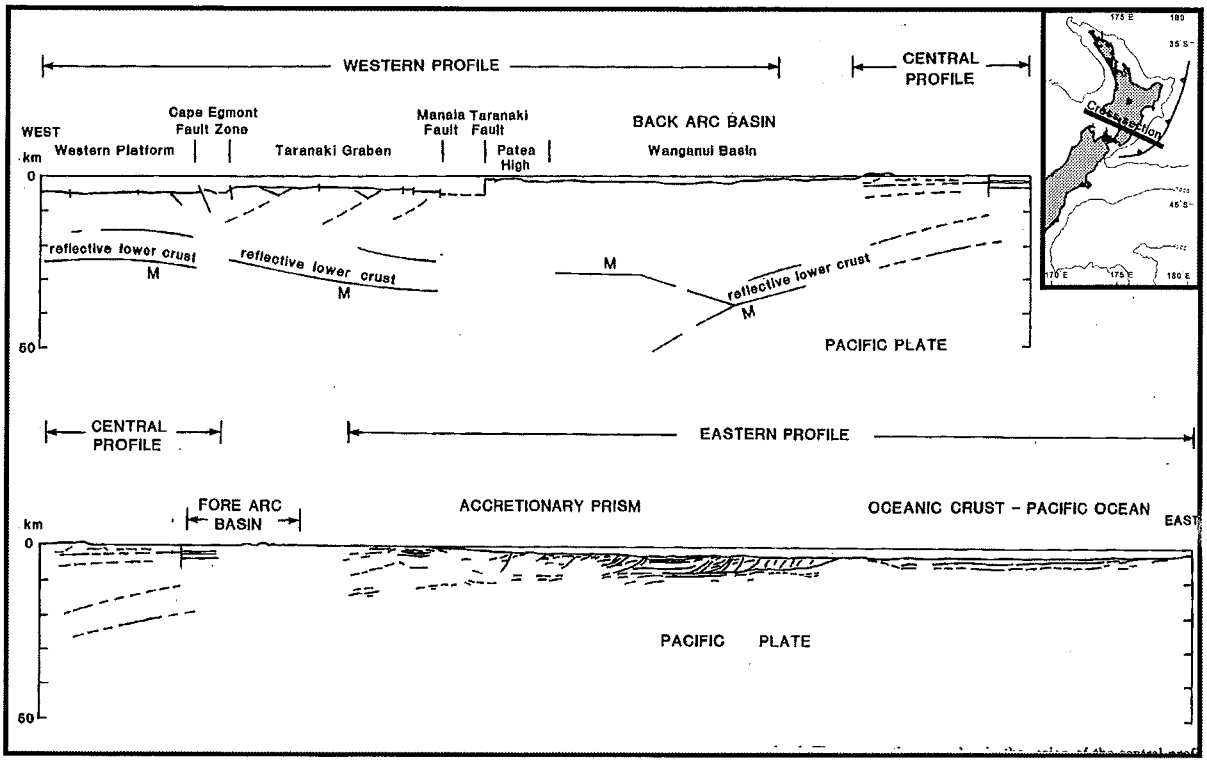
Cross-section of the central North Island showing earthquake locations (upper adapted from Anderson & Webb, 1994) and crustal and mantle structure (adapted from Cole, 1990)

The oblique subduction of the Pacific plate westward from the Hikurangi Trough has been accompanied by thrusting, folding and uplift of Cenozoic sedimentary rocks on the overriding Australian plate (Pettinga, 1982; Barnes & de Lepinay, 1997). The shortening is reflected in geodetically observed strains, which are relatively high in the central North Island and close to the Hikurangi Trough. Plate motion is also accommodated by large dip-slip faults that comprise the North Island Shear Belt in the Central North Island (Walcott, 1978; Cashman et al., 1992; Beanland, 1995).



Active faults and provincial styles of surface deformation in New Zealand (after Officers of New Zealand Geological Survey 1983)> AF = Alpine Fault; HF = Hope Fault; MFS= Marlbourgh Fault System; NISB= North Island Shear Belt; HSZ= Hikurangi subduction zone; TVZ= Taupo Volcanic Zone. Triangles are andesite volcanoes.

Beneath northern South Island the subducted Pacific plate is defined seismically by a northwest-dipping zone of earthquakes that shallows to a depth of about 50 km in the southwest (Robinson, 1986), where the subduction zone terminates against the northern slope of the Chatham Rise (Smith et al., 1989). Geodetic shear-strain rates derived from comparisons of triangulation surveys that span the last 100 years are comparable to the relative plate motion rates (Walcott,1979; Bibby, 1981; Lamb & Bibby, 1989; deMets et al., 1994). Contemporary horizontal velocity and strain-rate fields derived from GPS observations in the New Zealand region are summarised in Beaven & Haines (2001).



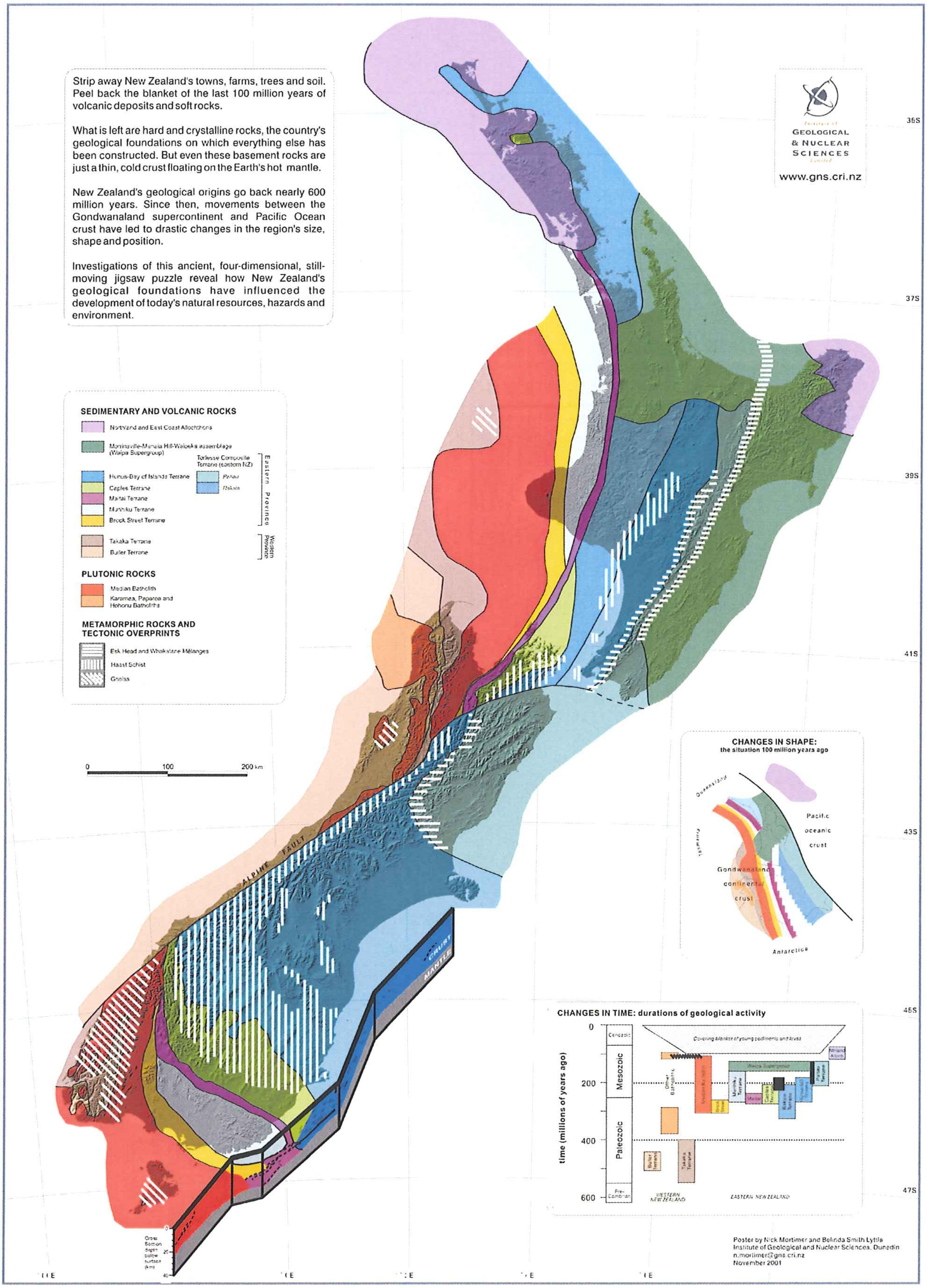
Composite section across the Australia-Pacific plate boundary through southern North Island. M is interpreted Moho (from Davey & Stern, 1990).

Seismic profiles recorded across southern North Island define the structural details of the convergent plate margin. The eastern profile (above) delineates the thrust wedges and back-tilt basins of the accretionary prism which overlies the detachment zone marking the top of the subducted Pacific plate. The western profile (above) defines a broad crustal downwarp in the "back-arc" region of the plate boundary overlying the 20 – 50 km deep subduction zone. The crustal section further to the west comprises a generally transparent middle crustal layer and a reflective lower crust. Detailed seismological data demonstrate the close association of the top of a zone of high seismicity, inferred to mark the subducted Pacific plate, with the base of the reflective sequence identified as the base of the overriding Australian plate (Davey & Stern, 1990).

Basement Geology

The hard crystalline basement rocks of New Zealand are up to 600 million years old. They are an amalgamation of Paleozoic (590 Ma – 250 Ma) metamorphic and plutonic rocks of western New Zealand and younger (~300 Ma to 100 Ma), mostly metamorphic terranes of eastern New Zealand. Amalgamation of the terranes was completed in the Early Cretaceous before the break-up of Gondwanaland and the separation of New Zealand continental rocks from Australia.

NEW ZEALAND'S GEOLOGICAL FOUNDATIONS



Strip away New Zealand's towns, farms, trees and soil. Peel back the blanket of the last 100 million years of volcanic deposits and soft rocks.

What is left are hard and crystalline rocks, the country's geological foundations on which everything else has been constructed. But even these basement rocks are just a thin, cold crust floating on the Earth's hot mantle.

New Zealand's geological origins go back nearly 600 million years. Since then, movements between the Gondwanaland supercontinent and Pacific Ocean crust have led to drastic changes in the region's size, shape and position.

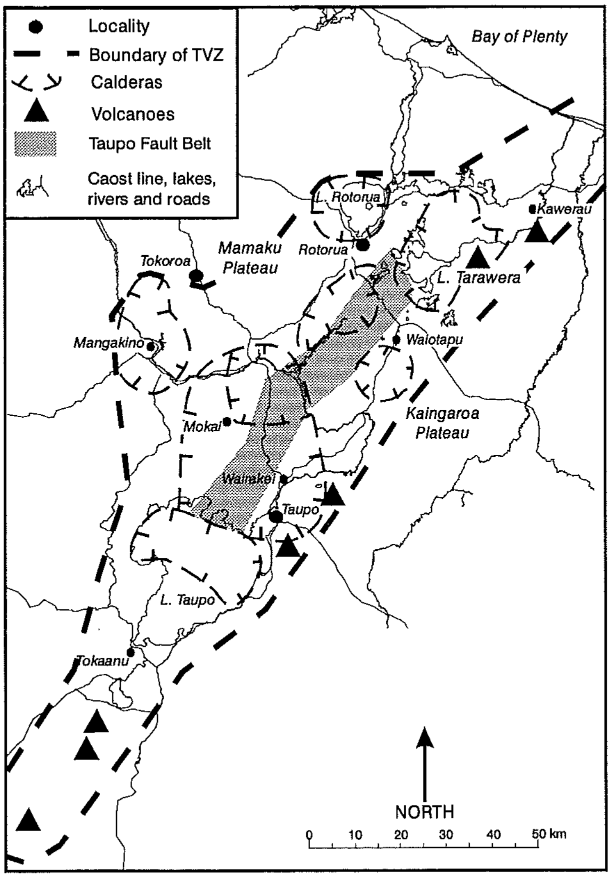
Investigations of this ancient, four-dimensional, still-moving jigsaw puzzle reveal how New Zealand's geological foundations have influenced the development of today's natural resources, hazards and environment.

Poster by Nick Mortimer and Belinda Smith Lyttle
Institute of Geological and Nuclear Sciences, Dunedin
n.mortimer@gns.cri.nz
November 2001

Map of New Zealand basement geology (from Mortimer, 2002)

DAY ONE - THE TAUPO VOLCANIC ZONE TO THE NORTHERN WANGANUI BASIN

The Taupo Volcanic Zone – Background information

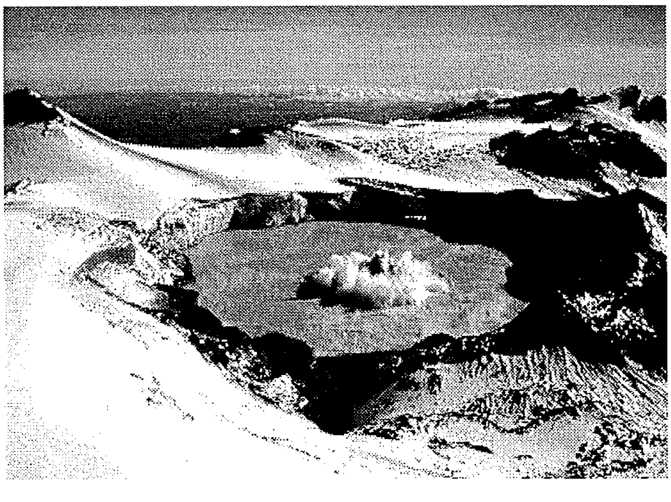


The Taupo Volcanic Zone (TVZ) is defined by an envelope containing all volcanism that has been active over the last 2.0 Myrs (Wilson et al., 1995). At the northern and southern ends of the TVZ, volcanism is dominated by andesitic volcanoes, Ruapehu in the south and White Island in the Bay of Plenty to the north. The central portion of the TVZ is characterised by numerous rhyolitic domes, ignimbrite sheets and their associated collapse calderas (Wilson et al., 1984; 1996). Calderas occupy approximately 55% of the central portion of the TVZ, which is rated by Wilson et al. (1995) as the largest and most frequently active rhyolitic magmatic system known.

The largest eruptions are infrequent ignimbite eruptions from rhyolite volcanic calderas, such as the Oruanui (26.5 ka) and Taupo (181 AD) eruptions which contributed to the formation of Lake Taupo. These catastrophic events lay down thick sheets of welded ignimbite or unwelded ash over tens of thousands of square kilometres. Andesite volcanic eruptions from stratovolcanoes such as Mt Ruapehu are more frequent, but generally less destructive.

Mt Ruapehu

From Taupo, Mt Ruapehu is seen to the south across Lake Taupo. It is the tallest mountain in the North Island, and the active vent is currently an acidic crater lake near its summit. The volcano has a volume of 110 km^3 and the surrounding ring plain has a similar volume. The volcano began to form more than 120,000 years ago. Water from Ruapehu feeds four major rivers and six glaciers flow down the mountain to elevations as low as 2,000 m. For the last 10,000 years there have been infrequent, low volume (usually < 1 km^3) and low magnitude eruptions The last eruption of Ruapehu occurred in 1995-1997.


A small eruption in Crater Lake, Mt Ruapehu

The Oruanui Eruption

The 26,500 year-old Oruanui eruption produced huge volumes of ash and other volcanic material that buried parts of the central North Island. Close to the vent, beneath the present day Lake Taupo, the ash reached depths of about 100 m. The size of the eruption is difficult to grasp, but roughly 1200 km^3 of pumice and ash were ejected in this one event. The ash blanketed a huge area of ocean floor to the east of New Zealand with a layer that varied in thickness from 20 cm to 1 cm. Even the Chatham Islands, 800 km to the east of New Zealand, received an 11 cm coating. The rapid eruption of so much material caused several hundred km^2 of the area around the vent to collapse to form the Lake Taupo basin, now partly filled by the lake (Wilson, 2001).

The 181 AD Taupo Eruption

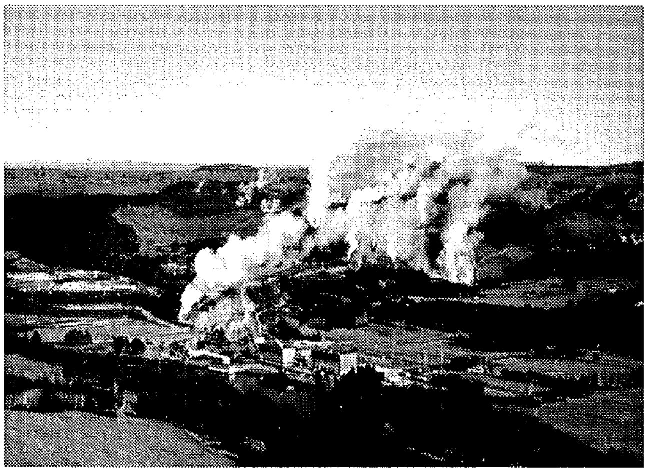
This eruption took place from a vent or vents near the Horomatangi Reefs, now submerged on the eastern side of Lake Taupo. The eruption lasted between several days and several weeks and produced a sequence of pumice deposits that blanketed the landscape east of Taupo. In total about 120 km^3 of pumice and ash was erupted. At the climax of this eruption, about 30 km^3 of pumice, ash and rock fragments was erupted in only a few minutes and travelled horizontally as a fluid flow, moving at speeds estimated at between 600-900 km/h. It crossed every obstacle in its path except the top of Mt Ruapehu.

The 181AD Taupo eruption is unusual in several ways.

- it produced an estimated eruption column 50km high - twice as high as the 1980 Mt St Helens eruption column
- it was the most violent eruption in the world in the past 5000 years
- the effects of the eruption were seen in the sky as far away as Europe and China
- the eruption devastated an area now populated by over 200,000 people

Geothermal Activity in the TVZ – Background information

An extremely high natural heat flow through liquid-dominated geothermal fields accompanies the volcanic activity in the TVZ. The total natural geothermal heat output of the TVZ, 4200 ± 500 MW (Bibby et al., 1995), discharges through these geothermal fields and is at least twice the long-term heat output released through volcanic activity (Hochstein et al., 1993). Unlike the andesitic arc environment, where the distribution of geothermal fields is aligned along the arc with spacings of the order of 100 km (Hochstein, 1991), the



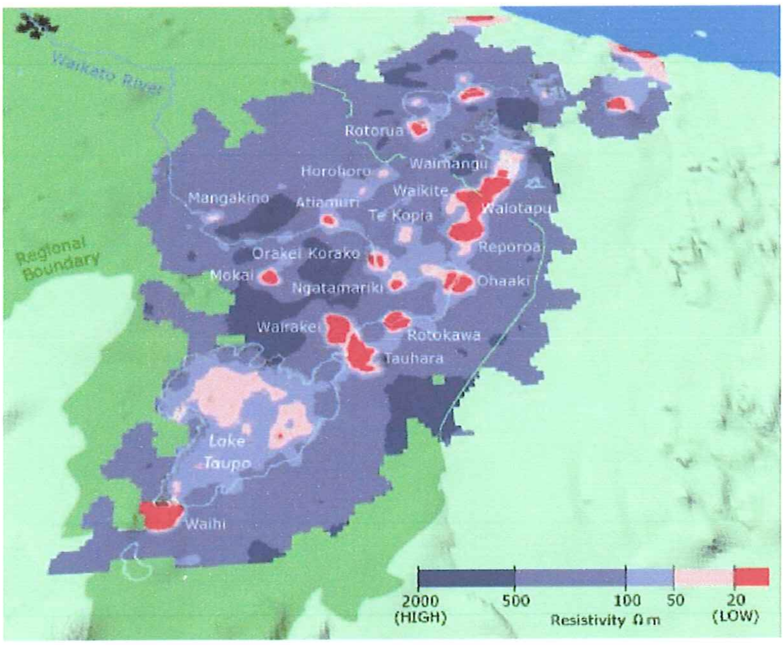
Aerial view of Wairakei geothermal power station

TVZ is characterised by a two-dimensional distribution of geothermal fields with average spacing of about 15 km. There is a clear association between the location of the high-temperature geothermal systems and the region of Pleistocene volcanism, although the link between individual geothermal systems and the calderas is no more than expected on a random basis (Bibby et al., 1995). About 75% of the heat output of the geothermal systems is concentrated along the eastern part of the TVZ. However, there are indications that the heat output from the western TVZ may have been greater in the past (Bibby et al., 1995). Most seismicity and surface faulting occurs in the Taupo Fault Belt, a region of low power output.

There are more than 20 distinct high temperature (> 160°C) geothermal fields. These fields are characterised by numerous hot springs, fumaroles, geysers, and boiling mud pools, although not all features occur in all fields. Seven of the geothermal fields have been developed for electric power production and industrial heating. The most well known is Wairakei where electricity has been continually produced since 1959.

Mapping Geothermal Fields

In New Zealand the most successful geophysical technique for mapping and investigating geothermal fields has been resistivity surveying (Stagpoole & Bibby, 1998; Bibby et al., 1998). The effectiveness of the resistivity technique used in the TVZ relies on a number of factors, all of which combine to lower the electrical resistivity of volcanic rocks. Geothermal fluids contain high concentrations of dissolved salts (typically 1000 ppm chloride), which provide a highly conducting electrolyte within the rock matrix. The electrical properties of geothermal fluids are also strongly temperature-dependent. Hot (>200°C) fluids may have only 10% of their resistivity at ambient temperatures. The rock matrix also makes an important contribution; the prolonged passage of geothermal waters causes the volcanic rock matrix to undergo hydrothermal alteration, which produces low-resistivity clay- and zeolite-rich products. Typical resistivities of altered volcanic rocks are in the range of 10 - 50 Ωm at temperatures of 20 - 100°C. These factors act together to reduce the electrical resistivity within geothermal fields, so that there may be a difference of up to three orders of magnitude between the resistivity of the young, unaltered volcanics that occupy the TVZ and the hydrothermal systems.



Low resistivity zones associated with geothermal fields (fWRC - GNS data)

Since the initial success of electrical techniques for delineating the Wairakei geothermal field

(Banwell and Macdonald, 1965), resistivity mapping has been routinely carried out for reconnaissance surveying and to provide detailed information on the boundaries of hot water geothermal fields for drilling purposes. Although most surveys concentrated on geothermal fields, a significant part of the resistivity mapping programme extended between fields so as to give a near-uniform coverage of the whole of the TVZ and its boundaries (Stagpoole & Bibby, 1998).

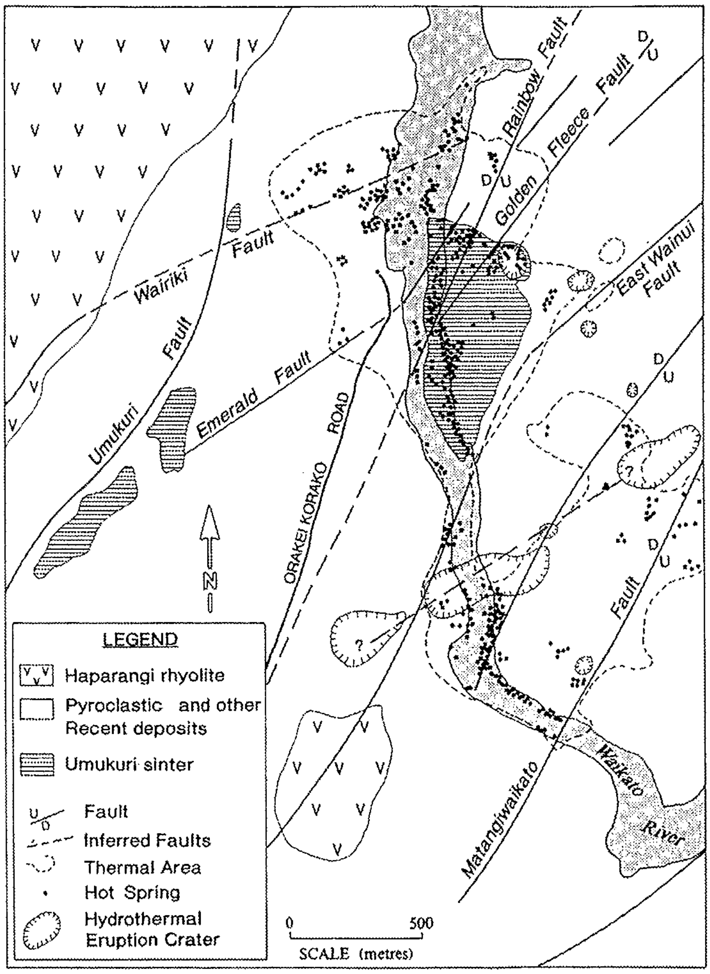
ORAKEIKORAKO GEOTHERMAL AREA

Nestled among rhyolite domes of the Maroa caldera and divided by Lake Ohakuri, Orakeikorako is one of New Zealand's most beautiful geothermal areas. Access to the main part of the thermal area (The Hidden Valley) is by a short boat ride. And the tour takes about 1 hour.

Activity is characterised by extensive sinter deposits in a series of terraces which step down to the lake. The hydrology of Orakeikorako was changed by downstream hydroelectric development. Before 1961, approximately 1100 springs issued along the banks of the Waikato River, but after the river was dammed, Lake Ohakuri flooded about 70% of these, including many spectacular geysers. Although many of the features were flooded, Orakeikorako still remains one of the most scenic and enchanting geothermal areas in the country.

In the mid-1960's, four wells were drilled outside the area of surface activity to assess the steam potential for generating electricity. A maximum temperature of 265°C was encountered at about 1400 m depth, however, the wells were poor producers due to the low rock permeability.

The low resistivity anomaly associated with the field is about 10 km^2, but surficial thermal activity at Orakeikorako encompasses an area less than 2 km^2 where northeast striking splays of the Paeroa Fault intersect the Waikato River. The first descriptions of the area were given by Hochstetter (1864) and Lloyd (1972) provides a comprehensive overview of



Location map (Lloyd 1972)

thermal activity and geology at Orakeikorako. The stratigraphy comprises a sequence of flat lying felsic ignimbrites, air fall tuffs and reworked equivalents, along with minor basalt scoria deposits. The black scoria is visible in outcrops along the west side of the road leading into Orakeikorako. Also along this road are good exposures of the 181 AD Taupo Ignimbrite, which attains a thickness of about 3 m here and contains distinctive charcoal logs. The steep-sided tree-covered slopes northwest of the thermal area form the flank of one of the eastern rhyolite domes of the Maroa Centre. Within the thermal area most surface exposures comprise the Orakeikorako tuff containing pumice, rhyolite lithics and ash.

The prominent Umukuri Sinter on the east side of the river attains a maximum thickness of 18 m, with the oldest deposits dating back more than 16,000 years ago (Lloyd, 1972). Just before the 181 AD Taupo eruption, seismic movement along the Paeroa Fault zone caused spring discharge from the East Wainui Fault to cease, with new springs breaking out along the traces of the Emerald, Rainbow and Golden Fleece Faults. These structures are typical of faults in the Orakeikorako area, striking northeast with normal downward displacement to the west.

The fluid chemistry is described by Sheppard and Lyon (1984). Most thermal springs discharge chloride or mixed chloride-bicarbonate waters of slightly alkaline pH. The chloride contents are low in comparison to other TVZ systems with concentrations of about 400 ppm. Based on fluid compositions, Sheppard and Lyon (1984) proposed that the main centre of upflow lies to the north of the area of thermal activity.

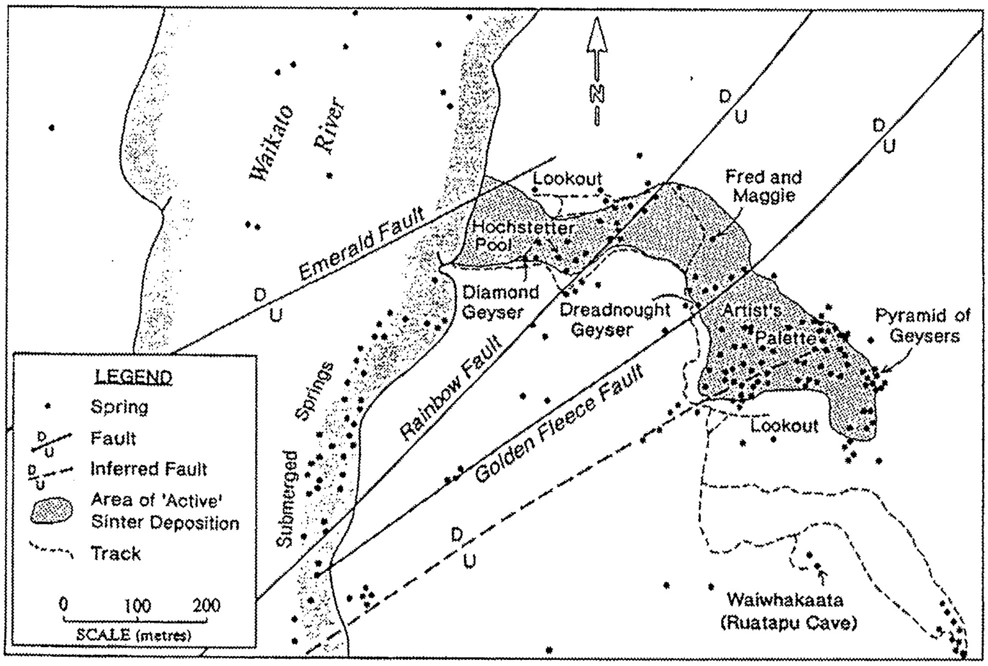
East Bank Waikato River (cross river)

From the boat landing, we walk up the hill which, in part, comprises the sinter covered Emerald Fault scarp. The Diamond Geyser erupts at irregular intervals, which last from a few minutes to several hours, and ejects water in brief, explosive bursts up to 9 m. Note the nodular sinter, termed geyserite, close to the vent; it only forms near vents where the area is wetted by splashing and evaporating water rapidly precipitates silica. Along the path green filamental algae grows in thermal water (<75° C); look for ancient traces of algae filaments in the Golden Fleece Terrace sinter ahead.

From the Waipapa Valley overview the two sinter-encrusted step faults; the lower Rainbow Fault and the upper Golden Fleece Fault are visible. Springs discharge at the base of both fault scarps illustrating structural control on fluid movement. The scarps expose pre-181 AD Umukuri Sinter.

The Golden Fleece Terrace is thickly coated with post-181 AD grey-white sinter, except at the south end where old laminated sinter is exposed. Three vents at the southern base of Golden Fleece Terrace are spectacular intermittent geysers, and most spring vents along the base of the terrace have also exhibited ephemeral geyser activity. Geyser action here is most intense when the water table is high.

The Artist's Palette is an almost level sinter-encrusted area of some 10,000 m^2 that occupies an old eruption crater which formed between 8,000 and 14,000 years ago. Remnants of the crater walls form steep, steaming ridges enclosing it on the northeast and southeast; note that steaming ground occurs above the water table as indicated from spring levels and sinter occurrence. Activity on Artist's Palette fluctuates, and at times the sinter flat is covered to shallow depth by hot chloride water discharged from boiling springs, but more often the flat is dry and spring water levels lie below the surface. Lloyd (1972) mapped 119 hot springs on Artist's Palette in 1960.



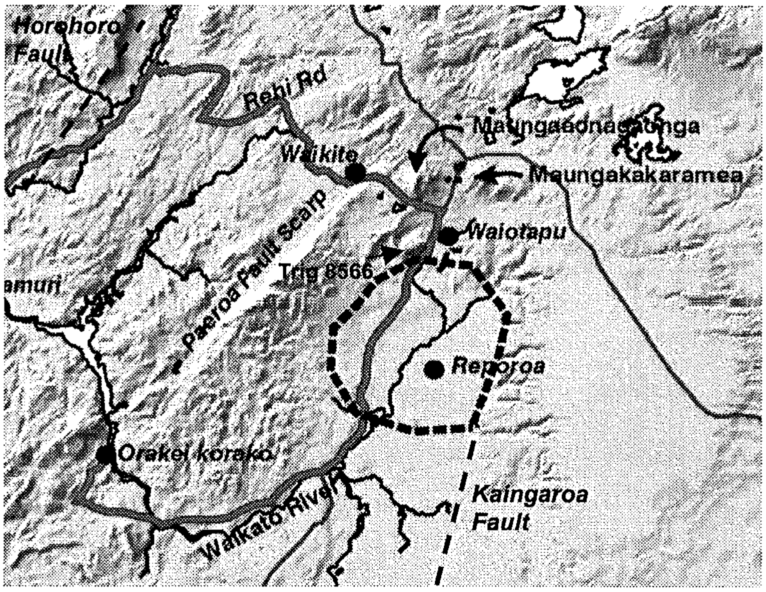
Distribution of thermal springs (Lloyd 1972)

Ruatapu Cave descends steeply into the south side of a remnant of hydrothermally altered rhyolite tuff and is surrounded by hydrothermal eruption craters. Mixed acid sulfate-chloride water (190 ppm Cl, pH=2.5, T = 40°C) fills Waiwhakaata which is the clear pool at the bottom of the cave. The origin of this cave is uncertain (Lloyd, 1972). A sequence of hydrothermal eruptions, sourced mainly from vents on the east side of the Waikato River, occurred between 181 AD and 14000 years ago (Lloyd, 1972). These were of similar magnitude to those at Waiotapu, having ejected material up to 0.5 km away from their vents.

ORAKEIKORAKO TO REHI RD

Reporoa Caldera

From Orakeikorako to the next stop we travel northward inside the northwest edge of the Reporoa caldera. The caldera has been proposed as the source of the Kaingaroa Ignimbrites which are Ar/Ar dated at 1.24±0.04 Ma (Wilson & Houghton, 1994). The Kaingaroa scarp on the east side of the basin is interpreted in this area as a caldera-bounding scarp, as thick, coarse-grained, lithic lag breccias have been found in the Kaingaroa Ignimbrite here (Nairn et al., 1994). Although a continuous feature for 55 km from Reporoa to beyond Taupo, the Kaingaroa scarp is apparently a composite feature of volcanic, tectonic and erosional origin.



The eastern edge of the TVZ can be viewed from the road above the Waiotapu geothermal area. To the north and northeast the two dacitic centres of Maungaongaonga and Maungakakaramea can be seen. The former is K/Ar dated at 183±9 ka (Wilson & Houghton, 1994), and the latter presumed to be of similar age. To the east and southeast, steam plumes from surface discharges at Waiotapu are visible, with the northern part of the Broadlands-Reporoa basin (ie Reporoa caldera) in the middle distance. The Kaingaroa Fault forms the eastern side of Reporoa caldera and marks the local eastern edge of the TVZ (Stagpoole, 1994). To the south the view is largely obscured by the Trig 8566 rhyolite dome whose south face has slumped into the Reporoa caldera.

Waikite Valley

From Waiotapu to Waikite Hot Springs the route climbs to a small plateau, then descends the northeastern part of the Paeroa Fault scarp. The Paeroa Fault is a major normal fault, with a throw exceeding 500 m, which separates two distinct NNE-SSW orientated zones within the TVZ; Broadlands-Reporoa basin (with little surface faulting) to the southeast, and the strongly block-faulted Ngakuru graben to the northwest.

Rocks visible in the Paeroa Fault scarp are welded ignimbrites mapped as the Paeroa (inferred youngest), Te Weta and Te Kopia (inferred oldest) units. All of these units yield similar Ar/Ar ages, thus (from Wilson & Houghton, 1994):

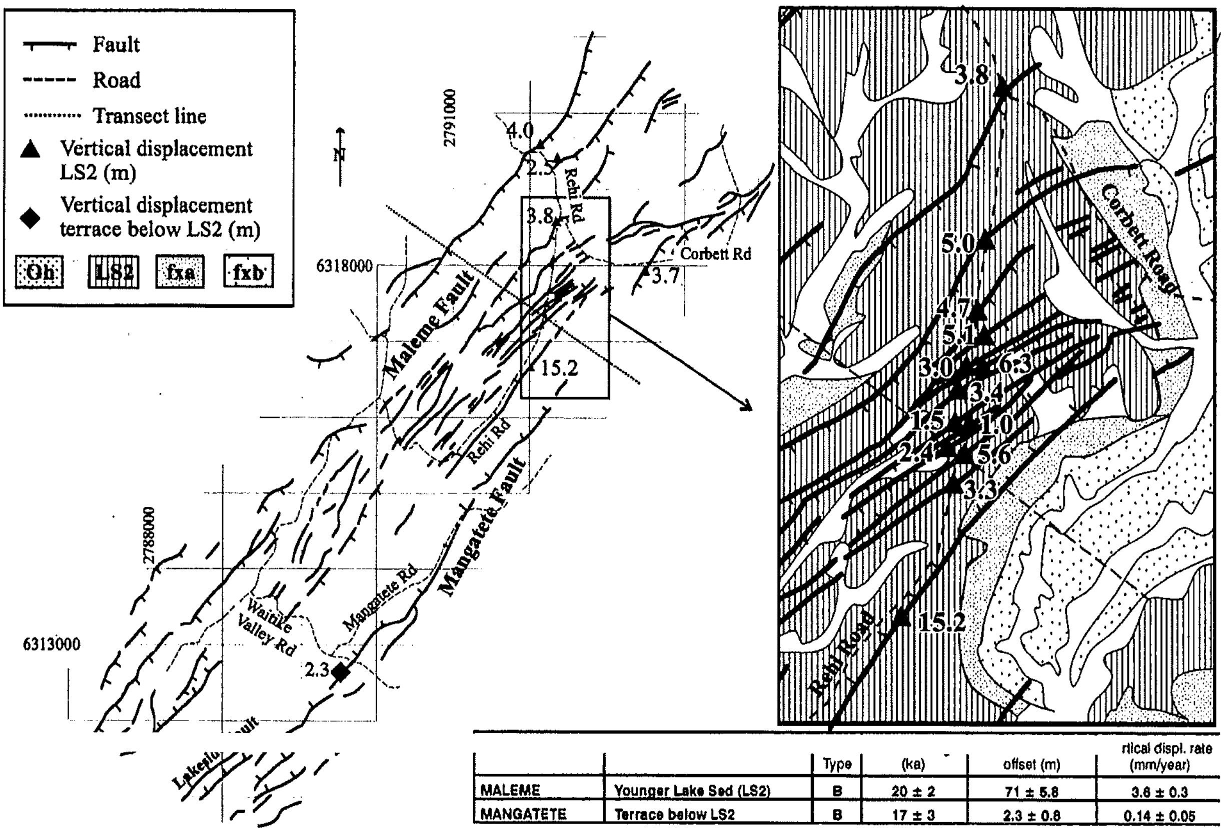
Paeroa Ignimbrite	330±10 ka
Te Weta Ignimbrite	360±10 ka
Te Kopia Ignimbrite	340±10 ka

These ages are close enough to those obtained on the Whakamaru-group ignimbrites (Pringle et al., 1992) in the west to imply some genetic connection. The Paeroa scarp cuts 300 ka ignimbrite, while the counterpart Horohoro scarp 15 km to the west displaces the 220±10 ka Mamaku Ignimbrite by a comparable amount. There appears to have been a major period of faulting and tectonism in this region of the TVZ between 330 and 220 ka, accompanying several major ignimbrite eruptions. Subsequent faulting has been limited to the zone between the Horohoro and Paeroa faults and areas along strike to the NNE and SSW and is scarce in the Broadlands/Reporoa basin.

The thermal features of Waikite cover an area of c 0.5 km^2, with an overall heat flux of about 70 MW. Little is known about the Waikite system, but recent resistivity surveys show that it is connected at depth with the much larger (545 MW) Waiotapu system and also with Waimangu. This trio of thermal areas represent the largest group of geothermal systems which remain unmodified by exploitation and as such have been the subject of intensive investigation.

STOP REHI ROAD: RIFT AXIS

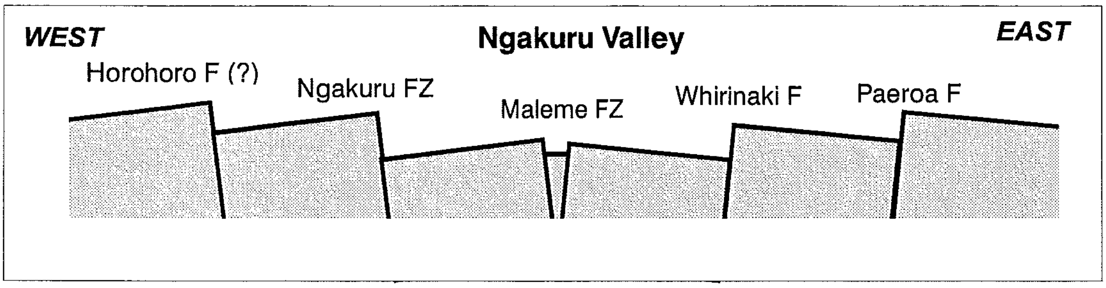
Extension in the TVZ is partly accommodated on a dense system of normal faults that dip both to the northwest and southeast, and have a predominant northeast-southwest trend. In many places, the faults are at a 1-3 km spacing, much closer than the inferred thickness of the brittle crust of 8-10 km (Anderson et al., 1990). Tectonically, the youngest part of the TVZ, termed the Taupo Fault Belt (TFB), is an approximately parallel-sided zone c. 20 km wide bounded by faults that have been active in the last c. 20,000 yrs. Based on a precedent argument, it is expected that future fault rupture will occur within the TFB.



		Type	(ka)	offset (m)	rtical displ. rate (mm/year)
MALEME	Younger Lake Sed (LS2)	B	20 ± 2	71 ± 5.8	3.6 ± 0.3
MANGATETE	Terrace below LS2	B	17 ± 3	2.3 ± 0.8	0.14 ± 0.05

Active traces of the Meleme Fault Zone. Numbers are vertical offset (m) on Lacustrine sediments (LS1 & LS2). Inset shows distribution of fault scarps near graben axis (from Villamor & Berryman, 2001).

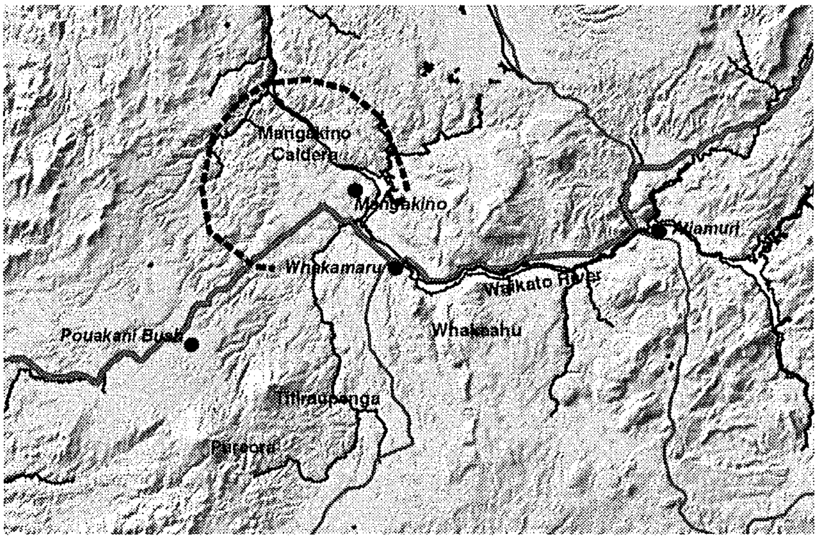
The modern rift axis is well defined at Rehi Rd, where it trends to the northeast. The rift forms a zone up to 2.5 km wide made up of at least nine discrete fault strands in the south and up to 16 discrete strands in the north. The strands all strike northeast but show overlapping and en-echelon patterns. Almost all of the fault strands are downthrown to the southeast in the Maleme Road area, but an increasing graben-like formation of traces is developed near Rehi and Corbett Roads. Scarp heights vary from 1.5 to 4.5 m in the Maleme Road area, and from 1.5 to 15 m in the Rehi and Corbett Road area. Individual strands are commonly 2-5 km long. North of Corbett Road, the fault traces abruptly change strike to c. N70°E to become the Tumunui Fault.



Cartoon cross-section of Maleme Fault Zone

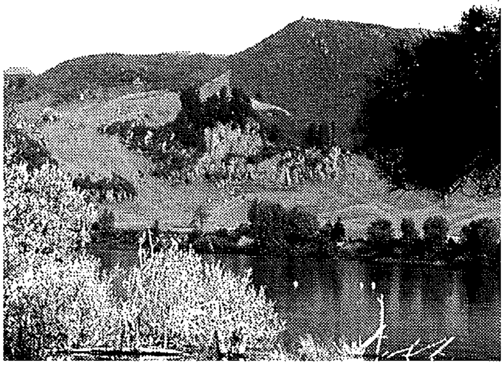
The faults at Rehi Road displace an extensive c. 20 ka surface. Vertical displacements measured by altimeter on single fault traces vary from 1.0 to 15.2 m, and the total vertical offset of the c. 20 ka surface, summing all the individual offsets, is 71 ± 5.8 m. This offset indicates a cumulative vertical displacement rate of 3.55 ± 0.3 mm/yr for the past c. 20 000 yr across the zone.

REHI ROAD TO THE WESTERN MARGIN OF TVZ



The route travels south to Atiamuri, then traverses the Ongaroto Gorge and passes beside the Waikato River to Whakamaru. The Waikato River which has been the major outlet for drainage from the central TVZ for at least the last 250-300 ka, to judge by the ages of lavas and domes that obstruct other potential drainage paths. Along the route several domes can be seen, including one spectacularly truncated by erosion from the Waikato River. These domes are the northernmost representatives of the Western Dome Complex, that post-date the c. 320 ka Whakamaru-group ignimbrites.

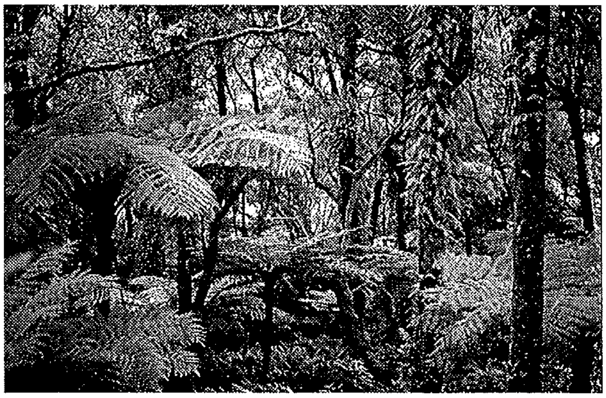
At Whakamaru on the south side of the river is the sharp ridge of Kaahu, composed of old, reversely magnetised rhyolite lavas surrounded by a bench of the 910±20 ka Marshall Ignimbrites (Wilson & Houghton, 1994). The Kaahu-Whakaahu ridge appears to lie just southeast of the main area of collapse inferred to have occurred at Mangakino caldera.



The Kaahu-Whakaahu ridge and Waikato River

From Whakamaru the route climbs southwest to the western margin of the TVZ. To the northwest there is a view of the Mangakino basin which has been proposed as one of the earlier calderas involved in central TVZ magmatism. The Mangakino Basin is inferred from geophysical and geological evidence to be a caldera which generated a complex and voluminous sequence of ignimbrites over a period from 1.6Ma to 910 ka (Wilson & Houghton, 1994). To the south the andesitic cones of Titiraupenga (K/Ar age of 1.9 Ma) and Pureora can be seen. These cones share similar chemistry and mineralogy and are thought to be linked. The centres may represent the earliest manifestation of activity in the TVZ.

STOP POUAKANI BUSH: NEW ZEALAND NATIVE BUSH WALK



New Zealand is home to a large variety of beautiful flora, 84% of which exists only in New Zealand. The forests range from sub tropical to temperate, evergreen rainforest and beech forests. Native trees include Rimu, Totara, Matai, Kahikatea and many species of ferns including some giant tree ferns. More notable trees include, the Cabbage Tree, the Nikau Palm which is New Zealand's only palm tree. Forest giants include Totara, as seen at Pouakani, Kahikatea New Zealand's tallest native tree, and Kauri. Some of the older Kauri trees rate as the largest trees on earth.

Flowering trees include the Kowhai, which has a beautiful yellow flower, plus the Rata and Pohutukawa tree's which both flower each summer with different shades of red. The Rata tree is concentrated in the South Island and the Pohutukawa tree is found mainly in the North Island. The Pohutukawa tree is also known as New Zealand's Christmas tree. New Zealand also contains large areas of tussock grass in areas of high altitude. Prominent areas of tussock include the South Island McKenzie Country and the Central Plateau of the North Island.

Other areas of New Zealand contain introduced species such as California's *Pinus Radiata* and the Canadian Douglas Fir. Both of these tree species are New Zealand's primary crop for forestry and they take about 30 years to fully grow, compared to 90 years in the Northern Hemisphere. This is attributed to New Zealand's lush volcanic soil and climatic conditions.

POUAKANI BUSH TO WAITOMO CAVES

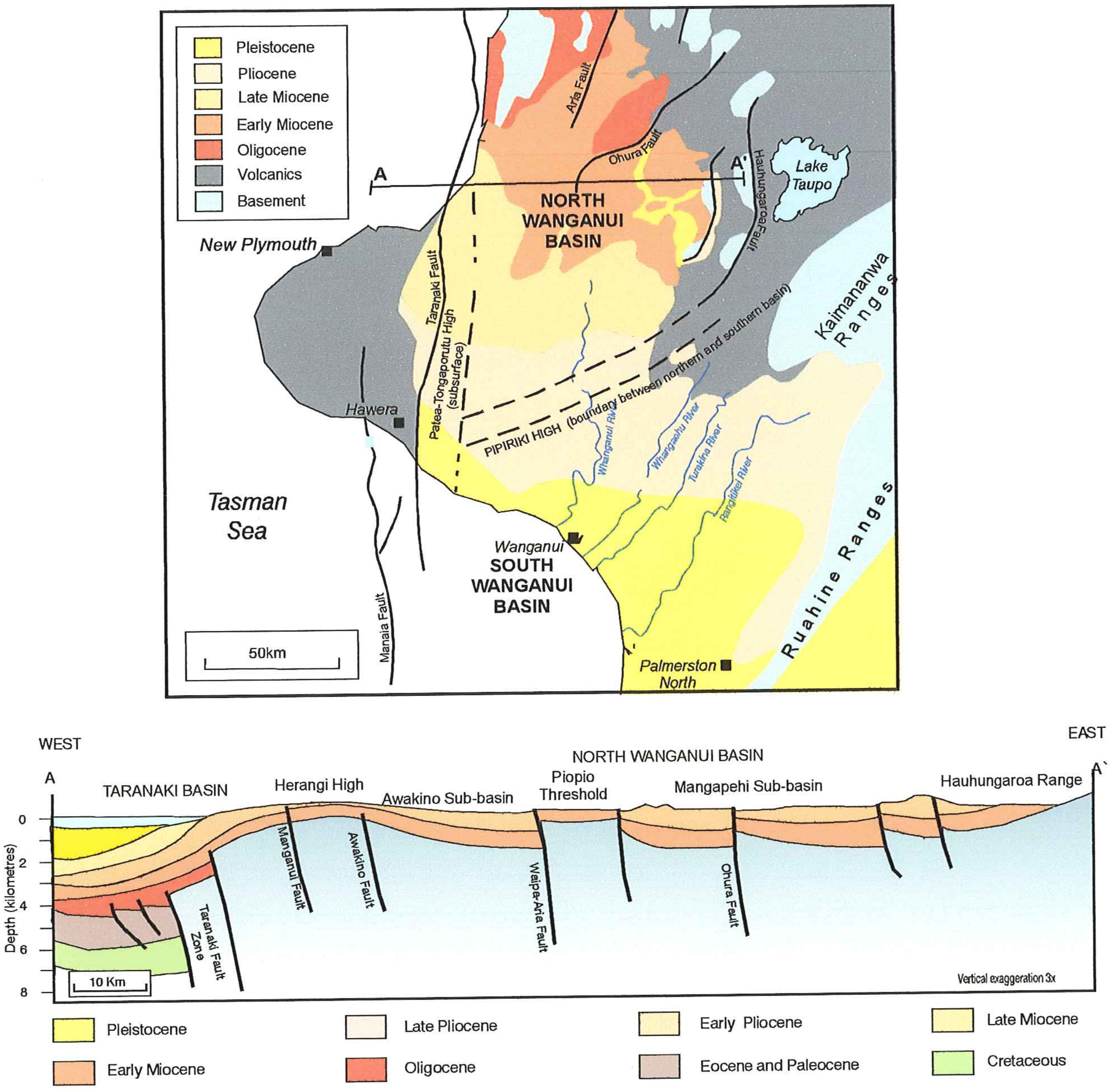
From the western TVZ we travel west into the North Wanganui Basin. Ignimbrite outcrops become uncommon and at Benneydale the route drops down into Tertiary sediments and exposed basement rock in road cuttings. From Benneydale we travel north, entering limestone karst country towards Waitomo Caves.

The Wanganui Basin – Background information

The Wanganui Basin underlies the western central North Island and the offshore region known as the Wanganui Bight. A basement high forms a natural boundary that divides the basin into two halves that have traditionally been treated separately as the North and South Wanganui basins. Sediments are contiguous between the two basins, and they form a depositional continuum from north to south. The North Wanganui Basin (viewed on day one and day two of the field trip) contains extensive limestone formations and coal. The South Wanganui Basin (viewed on day two of the field trip) is recognised as one of the best preserved sedimentary records of glacio-eustatic sea-level cycles in the world.

The western boundary of both the North and South Wanganui basins is marked by the basement cored Herangi Ranges. The eastern margin is at the central North Island axial ranges and the Taupo Volcanic Zone. The northern and southern boundaries are not clearly defined; to the north, the North Wanganui Basin merges with the coal-rich Waikato Basin, and the southern boundary of the South Wanganui Basin is generally considered to lie close to the Marlborough Sounds, at the northern tip of the South Island.

The North Wanganui Basin lies mostly onshore and occupies an area of about 10,000 km^2. The basin fill comprises an Eocene to latest Miocene terrestrial to bathyal succession up to 3000 m thick. The South Wanganui Basin is an elliptical shaped basin of about 22,500 km^2 with up to 5000 m of latest Miocene to Recent terrestrial and shallow marine sedimentary fill.



Wanganui Basin geological map (top) and cross-section A - A' (GNS –unpublished data)

North Wanganui Basin

Formation of the North Wanganui Basin began in the Eocene (about 40 Ma) during post-rift subsidence of the proto-New Zealand continent. The basin evolved with the deposition of a transgressive succession of terrestrial and marine sediments. By the Late Oligocene most of the North Wanganui Basin was at outer shelf and bathyal depths.

During the Early Miocene (about 25 – 20 Ma) westward over-thrusting along the Taranaki Fault and rapid subsidence occurred in the North Wanganui Basin. Localised sub-basins formed, probably as "piggy-back" basins associated with back-thrusting along major faults. Sedimentation continued into the Miocene (25 Ma – 5 Ma) with the locus of deposition migrating southwards. Erosion associated with Pliocene and Pleistocene (5 Ma – 1 Ma) uplift centred to the east has exposed a southward-younging sedimentary section. The major structural attribute of the North Wanganui Basin is a series of high-angle north striking reverse faults that bound a number of localised depocentres and intervening basement highs.

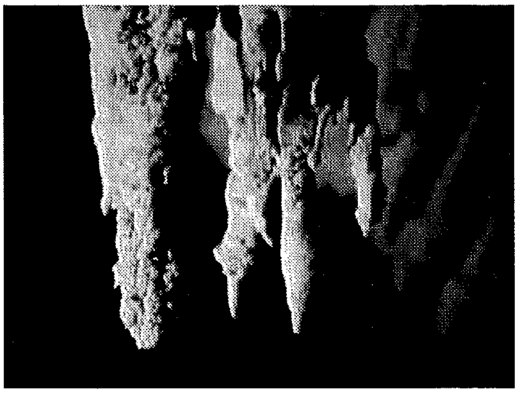
Basement rocks comprise a series of tectonostratigraphic terranes of Paleozoic and Mesozoic age. These include Paleozoic to Mesozoic, greenschist facies metasediments, ophiolites and Triassic to Jurassic volcaniclastic sandstones and mudstones. The oldest sediments in the North Wanganui Basin are Te Kuiti Group rocks of Eocene to Miocene age (~ 40Ma – 20 Ma) that crop out in the northwest. The Te Kuiti Group formations are generally thin (5 to 40 m), laterally extensive and range upwards from basal coal measures (Waikato Coal Measures), through marine, calcareous terrigenous mudstone and sandstone, to a widespread capping skeletal limestone.

The coal measures formed discontinuously within local basement depressions, rarely more than a few tens of metres across. In some areas the coal has been mined commercially. Early Oligocene calcareous mudstone (Whaingaroa Formation) and sandstone (Aotea Sandstone) generally overly coal measures. Late Oligocene and Early Miocene limestone, as viewed at Waitomo Caves, overlie the Aotea Sandstone. Unconformably overlying the Te Kuiti Group are mudstones, localised limestone (Mahoenui Group), strandline sandstones with interbedded coal measures (Mokau Group and Maryville Coal Measures) and thick intervals of terrigenous siltstone and sandstone (Mt Messenger, and Urenui formations), from 200 to 3000 m thick.

STOP WAITOMO CAVES

The rugged hill country of the north Wanganui Basin is studded by weather-worn limestone outcrops, which below the ground surface house a vast and largely uncharted series of caves. Only a small part of the cave system is open to the public and we shall visit this today.

Formation of limestone caves:
The limestone in this area was laid down in the Oligocene (35 Ma – 25 Ma) and uplifted in mid-Miocene time (about 12 Ma). Limestone can be dissolved only by water that contains carbon dioxide, and this was provided by the decaying vegetation on the floor of the forests which covered the deposits soon after they emerged from the sea. So the caves were slowly formed in the limestone layer by the dissolving action of rainwater.



Stalactites (from cave roof) and stalagmites (on the cave floor) inside the caves were formed by a reversal of this process. As each drip of rainwater seeps through the cave roof it dissolves limestone, and as it lingers before dropping each drip evaporates slightly to leave an infinitesimal ring of limestone behind. In this way endless millions of drips over countless centuries build a tube down from the roof. The stalagmite on the floor below the stalactite is also formed by evaporation but is a solid projection - unlike the generally hollow tube of the stalactite. When the two finally join to form a pillar a film of evaporating water may continue to run down it, thus imperceptibly but steadily increasing its thickness.

The New Zealand glow-worm:

The species *Arachnocampa luminosa* is rarely found outside New Zealand, and is abundant in Waitomo's Glow-worm Grotto. Unrelated to the European glow-worm (a beetle which uses its light to attract its mate), the New Zealand glow-worm belongs to the gnat family. Hatched from an egg, the larva (or glow-worm) grows to 2.5-3.5 centimetres in length. It prepares long sticky threads which it drapes down like fishing lines to snare the insects on which it feeds. The prey is lured to the lines by the glow-worm's light, which can be turned on and off at will and which is probably produced by a chemical oxidation process. The life cycle appears to be about 12 months, with the insect in the larva stage for up to nine months, finally hatching into a seldom seen and short-lived fly of about one cm with thin body and long legs.

STOP WAITOMO CAVES MOTEL

Day ends at motel for dinner, bed and breakfast.

DAY TWO: NORTH WANGANUI BASIN TO TARANAKI BASN AND SOUTH WANGANUI BASIN

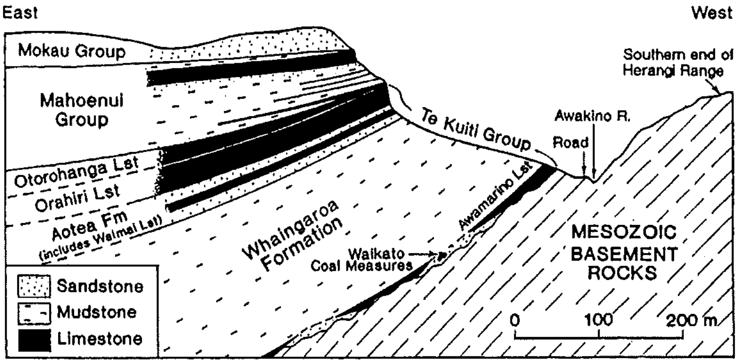
WAITOMO CAVES TO AWAKINO GORGE

The tour travels south through farmland to the Awakino Gorge. The route passes spectacular limestone outcrops with some basement exposure seen in road cuttings.

AWAKINO GORGE

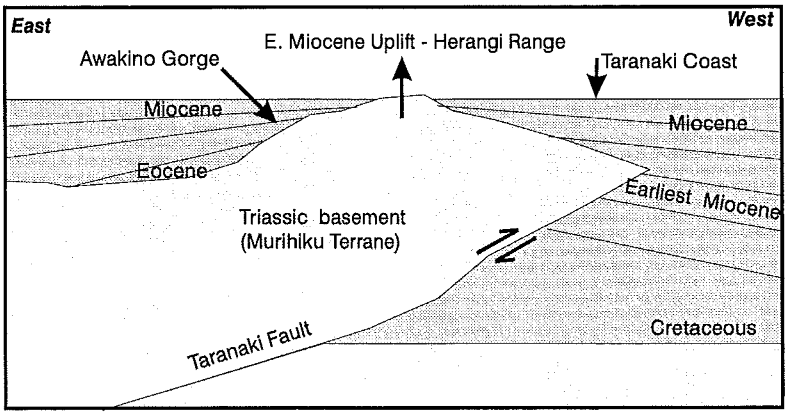
Exposures of the Te Kuiti Group in the southwestern corner of the North Wanganui Basin at Awakino Gorge are distinctive because, compared with elsewhere, the group is generally thicker (>300 m), has strong dips (25-45°E) and exhibits an up-section decrease in the amount of dip. The capping Orahiri Limestone includes several thick (up to 3 m) mass-emplaced units containing a variety of 1-10 cm sized calcareous lithoclasts of older Te Kuiti Group rocks (Nelson et al., 1994). The source region for the lithoclasts probably lay west of Awakino Tunnel and corresponds to the southern part of the basement Herangi High, that separates North Wanganui Basin from Taranaki Basin.

Uplift of this depocentre was accompanied by syn-sedimentary eastward tilting of the Te Kuiti Group strata already deposited immediately east of Herangi High, contributing to the dips now measured at Awakino Gorge. Inversion and tilting of the high began after 32 Mys ago, concomitant with the onset of rapid subsidence along eastern Taranaki Basin margin directly west of Herangi High. Uplift continued from 28 to about 22 Ma (Nelson et al., 1994).



Tilted strata at the Awakino Gorge (from Nelson et al. 1994)

The uplift and partial emergence of Herangi High is a topographic response to the initiation of basement over-thrusting from the east along the Taranaki Fault Zone. This late Oligocene phase of deformation developed in a mildly compressive regime, which corresponds to a time of proto-plate boundary development through New Zealand that preceded propagation of the present plate boundary through the country in the Early Miocene.



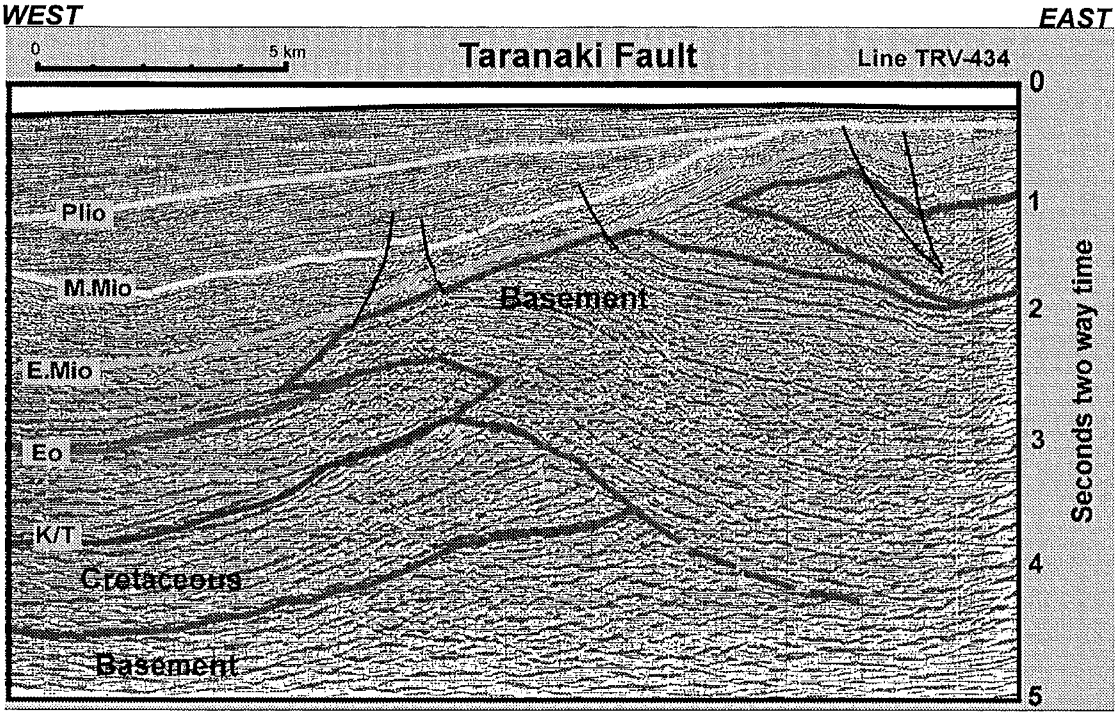
Cartoon of Early Miocene Taranaki Fault movement

The Taranaki Fault - Background information

The Taranaki Fault is a crustal scale reverse fault that is located along the eastern side of the northern Taranaki Basin. The fault forms the pre-Miocene edge of the Taranaki Basin. Early Miocene and younger sediments lie as unbroken cover over the hanging wall. The fault is inferred to form one of the fundamental geological boundaries in New Zealand (Mills, 1990; Thrasher, 1992).

The Taranaki Fault is clearly seen on seismic reflection profiles, and has a large positive gravity anomaly, associated with the up-thrown hanging wall. It extends from south of the Taranaki Peninsula to west of Auckland, a distance of over 400 km.

Seismic reflection profiles north of the Taranaki Peninsula show the fault dips at less than 45° and appears to flatten into the upper crust between 4 and 5 s TWT (11 - 15 km). Typically there is over 4 km of vertical displacement.



Seismic profile of the Taranaki Fault in offshore northern Taranaki (open file data, GNS interpretation)

The Cretaceous to Eocene history of the Taranaki Fault is inconclusive because the fault abruptly truncates the sedimentary sequence deposited before the Oligocene, leaving no trace of the pre-Oligocene structure. Sediments older than Eocene in age are not found on the eastern, upthrown side of the fault. Most studies have depicted the fault as normal throughout the Cretaceous and Paleogene, with inversion and thrusting occurring in the Late Oligocene and Early Miocene (eg Mills, 1990; King & Thrasher, 1992).

Evidence of Late Eocene (40 Ma - 35 Ma) uplift on the Taranaki Fault comes from several sources, including the occurrence of turbidity currents (Palmer & Andrews 1993), a westward shift in depocentres along the eastern margin of the basin (Voggenreiter, 1993), and evidence from the Awakino Gorge (Nelson et al. 1994). It is uncertain how much reverse movement was occurring on the fault at this time.

The timing of the most active thrusting on the Taranaki Fault can be constrained by sedimentary and geophysical evidence to the period from about 23 Ma to 20 Ma. The Taranaki Fault sharply truncates all sedimentary sequences older than earliest Miocene. Sedimentation rates in offshore wells increased in the earliest Miocene, coincident with a change from limestone deposition to mudstone dominated deposition.

Thrusting ceased in the Otaian Stage (about 20 Ma). Petroleum exploration wells that penetrate the hanging wall of the Taranaki Fault intercept Otaian sediment lying directly on basement (eg Pluto-1 and Tirua-1). The major amount of reverse faulting is therefore constrained to a period of about three My (23 Ma – 20 Ma), giving an uplift rate of 2.5 to 3.5 mm/year. This is between a half and a quarter of the present day uplift of the Southern Alps (Wellman 1979). North of the Taranaki Peninsula the Taranaki Fault has been inactive from the Middle Miocene and there is no evidence of reverse faulting anywhere in the area since that time.

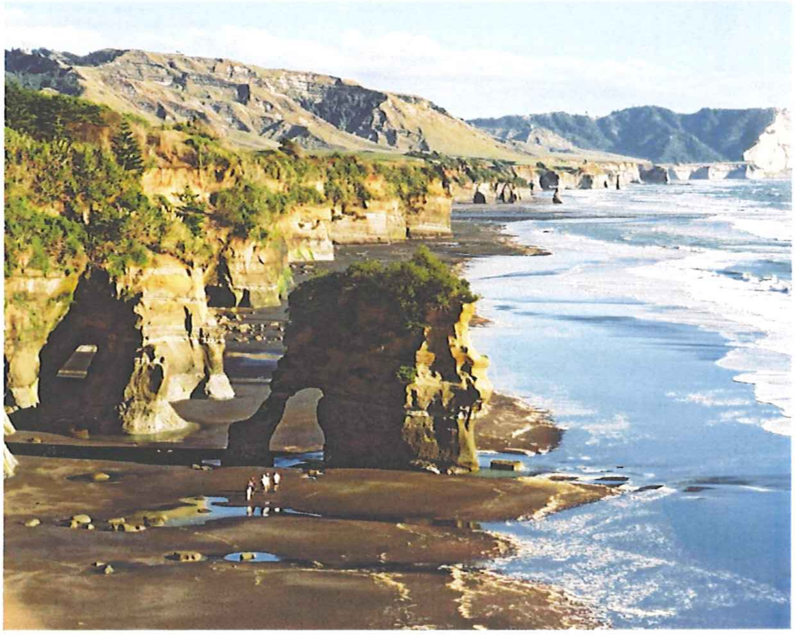
STOP FOSSIL HUNTING AWAKINO GORGE – OPTIONAL

An optional stop is where Lower Mokau Formation (Early Miocene) inner shelf sandstones onlap basement (Late Triassic) marine sandstones and siltstones containing *Monotis richmondiana.* The marine bi-valve *Monotis richmondiana* is the symbol used by the Geological Society of New Zealand.

Note: Please be aware of cars – this is the main road between New Plymouth and Auckland.

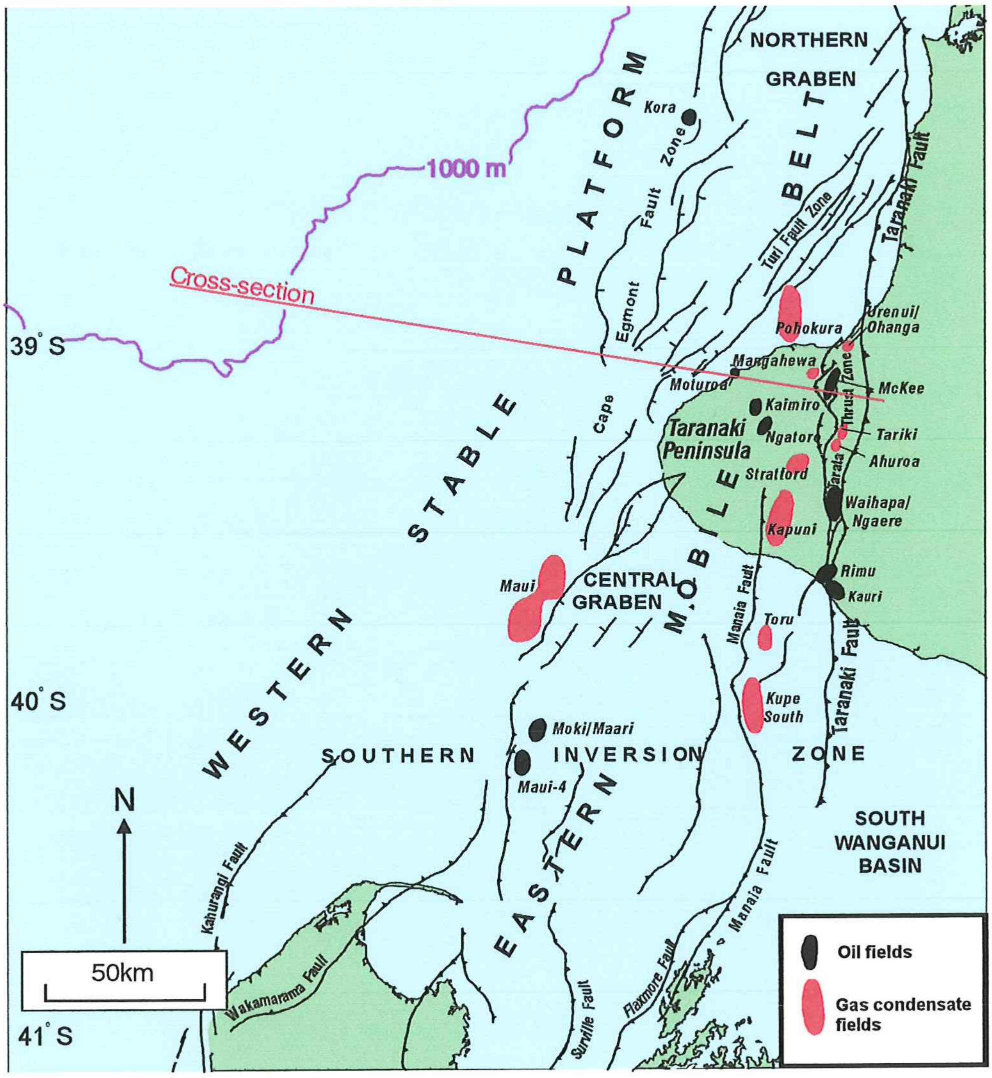
MOKAU TO TONGAPORUTU

The route passes along the top of marine terrace close to the coastline.



The Taranaki Basin – Background information

The Taranaki Basin is of New Zealand's most explored and commercially successful hydrocarbon province. The basin is principally a sub-sea feature, elongated north-south and covering c. 100,000 km^2. The basin comprises a variety of superimposed sub-basins that range in age from Late Cretaceous to Recent and contain thick accumulations (up to 9000 m) of sediment.



The Taranaki Basin showing structural zones, faults active in the Neogene, oil and gas fields (GNS)

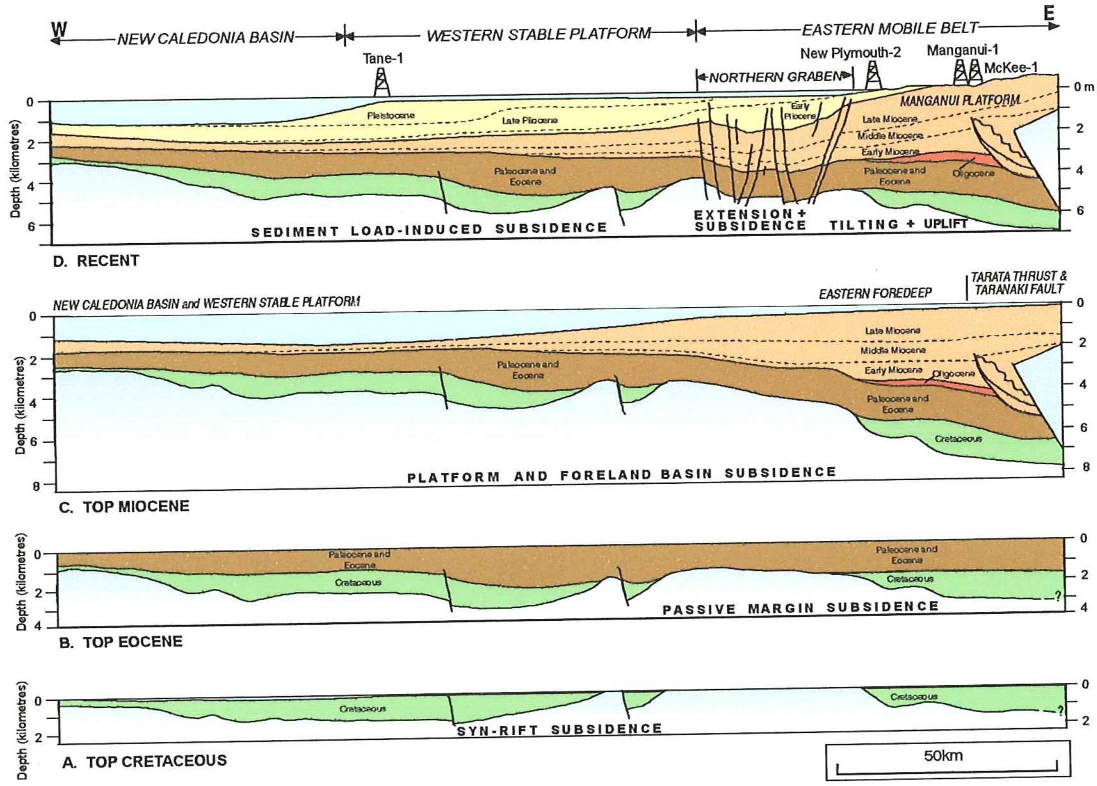
The boundaries of the Taranaki Basin are not clearly defined. On its eastern boundary lies the Taranaki Fault. Other limits of the Taranaki Basin are arbitrary; sedimentary cover is contiguous over all of offshore western New Zealand.

All nine of New Zealand's producing oil and gas fields, and another four under appraisal are in the Taranaki Basin. All fields contain oil, condensate and gas. The bulk of discovered reserves (60%) are contained in the offshore Maui Field, with a further 22% in the onshore Kapuni Field. Both feilds are nearing depletion.

Production for all fields in 2001 was 12.3 MMbbl of oil/condensate and 216 bcf of gas. Production from all fields to date has totalled about 261 MMbbl of oil and condensate and about 3492 bcf of gas. As at 1 July 2001 recoverable remaining reserves in all known fields was 90 MMbbls of oil and condensate and 2082 bcf gas (data from MED).

Tectonic setting of the Taranaki Basin

The tectonic history of Taranaki can be broadly divided into two main evolutionary phases; a Cretaceous to Oligocene passive margin phase and a Late Oligocene to present day convergent margin phase (King & Thrasher, 1996). The palinspastic reconstruction of a west-east cross-section shows the basin evolution. The passive margin phase began with break-up of the Gondwanaland and spreading in the Tasman Sea in the Late Cretaceous and Early Paleocene. Rifting and extension created a series of *en echelon* half-grabens, many of which underlie the Taranaki Basin (Profile A). By the end of the Paleocene basin growth was no longer controlled by rift tectonism, but instead by gradually declining regional subsidence (Profile B). Slow subsidence continued through to the Oligocene, by which time most of the Taranaki Basin was beneath the sea.



Taranaki Basin cross-sections showing basin development (from King & Thrasher 1996)

The convergent margin phase of the basin's history began in the Oligocene with the propagation of the modern segment of the Australia-Pacific Plate boundary through New Zealand (King & Thrasher, 1992). In the Taranaki Basin the onset of subduction was characterised by Late Oligocene basin-wide subsidence and Early Miocene over-thrusting of the Taranaki Fault. Thrust-belt loading led to foreland basin development and the formation of an asymmetric foredeep trough west of the Taranaki Fault (Profile C).

As subduction continued, extensional tectonism occurred north of the Taranaki Peninsula while compressive tectonism occurred in the southern part of the basin. In the north, a chain of submarine andesitic stratovolcanoes erupted in the Middle - Late Miocene. These volcanoes are now buried beneath Late Miocene and younger sediments (Stagpoole & Funnell, 2001). Shortening within the southern Taranaki Basin is expressed as Middle to Late Miocene structural inversion of relict rift half-grabens. Reverse faulting and uplift took place on reactivated graben-bounding normal faults.

Since the Late Miocene, normal faulting has propagated southward through the basin, and uplift, centred to the east of the Taranaki Basin, has caused southwest tilting of sedimentary formations along the Taranaki coastline (Profile D). Pliocene to Recent andesitic volcanism has occurred on the Taranaki Peninsula.

Basin structure

There are two main structural provinces of the Taranaki Basin, the Western Stable Platform and the Eastern Mobile Belt. The Eastern Mobile Belt comprises several sub-provinces of differing structural affinity that all formed as a consequence of Neogene tectonism. The junction between the Western Stable Platform and the Eastern Mobile Belt marks the western (outer) limit of this Neogene deformation in the Taranaki region. In the northwest of the basin, the limit of plate deformation is delineated by the Cape Egmont Fault. In the southern part of the basin the boundary is marked by a diffuse line defining the westernmost occurrence of inversion structures.

Unlike the Eastern Mobile Belt, the Western Stable Platform has remained comparatively undeformed since the Paleocene. This period of quiescence is reflected by the virtually undeformed mid-late Paleogene and younger sediments.

Stratigraphy

Taranaki Basin sediments are Cretaceous to Recent in age. The entire sedimentary record can be summarised as a major transgressive cycle culminating in the Early Miocene, followed by a major regressive cycle that is still continuing. The marine transgression relates to subsidence and encroachment of the sea from the northwest, and the following regression relates to uplift and deposition from the south and east.

The first sediments widely deposited in Taranaki are Late Cretaceous coals and terrestrial sands of the Rakopi Formation that are up to 3000 m thick (Profile A). During the latest Cretaceous regional subsidence resulted in the formation of complex tidal embayments represented by the widespread, predominantly marine North Cape Formation.

During the Paleocene and Eocene fluvial sandstones of the Farewell Kaimiro and Mangahewa formations were deposited over a broad region in the southern and central part of the Taranaki Basin. In the northern part of the basin the Paleocene and Eocene is marked by the deposition of fine-grained and organically lean shelf sediments of the Turi Formation.

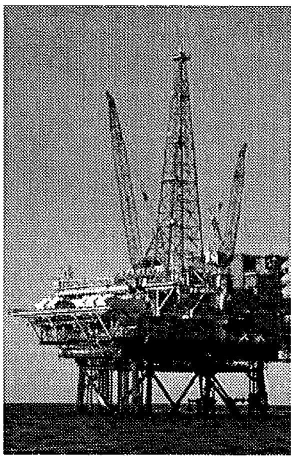
By the Oligocene the regional marine transgression had completely inundated the Taranaki Basin, and subsidence was minimal. Calcareous siltstones and mudstones were deposited in the east, while in the west, bioclastic limestones, calcareous mudstones and micritic oozes of the Tikorangi Formation continued to accumulate.

In the Early Miocene uplift and erosion in neighbouring eastern and southern hinterlands resulted in the introduction of fine-grained terrigenous clastics to the Taranaki Basin (Manganui Formation). During the Middle and Late Miocene a north-south trending chain of andesitic volcanoes (Mohakatino Volcanic Centre) erupted in northern Taranaki. Volcanism was accompanied by deposition of reworked marine and air-fall volcaniclastic sediments of the Mohakatino Formation.

Southern parts of the Taranaki Basin remained at shelf depths throughout the Late Miocene-Pleistocene. Erosion products were transported across this shelf by long-shore drift and deposited in northern and western downslope regions. Late Miocene turbiditic sands of the Mount Messenger Formation are in the north. An increase in sediment supply to the basin during the Pliocene-Pleistocene resulted in progradation of the slope onto the Western Stable Platform. Predominantly fine-grained slope sediments of the Giant Foresets Formation characterise this interval.

Exploration history

Ever since Dr E Dieffenbach's 1839 observation of "a strong smell of sulphuretted hydrogen gas about a mile from the high water mark" in the vicinity of New Plymouth, the Taranaki region has been the focus for hydrocarbon exploration and production in New Zealand. The first bona fide oil well in New Zealand, and the first in the British Commonwealth, named "Alpha", was drilled to a total depth of 55 m near the Moturoa seeps, New Plymouth in 1865. The well produced, for a short time, at a rate of two barrels per day, and by 1900 five separate companies, or syndicates, had drilled a total of 11 wells in the Moturoa field. The field was abandoned in 1972 after producing around 250,000 barrels of oil.



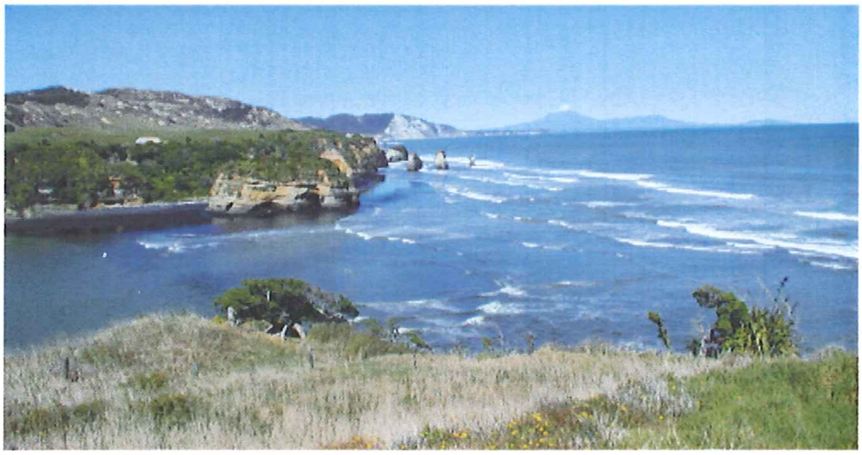
Maui A Platform

The "modern era" in petroleum exploration began in 1955 with the formation of the Shell, BP and Todd (SBPT) consortium and their first well, Kapuni-1, discovered gas-condensate at Kapuni in 1959. The Kapuni field commenced production in 1970. Offshore seismic reflection surveying began in the 1960s. With the third well drilled offshore (Maui-1) the SBPT consortium discovered the 'giant' Maui gas-condensate field in 1969. Over the next decade several other smaller and/or sub-commercial discoveries offshore. In 1993, oil was discovered in deeper sands during the drilling of Maui-B gas wells and in 1996 a floating production, storage and offloading facility (FPSO) successfully completed its first offloading of Maui-B crude. In 1998 oil was found in the Maari-1 well, south of Maui and is presently under appraisal. In 2000 the Pohokura gas and condensate field was discovered 4 km offshore. Initial reserve estimate of 1 tcf gas and 53 MMbbls of condensate. In terms of total remaining reserves, Pohokura is New Zealand's second largest gas-condensate field behind Maui.

Onshore, a vigorous exploration programme was conducted from 1978 and several discoveries were made, mainly on the Tarata overthrust trend. The McKee oil field was discovered in 1979, and from 1982 to 1987, a number of other small oil and gas-condensate fields were discovered on the Taranaki Peninsula. In 1999 Swift Energy began production from the 27 MMbbl Rimu/Kauri field, adjacent to the Taranaki Fault in southern Taranaki. The success of this venture prompted further exploration along the fault and currently several wells are being planned or tested as part of this new play.

TONGAPORUTU

At Tongaporutu the northern Taranaki coast can be viewed. This is close to the eastern edge of the Taranaki basin. The Taranaki Fault lies about 5 km offshore and Miocene sediments deposited on top of its hanging wall are exposed in cliffs along the coast. A photo stop at the top of the coastal cliffs gives an overview of the Tongaporutu to Pukearuhe Beach coastal section which youngs to the south. The sea stacks in the foreground are referred to as the "Three Sisters". Such stacks and caves and are common along this part of the coast and form where faulting and fracturing occurs. In many cases the margins of the stacks are defined by northeast-southwest striking normal faults.



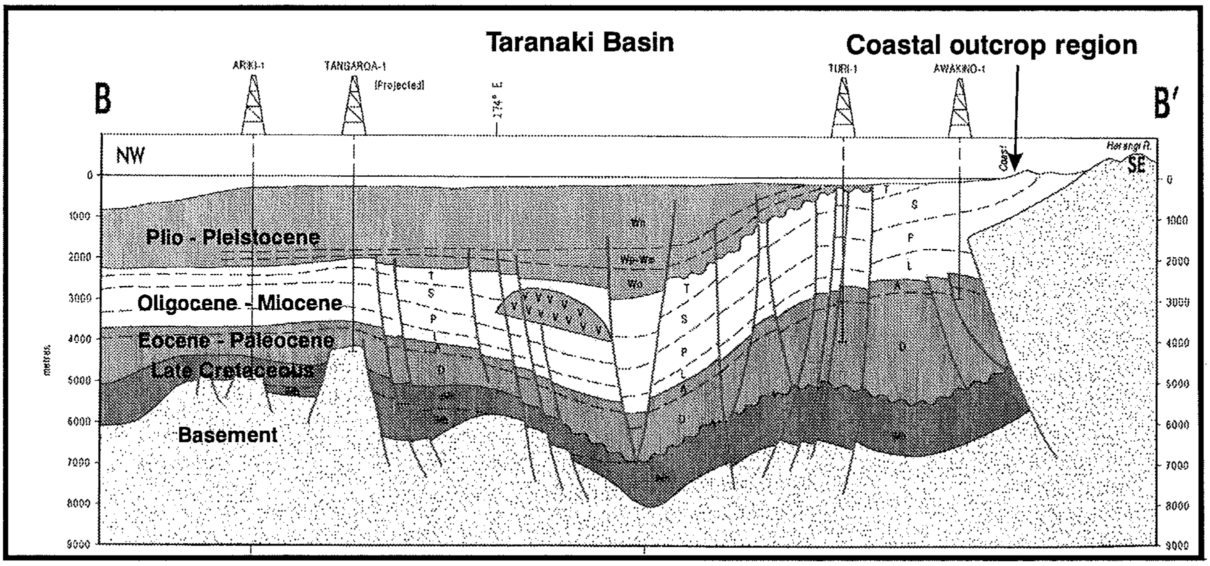
Coastal exposure at Tongaporutu, White Cliffs and Mt Taranaki in the distance

TONGAPORUTU BEACH

In terms of health and safety issues, please be aware of certain inherent hazards and dangers of working along the coastline and adjacent areas. The cliffs can be unstable and portions may collapse or shed debris without prior warning. Caution should therefore be exercised when examining rocks at the base of natural or man made cliffs. In addition, wave, river, and tidal conditions can be such that there is a danger when walking along the coast. Please observe the warnings and time limitations imposed at certain stops by your leaders – they exist for good reason! Please also be aware that we may be crossing busy public roads or farm tracks where heavy machinery may be in use.

At the beach Mt Messenger Formation is exposed. This is the type section of the New Zealand Tongaporutuan Stage (10.9 Ma – 6.6 Ma). This section is part of an overall Late Miocene Mount Messenger to Urenui Formation transect from Awakino in the north to Onaero in the south. Paleobathymetry changes up-section from lower bathyal to upper bathyal/outer shelf, and the entire succession is an excellent example of a progradational and aggradational system that ultimately reflects the arrival of the continental slope in the region. This exposed basin floor to slope system is characteristic of Miocene depositional patterns throughout the Taranaki Basin.

In sequence stratigraphic terms, the Mount Messenger and Urenui Formations appears on a broad morphological scale to represent a single complete lowstand systems tract from basin-floor fan to prograding complex, deposited over a period of c. 4 My (3rd-order cycle). In detail several sequences of inferred 4th-order cyclicity (~ 300 kyr cycles) are identified in the coastal section. These are superimposed upon the 3rd-order succession, and attest to periodic variations in relative base level due to eustatic sea-level variations (King et al., 2002).



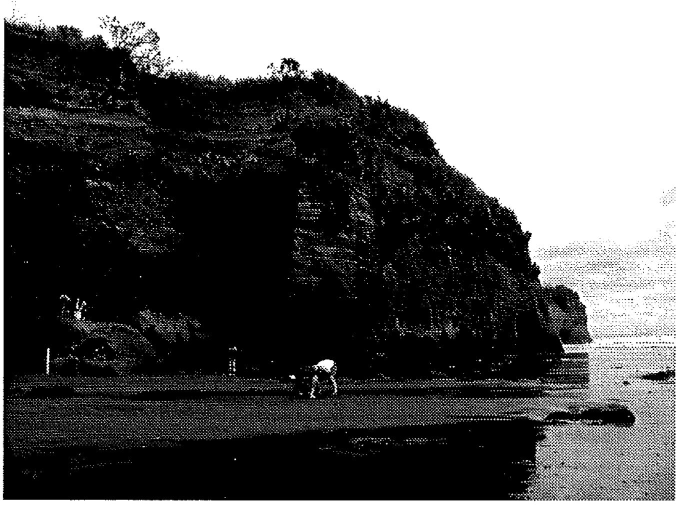
Cross-section of Taranaki Basin through coastal outcrop region (adapted from King & Thrasher 1996).

The exposure at Tongaporutu runs from the river mouth, and extends south along the beach for several hundred metres. This locality is part of the lower portion of the Mount Messenger Formation. Three main basin floor fan facies are present within a 4th-order cycle: in ascending order these are: thick-bedded sandstone, thin-bedded sandstone/mudstone, and mudstone. These overly a sharp sequence boundary, that in turn, overlies slumped siltstones of the preceeding 4th-order cycle.

Thick-bedded facies comprises up to 5 m thick, often amalgamated, moderately to well sorted, fine- to very fine-grained bioturbated, interbedded with cm-thick bioturbated mudstone. Loading, flame structures, sole marks, convolute bedding, and mild scouring is present. They are interpreted as high density, sand-rich mass flow sediments deposited as lobate basin floor sandstones and associated pelagic siltstone.

The thin-bedded sandstone and mudstone interval grades abruptly up from the thick-bedded facies. They consist of cm- to dm-thick, moderately to well-sorted, fine- to very fine-grained, bioturbated sandstone, interbedded with bioturbated, often tuffaceous mudstone. At the top of the section is a ~10 m thick siltstone with thin interbedded sandstone beds It is interpreted as late-stage prograding complex siltstone.

Above the Miocene section an unconformity separates a thin marine terrace of about 120 ka.

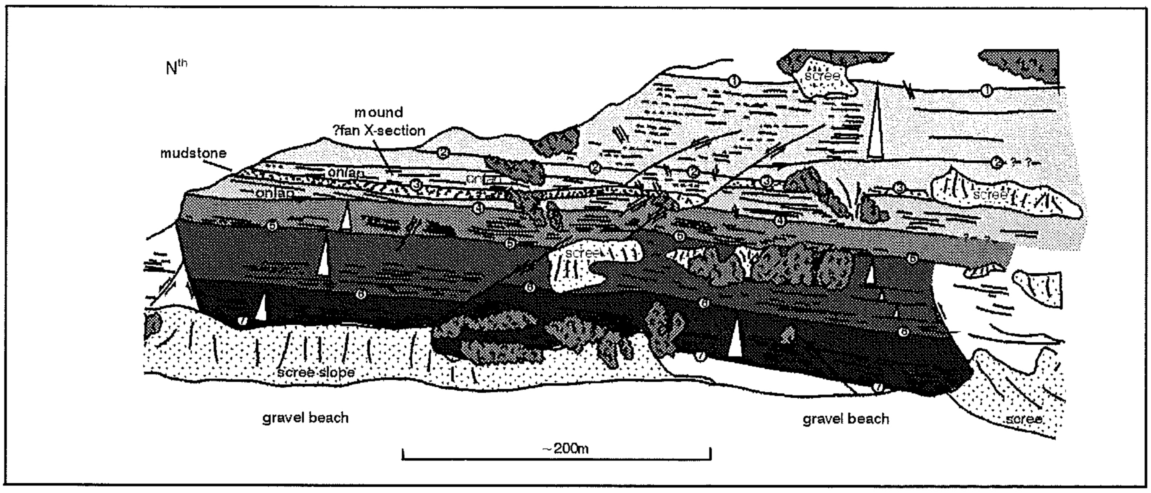


Faulted thick-bedded sandstone at Tongaporutu

The Miocene turbidites exposed in vertical coastal cliffs (10-250m in height) are cross-cut by normal faults. Individual faults range in displacement from 100m down to less than 1mm and typically form conjugate sets which strike N-NNE. The largest of these faults mainly dip to the west. They are dominated by slip directions which are within 10° of the their dip direction and suggest extension normal to the rift axis. Analysis of offshore seismic data suggests that the faults are mainly Pliocene in age. The faults do not offset the ca. 120 ka marine terrace and are inferred to be inactive.

HIGH-RESOLUTION SEISMIC REFLECTION EXPERIMENT

In December 2000, a high-resolution seismic reflection experiment was carried out at Pukearuhe Beach, south of Tongaporutu, immediately adjacent to the cliff exposures. The same line was surveyed twice, once using 100 Hz one-component (vertical) geophones, and once using 40 Hz three-component geophones. The geophones were spaced at an interval of 2 m, while the shot spacing was 8 m.



The figure (Henrys pers. com., 2002) shows the processed vertical component section translated updip 2 km and superimposed over outcrop at Whitecliffs, south of Tongaporutu. The seismic data are able to resolve bed thickness of 10 m and uncomformities mapped in outcrop appear to match seismic sequence unconformities.

TONGAPORUTU TO INGLEWOOD

The route travels south over Mt Messenger and back to the coast at Urenui and on to Motunui where a Methanex gas-to-methonol plant is located. Natural gas from two Taranaki fields, Maui and Kapuni, is piped to the plants. The two plants have a combined annual operating capacity of 2,430,000 tonnes. Originally, the Motunui plant had a dual capability. It was constructed to convert natural gas to gasoline, with methanol as an intermediate step in the process. In 1997 the gasoline production facility was permanently mothballed due to the low international price of petrol. Now, the entire crude methanol production of Motunui is distilled into chemical grade methanol. Both plants are linked together by a 4 km pipeline with another pipeline used to transport methanol to the port for transfer to ship. The New Zealand facility is a key distribution point to the Asia Pacific region.

MT TARANAKI - EGMONT VOLCANO

The Taranaki landscape is dominated by the 2518 m andesitic Egmont Volcano. Egmont, the youngest and most southerly volcano of the Taranaki Volcanic Succession, is the second highest mountain in the North Island and the largest andesitic stratovolcano in New Zealand. Over a horizontal distance of 25 km the slopes of Egmont Volcano rise from sea level to a summit at 2518 m. Its slopes within a 9.6 km radius of the summit are conserved within Egmont National Park. Egmont Volcano last erupted c. 1755 A.D., prior to European settlement.

Egmont Volcano can be sub–divided into upper and lower sections. The upper section comprises principally lava flows that form a prominent cone with summit crater. The lower section, volumetrically much larger, consists of an extensive apron of coalesced fans of laharic, pyroclastic and alluvial volcaniclastic detritus. This section has been named the Egmont ring plain and is near circular in outline except where Pouakai Volcano and the Eltham laharic planeze break the landscape to the north, and where it merges with the dissected Tertiary hill country of east Taranaki. The Egmont ring plain in the vicinity of Inglewood is bordered by elevated and dissected remnants of a northward sloping planar surface mapped by Hay (1967) as Eltham Lahars.

A comprehensive record of the volcano's eruptive activity has now been elucidated for central and north-eastern Taranaki (Alloway, 1989; Alloway *et al.*, 1995) and results indicate that tephra emission has been surprisingly frequent. At least 76 eruptive events ($>10^7$ m^3) are recorded from Egmont Volcano since the early onset of the Last Glacial Maximum (< c. 28 ka) — an average eruptive periodicity of one in every 320 years. This interval is considered a minimum since many more tephras of lesser magnitude were presumably erupted but are not represented beyond the confines of Egmont National Park except as intermittent accretion of fine-grained ash that rapidly weathered to soil material.

In the vicinity of Inglewood, on the north-eastern margin of the Egmont ring plain (20 km from the present Egmont summit) prominent mounds of a voluminous debris avalanche deposit mapped as Okawa Formation (Alloway 1989) can be clearly observed. This debris avalanche deposit has been mapped over a minimum area of 255 km^2 in northern and north-eastern Taranaki, and has a calculated minimum volume of 3.62 km^3.

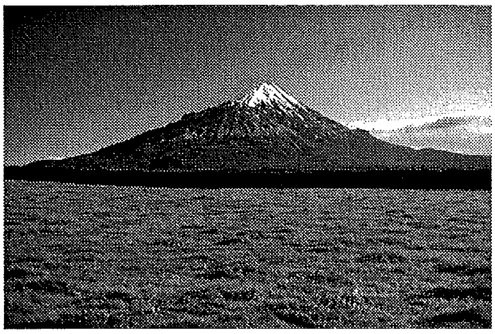
Mounds of Okawa Formation are principally concentrated within a c. 2.5 km wide belt that extends north-east to just west of the Waitara River. Immediately north-east of Inglewood, hummocky mounds are also conspicuous on a small area of elevated and dissected terrain of the Eltham laharic planeze. Further

Debris flow mounds near Inglewood

towards Egmont Volcano, mounds have little or no surface expression, because they have been buried beneath a thickening succession of younger volcaniclastic material. In the vicinity of Inglewood, some mounds were measured with basal diameters as much as 350 m across and heights of 45 m. With increasing distance north from the ring plain, the mounds gradually become equidimensional in shape, are mantled by a progressively thinner sequence of cover beds, and progressively decrease in basal diameter and height.

Although not directly dated, the Okawa Formation is indirectly dated at c. 105 ka based on the position of interbedded with a prominent paleosol which is correlated by Alloway (1989) to the global warm period of oxygen isotope substage 5c.

STOP HAWERA – DAIRYLANDS



On the outskirts Hawera, in southern Taranaki, is the Kiwi Dairy Factory, the largest one site, multi-product dairy factory in the world.

Annual Manufacturing Capacity: Whole Milk Power 339,000 tonnes; Skim Milk Powder 49,000 tonnes; Milk Protein Concentrate 12,500 tonnes; Lactic Casein 18,000 tonnes; Cheese 80,000 tonnes; Butter 85,000 tonnes; Anhydrous Milk Fat 1,500 tonnes; Whey Protein Concentrate/Whey Protein Isolate 5,700 tonnes; Alamin 900 tonnes.

The Dairyland Centre gives an insight into the processes involved in producing dairy products. Dairyland encompasses interactive audio-visual displays, a souvenir shop and revolving restaurant all under one roof

HAWERA TO WANGANUI

The route travels through dairy farm country across the South Wanganui Basin. The South Wanganui Basin is Latest Miocene to Recent in age. Its formation is attributed to coupling of the subducting slab to the overriding plate that has caused downwarping of the lithosphere, at present centred on the Wanganui Bight (Stern et al., 1992). Uplift of the axial ranges at the eastern edge of the basin may also have contributed to basin formation through crustal shortening and lithospheric loading. Through the Pliocene and Pleistocene the centre of subsidence has migrated southwards while there has been a concomitant regional uplift along the northern margin of the basin

The greatest subsidence is in a roughly bowl shaped depression offshore of Wanganui. Sedimentation has evidently kept pace with subsidence throughout much of the basin history, resulting in a 5000 m thick succession of predominantly shelf and shallow-water sediment. On seismic data the floor of the basin is rugged with up to 2000 m relief, and is dissected by many northeast trending, mostly reverse faults.

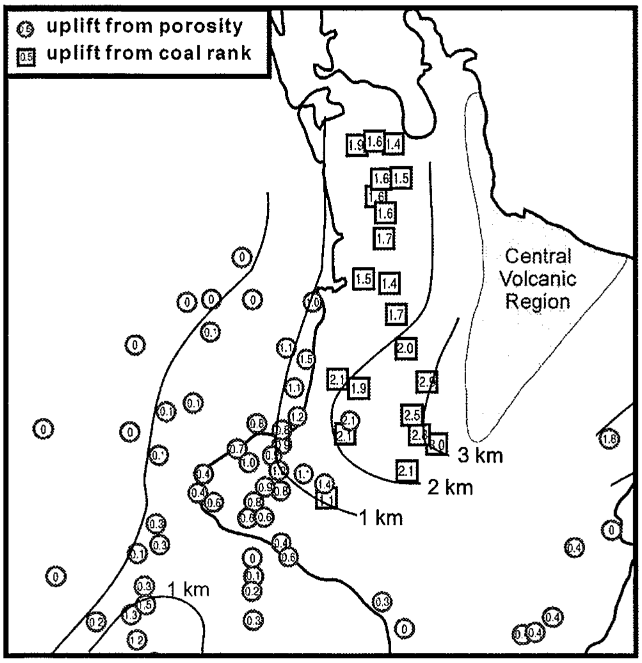
During the late Quaternary, marine sediments within the South Wanganui Basin have been uplifted at rates of 0.3 to 0.5 m/ka in the vicinity of the modern coastline, and at rates of 1 to 3 m/ka in the east, adjacent to the axial ranges. Consequently, a series of marine terraces are exposed along the route. These are most clearly seen at Nukumaru near Kai-iwi. The gently dipping (2 to 15°) strata are well exposed along the coastline northwest of Wanganui City and within deeply incised river valleys farther to the east, thus providing excellent on land exposures through the entire basin-fill.

The oldest sediments are Late Miocene to Early Pliocene shelf and shoreline sandstones and siltstones with intervening coquina shellbeds. Overlying strata comprises thick (up to 700 m) siltstone dominated intervals and regressive units of well-sorted tidal channel and shoreface sands, and upper slope/outer shelf massive siltstones.

The Pliocene and Pleistocene strata of the South Wanganui Basin display remarkably rhythmic alternations from coarser-grained nearshore facies to finer-grained shelf and slope facies. The Quaternary sedimentary sequences is recognised as one of the best preserved sedimentary records of glacio-eustatic sea-level cycles in the world. More than 50 superposed Pliocene and Pleistocene (3.6 to 0.1 Ma) depositional sequences have been identified within the younger part of the basin fill (Naish & Kamp, 1997). These depositional sequences (from 10 to 200 m in thickness) comprises transgressive, highstand and regressive facies successions, and were deposited in a range of coastal plain, shoreface and shelf environments.

Pliocene and Pleistocene uplift – Background information

Uplift, centred on the TVZ, has exposed a southward-younging sedimentary section along the Taranaki and Wanganui coast. King & Thrasher (1996) and Armstrong et al., (1998) give estimates of Late Neogene erosion (exhumation) in exploration wells in Taranaki Basin, based on porosity measurements. Further exhumation estimates have been derived from coal rank studies, (R. G. Allis pers. com., 1995). These data give an estimate of the magnitude of uplift, but have little age control, however, seismic reflection data constrain the timing of uplift to 5 Ma and younger in most places. A possible cause of this uplift is a thermal anomaly in the mantle beneath the TVZ.



The uplift data depicted in this figure (in km) is calculated from the amount of erosion plus the elevation determined from drill holes in the region. The amount of erosion is calculated from either porosity or coal rank (from R Funnell pers. com., 1998)

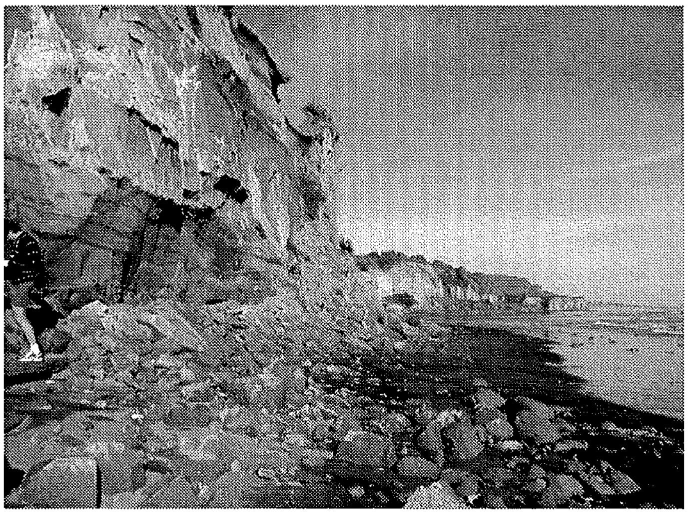
STOP KAI-IWI BEACH - QUATERNARY SEDIMENTARY CYCLES - OPTIONAL

Kai-iwi Beach near the seaside village of Mowhanau provides access midway along the Castlecliff section (mid Pleistocene). The sediments dip at between 2 to 3 degrees to the south. Thus progressively older sediments are exposed to the northwest along 10 kms of the coastal outcrop. The fossiliferous coastal cliffs northwest of Wanganui City comprise the stratotype of the Pleistocene New Zealand Castlecliffian Stage (1.7 to 0.34 Ma) and form an important global reference section in Pleistocene stratigraphy.

The first comprehensive description of the sediments and their constituent fauna was provided by Sir Charles Fleming in 1953 (NZGS Bulletin – Geology of Wanganui Subdivision). Fleming described 10 sedimentary cycles in the Castlecliff section; each bounded by an erosion surface and comprising a basal shellbed, shelf siltstone and sandstone deposited during water depth changes of up to 50m.

Detailed examination of the Pliocene to Pleistocene sedimentary rocks in the Wanganui Basin has revealed a high degree of order and cyclicity in the sedimentary architecture. Interpretation of sedimentary cyclicity in the Wanganui succession, and the recognition of the differing sequence architecture, depends on the correct identification of sediment-bounding surfaces associated with each sequence (Abbott and Carter, 1994; Naish and Kamp, 1997; Saul et al., 1999). Accurate interpretation is greatly aided by an understanding of shellbed types present and the habitat of their faunas, as first appreciated by Fleming (1953).

Around 100 depositional sequences have been described in the Pliocene-Pleistocene shallow-marine basin fill of Wanganui and Eastern Taranaki basins. An integrated chronology based on radiometric ages on interbedded rhyolitic tephra, on biostatigraphic data, on paleomagnetic polarity measurements, allow cycles/sequences to be correlated precisely with the oxygen isotope timescale (e.g. Naish et al., 1998). Individual sequences spanning the last 2.5 Ma with 40 and 100-kyr sea-level cycles match the deep marine oxygen isotope curve. With minor exceptions the high-frequency basin architecture is controlled by glacio-eustatic sea-level fluctuations, primarily every 40-kyrs. The exception is the last 800-kyr where the 100-kyr duration climate cycle has controlled global sea-level changes.



Pleistocene strata at Kai-iwi Beach

STOP WANGANUI

Day ends at Wanganui for dinner, bed and breakfast.

DAY THREE: SOUTH WANGANUI BASIN TO EAST COAST FORE-ARC

WANGANUI TO MT STEWART

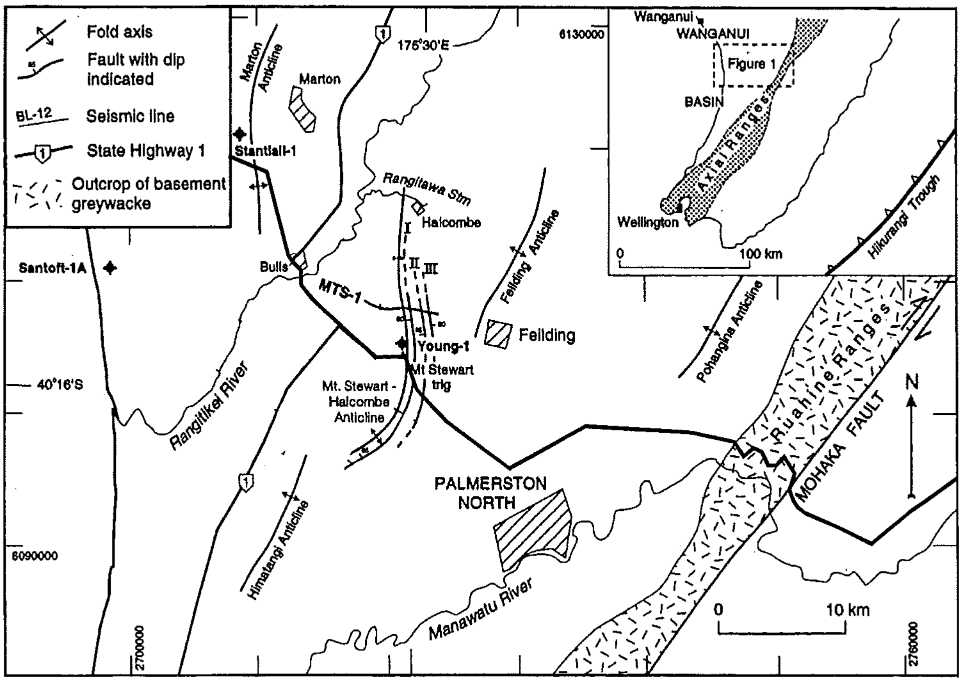
The tour travels east towards the axial ranges. Several large rivers that drain the central highlands of the North Island are crossed, including the Whangaehu River that drains Crater Lake on Mt Ruapehu. During eruptions lahars from Crater Lake flood down the river. The worst railway disaster in New Zealand's history occurred on Christmas Eve 1953 when the Wellington-Auckland night express plunged into the lahar flooded Whangaehu River at Tangiwai, 8 km west of Waiouru. Of the 285 people on board, 151 were killed.

Fallen bridge span and locomotive, 25 December 1953
(AAVK W3493, Archives New Zealand)

STOP MT STEWART

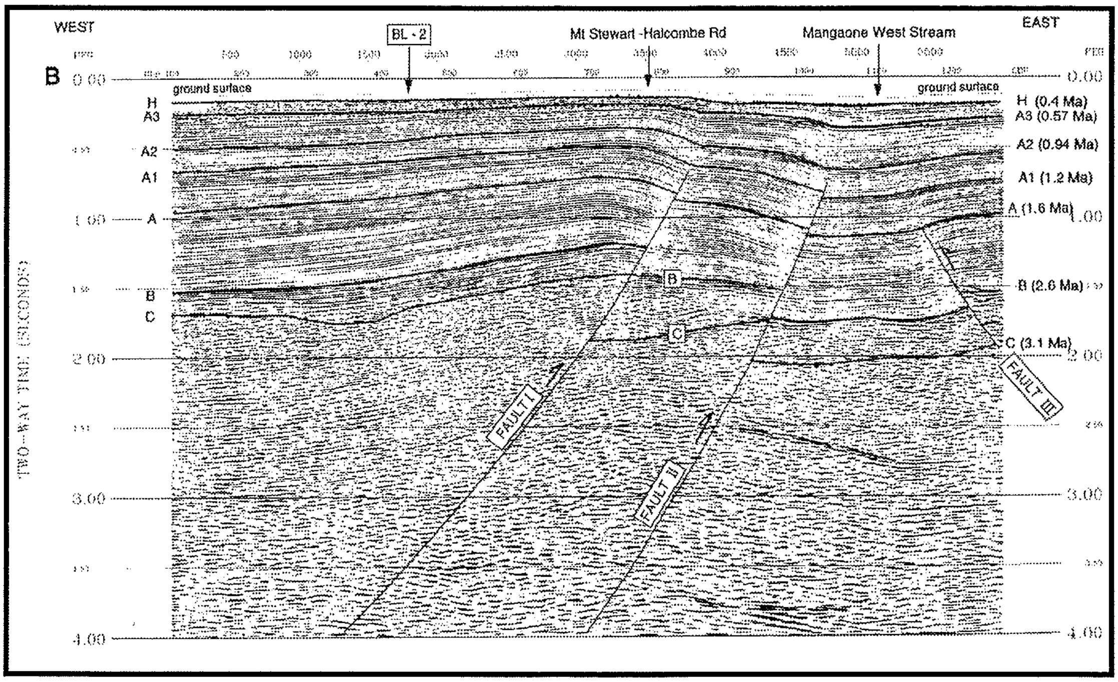
The Mt Stewart-Halcombe Anticline is a growing fold which started to form about 3 Ma. Melhuish et al. (1996) showed that the anticline is asymmetric and controlled by two reverse faults. The two planar faults, I and II, dip at 60-65° west, and appear to have predominantly dip-slip displacement.

The anticline is at least 25 km in length and continues as a subsurface feature to the south of its area of topographic expression between Mount Stewart and Halcombe. The anticlinal trace and its controlling faults curve from a northerly trend at the location of the seismic line MTS-1 to a more ENE trend farther south.



Location Map of Mt Stewart and seismic line MTS-1 (from Melhuish et al., 1996)

Dip-slip displacement rates on the two west dipping faults are between 0.1 and 0.2 mm/yr. These rates are low by comparison to structures in the forearc region, but are consistent with low strains that are generally observed in the western North Island.



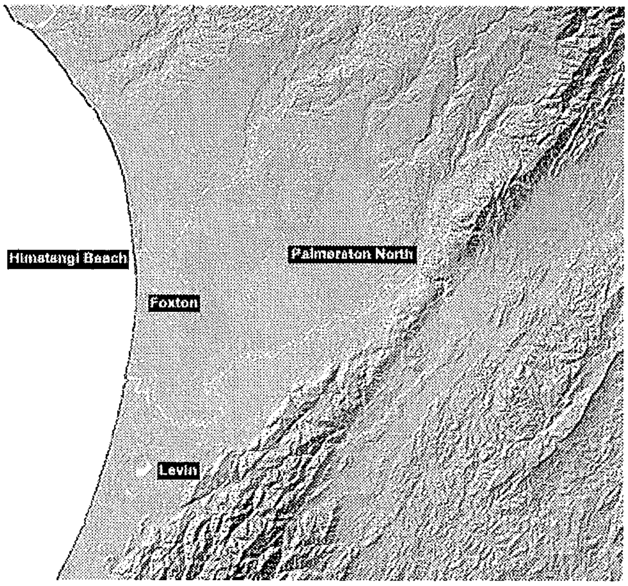
Migrated section of seismic line MTS-1 with interpretation. Zones of reflections at 2.5 and 4s TWT east of Fault II are probably out of plane of the seismic section (Melhuish et al. 1996).

MT STEWART TO SADDLE RD

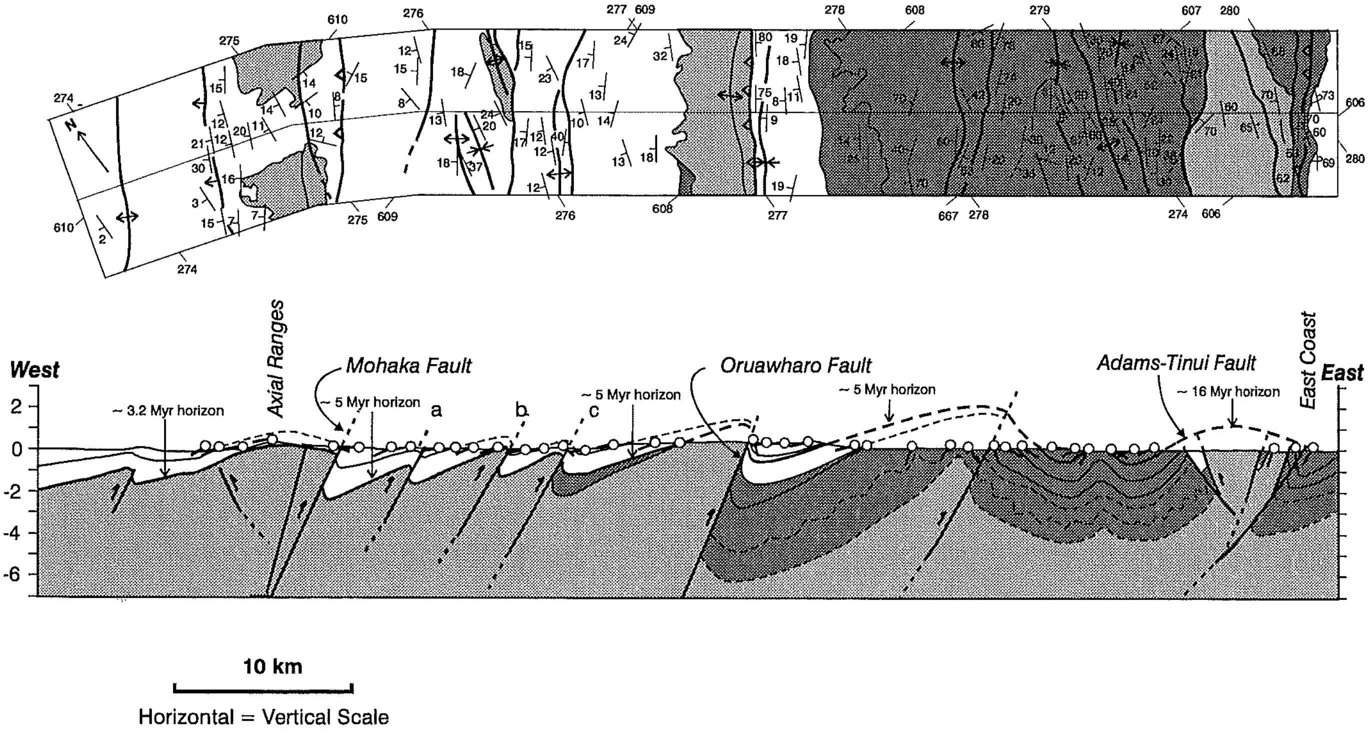
The route travels down the eastern side of Mt Stewart and past Bunnythorpe, a major switching sub-station on the national power grid, to the small rural town of Ashurst. From Ashurst we ascend the Ruahine Ranges along Saddle Rd. The Tararua wind farm (40 MW) can be seen on the hills to the southeast.

Tararua Wind Farm

SADDLE RD



Saddle Road crosses the Axial Ranges at their lowest point within the central North Island. On a good day this stop provides a view of the relatively low strain region in the Wanganui and Taranaki basins to the west with the higher strain inner forearc region to the east. The location of the high-strain zone is approximately coincident with the down-dip end of the locked plate interface, as inferred from GPS data. The low strains observed in the geological record of the overriding plate suggest that locking of the plate interface is an interseismic phenomena with slip on the subduction thrust occurring during large magnitude earthquakes. The concentration of high strains in the geological record may reflect preferential loading of faults above the down-dip end of the interseismically locked plate interface which ultimately triggers slip and leads to the accommodation of relatively high permanent strains at this location in the overriding plate.



Map and cross-section constructed from outcrop data through East Coast fore-arc Tadpoles on cross section indicate bed dips in the plane of the section. Ornamentation in map and cross section indicate distribution of Torlesse basement (light grey), sedimentary rocks of Cretaceous to Miocene in age (dark grey) and Pliocene to Quaternary strata (white) (from Nicol and Beaven in prep).

Cumulative shortening compiled from west to east along the profile. Filled circles are for c. 2.5 Ma horizon and open circles are for c. 5 Ma horizon. Regions dominated by margin-normal shortening and extension are indicated at the top of the diagram. Bin size ranges from 10 to 100 km and errors are cumulative (from Nicol and Beaven in prep).

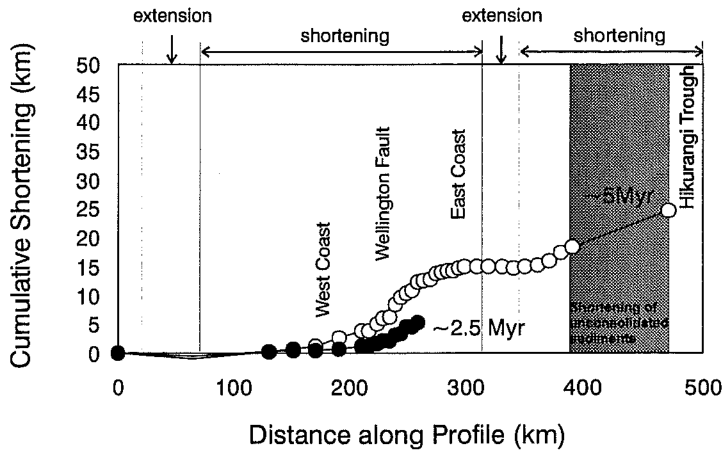
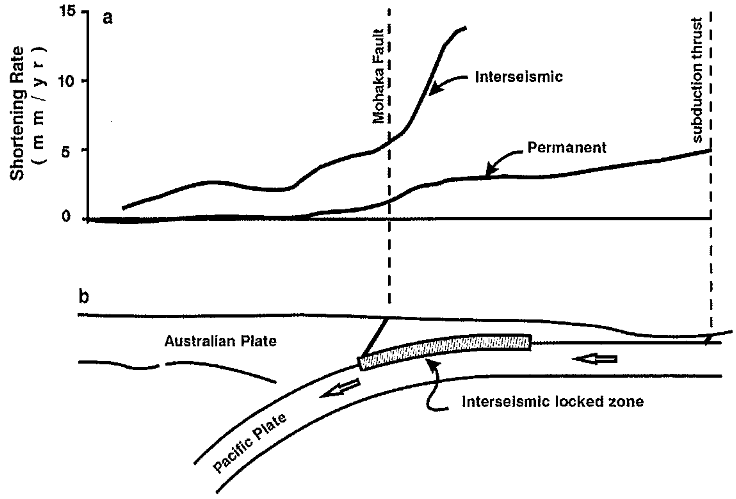
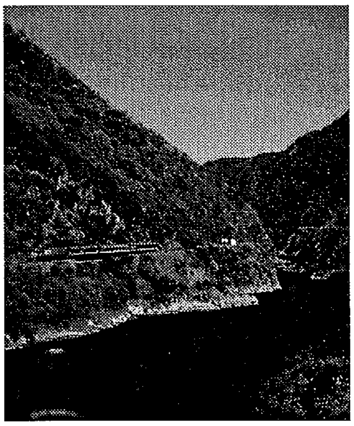


Diagram showing profiles of cumulative shortening rates (in mm/yr) from geological and GPS data across the central Hikurangi margin. b) Plate boundary cross section indicating the location of the inferred interseismic locked zone relative to the Mohaka Fault and the high strain zone in the overriding plate (from Nicol and Beaven in prep).



The Saddle Road area is the only location where Tertiary sedimentary strata can be traced across the Axial Ranges. Here Pliocene-Pleistocene strata rest on greywacke basement rocks and indicate the presence of an anticline, the hinge of which coincides approximately with the range crest. At the highest point on Saddle Rd marginal marine siltstones and conglomerates crop out and range in age from ca. 2.5-3.0 Ma.

In contrast, south of the Manawatu Gorge at the wind farm non-marine conglomerates of about 1 Ma in age rest directly on basement (i.e. older Pliocene strata were removed prior to deposition of this unit). These observations together with the apparent uniformity in the thickness of ca. 2.5-3.0 Ma strata across Saddle Rd suggest that the most recent period of accelerated uplift of the ranges probably commenced between 1 and 2.5 Ma (Beanland, 1995). This timing is consistent with the onset of the influx of basement detritus into basins east of the ranges (Melhuish, 1990, Nicol et al. 2002).



Manawatu Gorge

The presence of non-marine conglomerates high up on the ranges suggests that a river(s) once flowed across the ranges at the wind farm. The difference in altitude between non-marine river-deposited conglomerates on the top of the range and the active bed of the Manawatu River in the gorge is inferred to principally reflect uplift of the ranges in the last 1 Myr. First order estimates suggest that the ranges at Saddle Rd experienced uplift rates of about 0.5-1 mm/yr over the last 1-2 Myr. Debate continues as to whether uplift is occurring today.

SADDLE RD TO LAKE POUKAWA

From Saddle Road the route descends the Ruahine Ranges and enters the East Coast Basin. We travel north through rolling farm country with the Axial Ranges on the left (west).

STOP **NORSEWOOD** - a small rural town for lunch.

East Coast Basin – Background Information

The East Coast Basin covers both the onshore and offshore area (c. 75,000 km^2) along the eastern side of the North Island and the northeastern part of the South Island. The northern boundary is arbitrarily defined as lying north of East Cape. The western boundary is the axial ranges of the North Island and the Wairau Fault in the South Island where Mesozoic basement is exposed or sediments are thin. The southern and eastern boundaries of the East Coast Basin are at the Hikurangi Trough, although sedimentary cover extends unbroken onto the Chatham Rise.

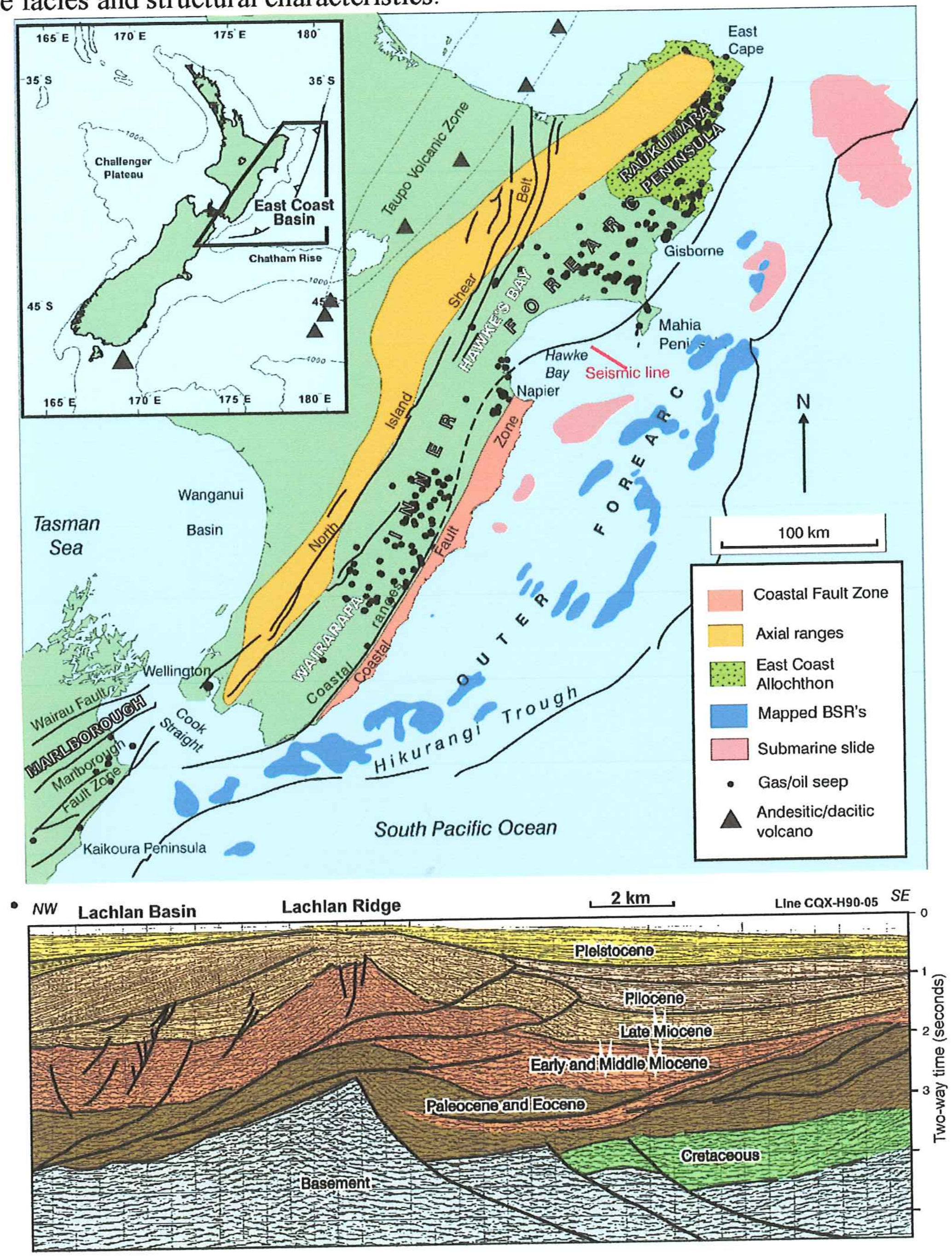
The geological history of the East Coast Basin is not yet fully understood and some tectonic interpretations remain controversial (Field et al., 1996, Mazengarb & Harris, 1994). For at least a part of the Early Cretaceous, the area was a convergent margin on the northeastern edge of Gondwanaland, but by the latest Cretaceous, when rifting and spreading in the Tasman Sea was occurring, the East Coast Basin was a passive margin. Throughout the Paleogene there was gradual regional subsidence and slow sedimentation, reflecting the post-rift foundering of the New Zealand region.

In the Early Miocene, deformation and sedimentation patterns changed markedly when subduction began in northern New Zealand. Oblique convergence of the Pacific and Australian plates resulted in more than 1,000 km of lithosphere being subducted in the north, while to the south, where strike-slip motion predominated, there has been little or none subducted. During the Neogene the northern part of the East Coast Basin became a classic forearc basin with subsidence and deposition occurring between the subduction trench (the Hikurangi Trough) in the east and a volcanic arc (the TVZ) in the west.

In the north, the onset of subduction was accompanied by obduction of the East Coast Allochthon. South of the allochthon subduction induced compression formed structures that trend approximately parallel to the present day plate boundary, with uplift, thrusting, oblique-slip and normal faulting occurring at various times during the Neogene.

Basin structure

The East Coast Basin is structurally complex. There are two main structural belts; The western belt, or inner forearc, comprises most of the onshore part of the basin (Beanland et al., 1998), while the eastern belt, or outer forearc, includes the coastal areas of the North Island and most of the offshore parts of the basin (Lewis & Petinga, 1993). In Wairarapa and southern Hawke's Bay, the boundary between the inner fore-arc and the outer fore-arc is along a range of hills (the Coastal ranges) where Cretaceous basement greywacke crops out. The structural belts are further subdivided into separate structural blocks based on distinct pre-Neogene facies and structural characteristics.



Location map of East Coast and offshore seismic line from Hawke Bay showing the typical reverse faulting and imbricate thrust wedge structure of the region (adapted from Field et al., 1997).

The outer fore-arc is primarily an imbricate thrust wedge with predominantly east-verging low-angle thrust faults. Late Miocene to Recent deformation is characterised by normal faulting and large-scale gravity collapse toward the trench north of Hawke Bay. In areas to the south, the orientation of faults and folds is much more variable but are generally parallel to the plate boundary. Diapiric processes have also influenced the formation of some Neogene structures. Footwalls of some normal faults are upturned by the intrusion of diapiric muds and shale, and are often associated with seeps of oil, gas, and hot water. The East Coast is one of New Zealand's most seismically active areas and several major earthquakes have been recorded in the last 200 years.

Stratigraphy

Basement consists of weakly metamorphosed Triassic to Early Cretaceous greywacke sandstone and mudstone of the Torlesse Terrane. The overlying mid-Cretaceous and younger stratigraphy is almost solely described from onshore outcrop and consists of three major elements:

1. Cretaceous rocks ranging from paralic sandstones to bathyal mudstones, deposited in a variety of compressional and extensional tectonc settings prior to and during rifting associated with the break-up of Gondwanaland and Tasman Sea spreading. Mid- and Late Cretaceous stratigraphic thicknesses of c. 3000 m have been measured in many places.

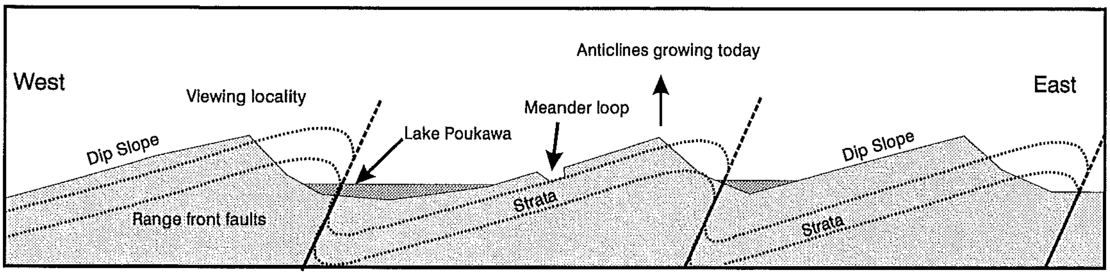
2. Latest Cretaceous and Paleogene rocks, mainly mudstone and micritic limestone, deposited at a passive margin. Late Cretaceous and Paleogene sedimentation rates were low throughout the East Coast Basin, and this part of the sedimentary succession is typically less than 1000 m thick.

3. Miocene to Recent rocks dominated by bathyal flysch and mudstone, with intercalated neritic sands and limestones. The maximum known thickness of these strata is more than 5000 m.

STOP LAKE POUKAWA

The Poukawa Depression lies at the southern end of the c. 15 km long, surface rupture of the 1931 Napier earthquake. One of the Poukawa faults experienced slip during the 1931 earthquake, and the steep-sided scarps visible at the base of the escarpment northwest of Mahanga Road, are features of that event.

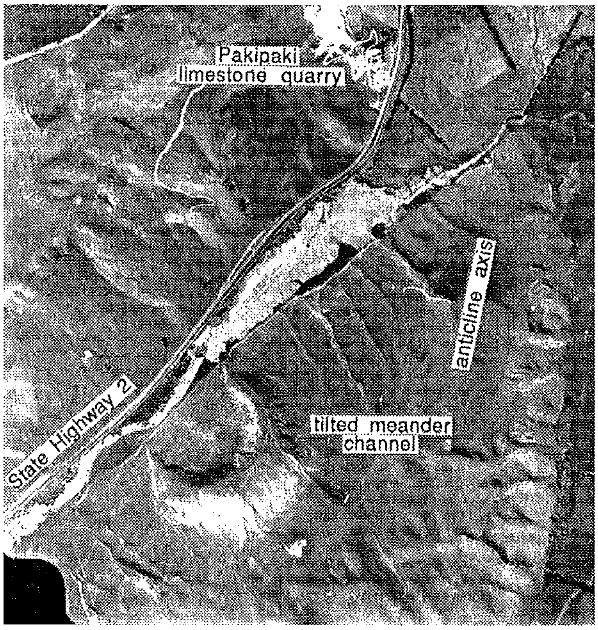
The Poukawa Depression represents an elongate basin that has formed between ridges capped by Plio-Pleistocene (3 – 1 Ma) shelf limestones. There is no evidence that a major river has ever flowed through this depression, so the basin presumably has evolved as a result of folding and uplift on northeast-striking thrust and oblique-thrust faults. Faults are believed to accommodate oblique strike-slip displacement beneath the basin, and studies of tephra and peat layers offset within the depression indicate progressive vertical displacements during the last 7000 radiocarbon years, with average return periods of 500-1500 years (Froggatt & Howorth, 1980).



Cartoon showing the location of actively growing anticlines and faults seen in the Lake Poukawa area.

TILTED MEANDER LOOP

Spectacular evidence of recent deformation in the Lake Poukawa area is preserved as an uplifted and tilted meander loop of the ancestral Poukawa Stream, located on an actively growing anticline at Pakipaki. Limestone of Pliocene age (5 - 1.6 Ma) dips 22 – 25° NW in the west limb of the fold, while the floor of the ancestral channel dips 6 – 8° NW. The age of the meander loop is unknown, but the loop is related to the present drainage pattern and presumably is not older than the latest Pleistocene (< 0.5 Ma).



TE MATA ESTATE WINERY

Te Mata Estate Winery originated as part of Te Mata Station, a large pastoral land holding established by English immigrant John Chambers in 1854. His third son, Bernard, planted vines in 1892. Wine was made from those grapes in 1896, establishing Te Mata Estate as the first winery in New Zealand to make a century. By 1909, 17 hectares of vines were being cultivated and in that year 55,000 litres of 'claret, hock and madeira' were made.

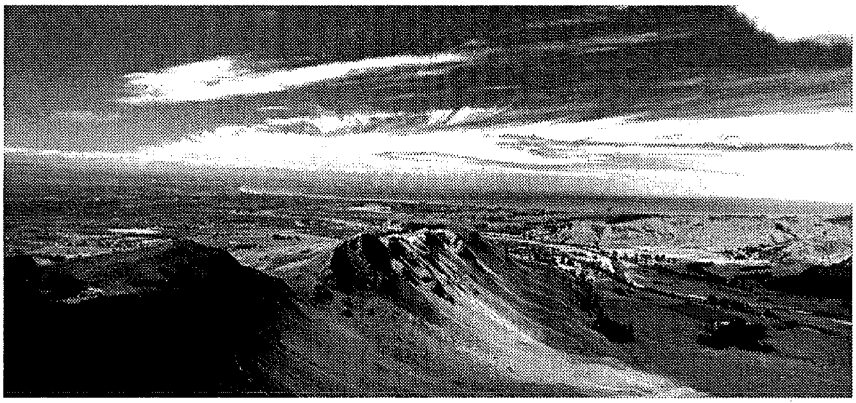
The property had various owners from 1919 until it was acquired by the current owners in 1978. Both vineyards and winery were run down, although still making wine. A twenty year development programme was commenced, beginning with a restoration and re-equipping of the original building. All the original vineyards were replanted and viticulture underwent a further detailed review in 1989. The winemaking policy is producing small lots of high-quality wine. Te Mata Estate currently produces 25,000 cases of wine and is at full production. Sixty percent of this is red. Another feature of Te Mata Estate is its architecture.

Apart from the restored original building the rest of the premises have been progressively built since 1987.

STOP TE MATA PEAK – OPTIONAL

The Te Mata Peak lies above the fertile Heretaunga plains of Hawkes Bay, standing 399 metres above sea level. It is an east verging anticlinal fold with outcropping Pliocene – Pleistocene limestone . On a clear day from the lookout at the summit, the Ruahine, Kaweka and Maungaharuru ranges form the western horizon, with the volcano Ruapehu visible in the distance. Beyond the sweep of mountains and across the curve of Hawke Bay, Mahia Peninsula and Portland Island jut into the Pacific. Southwards lie the coastal hills, while meandering across the plains flow the Tutaekuri and Ngaruroro rivers, and around the base of the Peak, the Tukituki valley.

Prior to European times, vegetation in the park was fire-induced bracken and manuka with native grasses in clearings. Today the predominant vegetation is short tussock grassland with a wide variety of introduced trees and shrubs in the valleys and on the lower ridges. Since 1927, thousands of native and exotic trees and shrubs have been planted throughout the area.



The Legend of Te Mata

Legend has it that the hill is the body of Maori Chief, Te Mata 0 Rongokako (the face of Rongokako). Looking from Hastings, the gargantuan bite can be seen, as can the body of the powerful Chief forming the skyline. Many centuries ago the people living in pa (fortified villages) on the Heretaunga Plains were under constant threat of war from the coastal tribes of Waimarama. At a gathering at Pakipaki (5km south of Hastings) to discuss the problem, the solution came when a wise old woman (kuia) sought permission to speak in the marae. "He ai na te wahine, ka horahia te po, " she said. (The ways of a woman can sometimes overcome the effects of darkness). Hinerakau, the beautiful daughter of a Pakipaki chief, was to be the focal point of a plan. She would get the leader of the Waimarama tribes, a giant named Te Mata, to fall in love with her, turning his thoughts from war into peace. The plan succeeded, but she too fell in love.

The people of Heretaunga, however, had not forgotten the past and with revenge the motive, demanded that Hinerakau make Te Mata prove his devotion by accomplishing seemingly impossible tasks. The last was to bite his way through the hills between the coast and the plains so that people could come and go with greater ease. Te Mata died proving his love and today his half-accomplished work can be seen in the hills in what is known as The Gap or Pari Karangaranga (echoing cliffs).

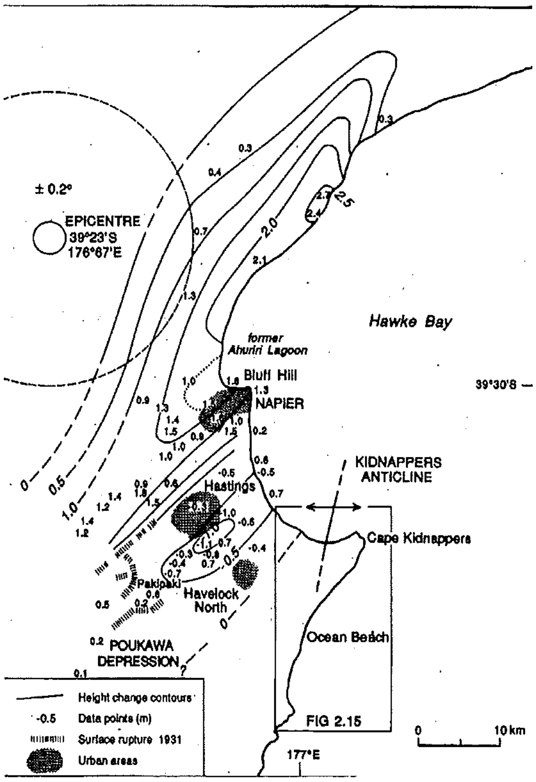
His prostrate body forms Te Mata Peak, the legend says. At sunset one can often see, in the mists which stretch from the crown of Kahuraanake, the beautiful blue cloak with which the grieving Hinerakau covered the body of her husband before leaping to her own death from the precipice on the Waimarama side of the peak. The gully at the base of the cliff was formed when her body struck the earth.

1931 Napier Earthquake – Background Information

At 10.47 am on 3 February 1931 local time (2 Feb, 22h 46m UT), a large (M_S=7.8) earthquake struck Hawkes's Bay and was felt throughout most of New Zealand. Within minutes, the business districts of Napier and Hastings lay in ruins and were engulfed by fire. The death toll of 256, mostly in Napier and Hastings, makes this earthquake New Zealand's greatest disaster.

Bullen (1938) judged the earthquake to have been a multiple event, comprising the initial shock, followed by two large events, 6 seconds and 14 seconds later. There were no major foreshocks, and no earthquakes had been felt at Napier for 30 days prior to the February 2 shock (Adams et al., 1933). Bullen (1938) located the earthquake at 39.33^{o}S, 176.67^{o} E ($\pm 0.2^{o}$), 32-km northwest of Napier.

The earthquake had a focal depth between 15-20 km and a surface wave magnitude of 7.8 (Smith, 1978). Aftershocks continued throughout 1931, the largest being Ms 7.3 event on February 13, which appeared to have a similar epicentre but shallower focus than the mainshock (Bullen, 1938).

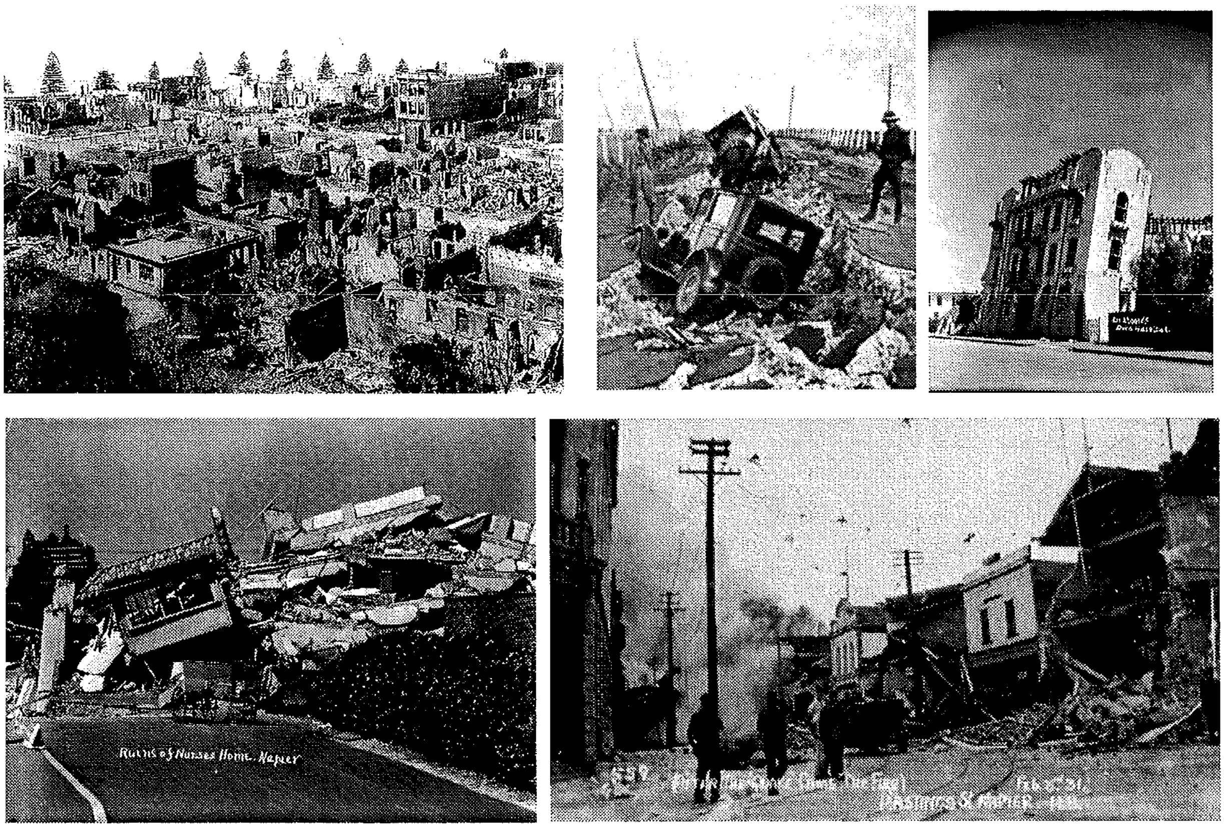


Post earthquake geological investigations and re-levelling of the Wellington-Gisborne railway, revealed uplift of a >90 km long, 17 km wide asymmetric dome, from southwest of Hastings to northeast of the Mohaka River mouth, and a total of 15 km of surface rupture on several faults at the southwestern end of the dome (Henderson,1933; Hull, 1990).

Coseismic slip was probably in the order of 6-8 m dip-slip and a 4-8 m strike-slip, but after 60 years, only the uplift of Napier's former harbour-Ahuriri Lagoon-remains well preserved in the geological record. Present geological techniques for recognising prehistoric earthquakes would therefore fail to identify the magnitude of deformation associated with this event (Hull 1990).

Fault modelling from the observed elevation changes and retriangulation data suggest that the 1931 earthquake occurred on a dextral-reverse fault that dips steeply to the northwest (Haines & Darby, 1987), within sediments of the accretionary plain beneath Hawke's Bay. Their work suggests that the rupture probably extended upward from the subducted plate interface into sediments of the accretionary prism, but without involving rupture of the interface itself, which is about 20 km beneath the region (Reyners, 1980).

During our visit to Hawke's Bay we will examine some of the geological effects of the 1931 earthquake, and consider its role in accommodating plate motion across eastern North Island. Other localities will provide evidence of cumulative deformation that has occurred across the forearc, throughout the late Pleistocene and Holocene.



1931 Napier Earthquake damage

STOP NAPIER

Day ends at Napier with dinner at Brookfields Vineyards.

DAY FOUR: NAPIER TO TAUPO – EAST COAST FORE-ARC TO TVZ

NAPIER TO TAUPO

The route to Taupo passes Napier Airport, which lies on land uplifted during the 1931 Napier Earthquake. We then turn inland where the road climbs up towards the axial ranges. Farm and forestry land dominates this area.

Land rose by over 1 metre in the Napier estuary

TE POHUE – VIEW OF FOREARC ACROSS HAWKES BAY

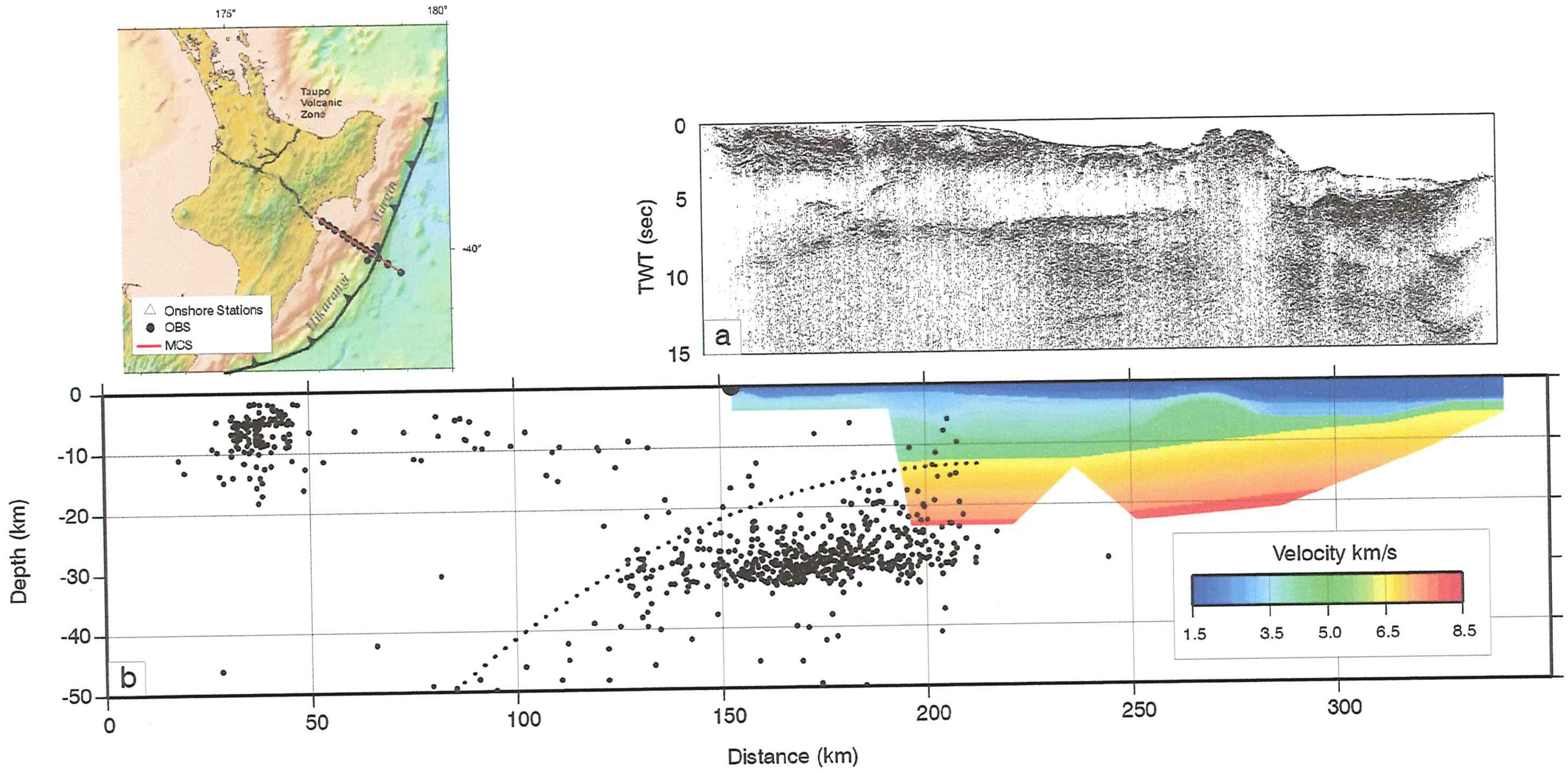
Weather permitting, this road-side stop on the Napier-Taupo Highway provides a panoramic view, southeast across the landscape of the fore-arc. Strata underlying the hill country in the foreground and middle-distance are late Pliocene to Pleistocene (3-1 Ma) marine siltstones and shelf limestones.

NIGHT SURVEY

During January and February 2001 and again in December of the same year a combined near-vertical and wide-angle active source experiment NIGHT (North Island GeopHysical, Transect) was designed to compliment the passive CNISPE deployment of the central North Island. The aim was to provide data that would allow detailed velocity and upper crustal structure to be evaluated. NIGHT involved scientists from Institute of Geological & Nuclear Sciences, Victoria University of Wellington, Cambridge University (UK) and Hokkaido University.

The land refraction profile involved 14 explosive shots, each 500 kg, recorded at 200 one-to-three component stations in two deployments across the central North Island and NE-SW along the Taupo Volcanic region. For the wide-angle onshore/offshore experiment 200 land and 15 OBS receiver sites were distributed along the central transect. The value of a combined passive and active experiment meant that the airgun shots were also recorded on the short period and broadband recorders that were installed for CNIPSE.

Similarly the one month deployment of the OBS instruments allowed a number of local earthquake events to be recorded. The *M/V Geco Resolution* collected 300 km of MCS data using a 8200 in^3 airgun and 6000 km-long active 480-channel streamer. Shot spacing was 100 m and record length was 20 s. The airgun array and streamer depth was tuned to maximise energy in the range 10 to 100 Hz. The near-field airgun signal was also recorded for each shot to be used later in signature deconvolution.



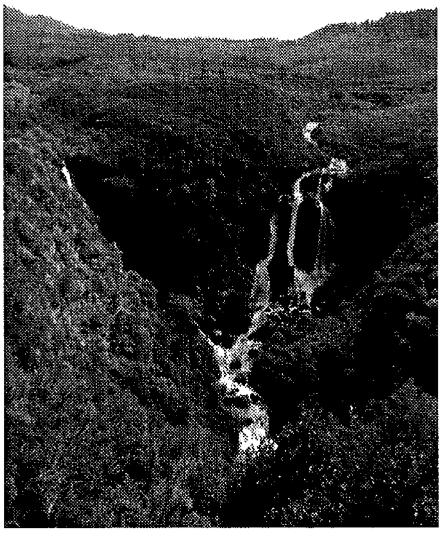
The composite section along the North Island GeopHysical Transect (NIGHT). (A) Migrated stack of offshore MCS line. The prominent lower crustal reflector that can be traced the length of the profile is the top of the subducted Pacific plate. (B) circles are earthquakes that occurred within or close to the CNIPSE network during the period January 08 – June 27, 2001. The dash line is the inferred Benioff Zone defining the top of the subducted plate. The preliminary velocity model is determined from first arrival tomography of OBS data (From Henrys pers. com., 2002).

TE POHUE TO TAUPO

From Te Pohue we travel west across the North Island axial ranges to Taupo. We descend to cross the Mohaka River, and then ascend into the ranges. Views include spectacular scenery and highland native bush. Basement greywacke rocks outcrop in many of the road cuttings, but from Waipunga Falls to Taupo, the route is over the ignimbrite covered Rangataiki plains.

STOP WAIPUNGA FALLS

At Waipunga Falls the Waipunga River cascades over the edge of the Rangataiki ignimbrite. This is close the eastern extent of welded ignimbrites that originate from the TVZ, although thick unwelded ash and air-fall volcanic material is found much further east. Basement greywacke is found close to the foot of the falls and the contact can be observed in a road cutting nearby.



STOP TAUPO

Trip ends In Taupo.

Abbott, S.T.; Carter, R.M. 1994: The sequence architecture of mid-Pleistocene (c.1.1-0.4 Ma) cyclothems from New Zealand : facies development during a period of orbital control on sea-level cyclicity. *In* Orbital forcing and cyclic sequences. Pp. 367-394.

Adams, C.E.; Barnett, M.A.F.; Hayes, R.C. 1933: Seismological report of the Hawke's Bay earthquake of 3rd February 1931. *New Zealand Journal of Science and Technology 15*: 93-107.

Alloway, B.; Neall, V.E.; Vucetich, C.G. 1995: Late Quaternary (post 28,000 year B.P.) tephrostratigraphy of northeast and central Taranaki, New Zealand. *Journal of the Royal Society of New Zealand 25(4)*: 385-458.

Alloway, B.V. 1989: Late Quaternary cover bed stratigraphy and tephrochronology of north-eastern and central Taranaki, New Zealand. Ph.D thesis, Massey University, Palmerston North.

Anderson, H.J.; Smith, E.G.C.; Robinson, R. 1990: Normal faulting in a back-arc basin : seismological characteristics of the March 2 1987, Edgecumbe, New Zealand, earthquake. *Journal of geophysical research. B 95(B4)*: 4709-4723.

Ansell, J.H.; Bannister, S.C. 1996: Shallow morphology of the subducted Pacific Plate along the Hikurangi margin, New Zealand. *Physics of the earth and planetary interiors 93*: 3-20.

Armstrong, P.A.; Allis, R.G.; Funnell, R.H.; Chapman, D.S. 1998: Late Neogene exhumation patterns in Taranaki Basin (New Zealand) : evidence from offset porosity-depth trends. *Journal of geophysical research. Solid earth 103(B12)*: 30269-30282.

Banwell, C.J.; Macdonald, W.J.P. 1965: Resistivity surveying in New Zealand thermal areas. *In* 8. Commonwealth Mining and Metallurgical Congress, Australia and New Zealand ; Australia and New Zealand ; 1965. Pp. Paper 213:1-8.

Barnes, P.M.; de Lepinay, B.M. 1997: Rates and mechanics of rapid frontal accretion along the very obliquely convergent southern Hikurangi margin, New Zealand. *Journal of geophysical research. Solid earth 102 (B11)*: 24931-24952.

Beanland, S. 1987: Ruahine Fault reconnaissance. *New Zealand Geological Survey report EDS 109*. Lower Hutt, New Zealand Geological Survey. 15 p. p.

Beanland, S. 1995: The North Island dextral fault belt, Hikurangi subduction margin, New Zealand. Unpublished PhD thesis, Victoria University of Wellington, New Zealand.

Beanland, S.; Melhuish, A.; Nicol, A.; Ravens, J.M. 1998: Structure and deformational history of the inner forearc region, Hikurangi subduction margin, New Zealand. *New Zealand journal of geology and geophysics 41(4)*: 325-342.

Beavan, R.J.; Haines, J. 2001: Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand. *Journal of geophysical research. Solid earth 106(B1)*: 741-770.

Bibby, H.M. 1981: Geodetically determined strain across the southern end of the Tonga-Kermadec-Hikurangi subduction zone. *Geophysical journal of the Royal Astronomical Society 66(3)*: 513-533.

Bibby, H.M.; Caldwell, T.G.; Davey, F.J.; Webb, T.H. 1995: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *Journal of volcanology and geothermal research 68*: 29-58.

Bibby, H.M.; Caldwell, T.G.; Risk, G.F. 1998: Electrical resistivity image of the upper crust within the Taupo Volcanic Zone, New Zealand. *Journal of geophysical research. Solid earth 103(B5)*: 9665-9680.

Bullen, K.E. 1938: An analysis of the Hawke's Bay earthquakes during February 1931. *New Zealand Journal of Science and Technology 19*: 497-519.

Cashman, S.M.; Kelsey, H.M.; Erdman, C.F.; Cutten, H.N.C.; Berryman, K.R. 1992: Strain partitioning between structural domains in the forearc of the Hikurangi Subduction Zone, New Zealand. *Tectonics 11(2)*: 242-257.

Davey, F.J.; Stern, T.A. 1990: Crustal seismic observations across the convergent plate boundary, North Island, New Zealand. *Tectonophysics 173*: 283-296.

DeMets, C.; Gordon, R.G.; Argus, D.F.; Stein, S. 1994: Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters 21*: 2191-2194.

Erdman, C.F.; Kelsey, H.M. 1992: Pliocene and Pleistocene stratigraphy and tectonics, Ohara Depression and Wakarara Range, North Island, New Zealand. *New Zealand journal of geology and geophysics 35(2)*: 177-192.

Field, B.D.; Uruski, C.I.; al, e. 1997: Cretaceous-Cenozoic geology and petroleum systems of the East Coast region, New Zealand. *Institute of Geological & Nuclear Sciences monograph 19*. Lower Hutt, Institute of Geological & Nuclear Sciences. 2 v. p.

Fleming, C.A. 1953: The geology of Wanganui subdivision ; Waverley and Wanganui sheet districts (N137 and N138). *New Zealand Geological Survey bulletin 52*: 372 p.

Froggatt, P.C.; Howorth, R. 1980: Uniformity of vertical faulting for the last 7000 years at Lake Poukawa, Hawke's Bay, New Zealand. *New Zealand journal of geology and geophysics 23(4)*: 493-497.

Haines, A.J.; Darby, D.J. 1987: Preliminary dislocation models for the 1931 Napier and 1932 Wairoa earthquakes. *New Zealand Geological Survey report EDS 114* . Lower Hutt, New Zealand Geological Survey. 64 p. p.

Hay, R.F. 1967: Taranaki. Scale 1:250,000. *Geological Map of New Zealand 1:250,000 7*. Wellington, DSIR. p.

Henderson, J. 1933: The geological aspects of the Hawke's Bay earthquakes [New Zealand], February 3, 1931]. *New Zealand Journal of Science 15*: 38-75.

Hochstein, M.P. Geothermal prospects of Sumatra (overview) *In ed.* Proceedings 13th Geothermal Workshop 1991, University of Auckland, 1991. Pp. 219-222.

Hochstein, M.P.; Smith, I.E.M.; Regenauer-Lieb, K.; Ehara, S. 1993: Geochemistry and heat transfer processes in Quaternary rhyolitic systems of the Taupo Volcanic Zone, New Zealand. *Tectonophysics 223(3/4)*: 213-235.

Hochstetter, F.v. 1959: Geology of New Zealand; contributions to the geology of the provinces of Auckland and Nelson. : 320.

Holt, W.E.; Stern, T.A. 1994: Subduction, platform subsidence, and foreland thrust loading : the late Tertiary development of Taranaki Basin, New Zealand. *Tectonics 13(5)*: 1068-1092.

Hull, A.G. 1990: Tectonics of the 1931 Hawke's Bay earthquake. *New Zealand journal of geology and geophysics 33(2)*: 309-320.

King, P.R. 2000: Tectonic reconstructions of New Zealand 40 Ma to the present. *New Zealand journal of geology and geophysics 43(4)*: 611-638.

King, P.R.; Browne, G.H.; Arnot, M. 2002: Miocene Slope-to-Basin Floor sequences exposed in North Taranaki, New Zealand. Field Trip Guide, Institute of Geological & Nuclear Sciences, Wellington.

King, P.R.; Thrasher, G.P. 1992: Post-Eocene development of the Taranaki Basin, New Zealand : convergent overprint of a passive margin. *In* Geology and geophysics of continental margins. Pp. 93-118.

King, P.R.; Thrasher, G.P. 1996: Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological & Nuclear Sciences monograph 13*. Lower Hutt, Institute of Geological & Nuclear Sciences. 243 p. p.

Lamb, S.H.; Bibby, H.M. 1989: The last 25 Ma of rotational deformation in part of the New Zealand plate-boundary zone. *Journal of structural geology 11(4)*: 473-492.

Lewis, K.B.; Pettinga, J.R. 1993: The emerging, imbricate frontal wedge of the Hikurangi Margin. *In* South Pacific sedimentary basins. Pp. 225-250.

Lloyd, E.F. 1972: Geology and hot springs of Orakeikorako. *New Zealand Geological Survey bulletin 85*. Wellington, Department of Scientific and Industrial Research. 164 p. p.

Mazengarb, C.; Harris, D.H.M. 1994: Cretaceous stratigraphic and structural relations of Raukumara Peninsula, New Zealand : stratigraphic patterns associated with the migration of a thrust system. *Annales Tectonicae 8(2)*: 100-108.

Melhuish, A. 1990: Late Cenozoic deformation along the Pacific-Australian plate margin, Dannevirke region, New Zealand. Unpublished M.Sc thesis, Victoria University of Wellington, New Zealand.

Melhuish, A.; Van Dissen, R.; Berryman, K. 1996: Mount Stewart-Halcombe Anticline : a look inside a growing fold in the Manawatu region, New Zealand. *New Zealand journal of geology and geophysics 39(1)*: 123-133.

Mills, C. 1990: Gravity expression of the Patea-Tongaporutu High and subsequent model for the Taranaki Basin margin. *In* New Zealand Oil Exploration Conference (1989 : Queenstown, NZ). Pp. 191-200.

Mortimer, N. New Zealand's geological foundations. *In ed.* Proceedings of the 11th International Gondwana Symposium, , 2002 (submitted). *Gondwana Research special issue*, .

Nairn, I.A. 1989: Mount Tarawera: sheet V16 AC. *Geological Map of New Zealand 1:50,000* Lower Hutt, New Zealand Geological Survey. 1 map and notes 55 p. p.

Nairn, I.A.; Wood, C.P.; Bailey, R.A. 1994: The Reporoa Caldera, Taupo Volcanic Zone : source of the Kaingaroa Ignimbrites. *Bulletin of volcanology 56*: 529-537.

Naish, T.R.; Abbott, S.T.; Alloway, B.V.; Beu, A.G.; Carter, R.M.; Edwards, A.R.; Journeaux, T.D.; Kamp, P.J.J.; Pillans, B.J.; Saul, G.; Woolfe, K.J. 1998: Astronomical calibration of a Southern Hemisphere Plio-Pleistocene reference section, Wanganui Basin, New Zealand. *Quaternary science reviews 17(8)*: 695-710.

Naish, T.R.; Kamp, P.J.J. 1997: High-resolution sequence stratigraphy of 6th order (40 ka) Plio-Pleistocene cyclothems, Wanganui Basin, New Zealand: A case for the regressive systems tract. *Geological Society of America Bulletin 109*: 978-999.

Nelson, C.S.; Kamp, P.J.J.; Young, H.R. 1994: Sedimentology and petrography of mass - emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand journal of geology and geophysics 37(3)*: 269-285.

Thrasher, G.P. 1992: Late Cretaceous geology of Taranaki Basin, New Zealand. G.P. Thrasher, Wellington.

Villamor, P.; Berryman, K.R. 2001: A Late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data. *New Zealand journal of geology and geophysics 44(2)*: 243-269.

Voggenreiter, W.R. 1993: Structure and evolution of the Kapuni Anticline, Taranaki Basin, New Zealand : evidence from the Kapuni 3D seismic survey. *New Zealand journal of geology and geophysics 36(1)*: 77-94.

Walcott, R.I. 1978: Present tectonics and Late Cenozoic evolution of New Zealand. *Geophysical journal of the Royal Astronomical Society 52(1)*: 137-164.

Walcott, R.I. 1979: Plate motion and shear strain rates in the vicinity of the Southern Alps. *In* The origin of the Southern Alps. Pp. 5-12.

Walcott, R.I. 1987: Geodetic strain and the deformational history of the North Island of New Zealand during the late Cainozoic. *Philosophical Transcations of the Royal Society of London A321*: 163-181.

Wellman, H.W. 1979: An uplift map for the South Island of New Zealand and a model for uplift of the Southern Alps. *In* The origin of the Southern Alps. Pp. 13-20.

Wilson, C.J.N. 1996: Taupo's atypical arc. *Nature 379*: 27-28.

Wilson, C.J.N. 2001: The 26.5 ka Oruanui eruption, New Zealand : an introduction and overview. *Journal of volcanology and geothermal research 112*: 133-174.

Wilson, C.J.N.; Houghton, B.F. 1994: Road Log and Guide for field excursions, Taupo Volcanic Zone Workshop Tuesday, 15 and Wednesday, 16 February 1994. Institute of Geological & Nuclear Sciences, Wairakei Research Centre, Taupo, New Zealand, 23 p.

Wilson, C.J.N.; Houghton, B.F.; McWilliams, M.O.; Lanphere, M.A.; Weaver, S.D.; Briggs, R.M. 1995: Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand : a review. *Journal of volcanology and geothermal research 68*: 1-28.

Wilson, C.J.N.; Rogan, A.M.; Smith, I.E.M.; Northey, D.J.; Nairn, I.A.; Houghton, B.F. 1984: Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. *Journal of geophysical research 89(B10)*: 8463-8484.

INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES LIMITED

Gracefield Research Centre
69 Gracefield Road
P0 Box 30368
Lower Hutt
New Zealand
Phone +64-4-570 1444
Fax +64-4-570 4600

Wairakei Research Centre
State Highway 1
Private Bag 2000
Taupo
New Zealand
Phone +64-7-374 8211
Fax +64-7-374 8199

Rafter Research Centre
30 Gracefield Road
P0 Box 31312
Lower Hutt
New Zealand
Phone +64-4-570 4637
Fax +64-4-570 4657

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
Phone +64-3-477 4050
Fax +64-3-477 5232

A Crown Research Institute