Constraints on the evolution of Taranaki Fault from thermochronology and basin analysis: Implications for the Taranaki Fault play

PJJ Kamp[1] , AJ Vonk[1], CS Nelson[1], RJ Hansen[1], A Tripathi[1], SD Hood[1], M Ngatai[1], and AJW Hendy[1&2]

[1]Department of Earth Sciences, The University of Waikato, Private Bag 3105, Hamilton 2001, New Zealand. Telephone 64-7-838 4876, Email p.kamp@waikato.ac.nz [2]Department of Geology, 500 Geology/Physics Bldg., University of Cincinnati, Cincinnati, OH 45221-0013, United States of America. Telephone: 1-513-556 3723, Email hendya@email.uc.edu

Abstract

Taranaki Fault is the major structure defining the eastern margin of Taranaki Basin and marks the juxtaposition of basement with the Late Cretaceous-Paleogene succession in the basin. Although the timing of the basement over-thrusting on Taranaki Fault and subsequent marine onlap on to the basement block are well constrained as having occurred during the Early Miocene, the age of formation of this major structure, its character, displacement history and associated regional vertical movement during the Late Cretaceous-Recent are otherwise poorly known. Here we have applied (i) apatite fission track thermochronology to Mesozoic basement encountered in exploration holes and in outcrop to constrain the amount and timing of Late Cretaceous-Eocene exhumation of the eastern side of the fault, (ii) basin analysis of the Oligocene and Miocene succession east of the fault to establish the late-Early Miocene - Early Pliocene subsidence history, and (iii), regional porosity-bulk density trends in Neogene mudstone to establish the late uplift and tilting of eastern Taranaki Basin margin, which may have been associated with the main period of charge of the underlying Taranaki Fault play.

We make the following conclusions that may be useful in assessing the viability of the Taranaki Fault play. (1) Mid-Cretaceous Taniwha Formation, intersected in Te Ranga-1 was formerly extensive across the western half of the Kawhia Syncline between Port Waikato and Awakino. (2) Taranaki Fault first formed as a normal fault during the Late Cretaceous around 85±10 Ma, and formed the eastern boundary of the Taranaki Rift-Transform basin. (3) Manganui Fault, located onshore north of Awakino, formed as a steeply east dipping reverse fault and accommodated about four km of displacement during the mid-Cretaceous. (4) Uplift and erosion, involving inversion of Early Oligocene deposits, occurred along the Herangi High during the Late Oligocene. This may have been associated with initial reverse movement on Taranaki Fault. (5) During the Early Miocene (Otaian Stage) the Taranaki and Manganui Faults accommodated the westward transport of Murihiku basement into the eastern margin of Taranaki Basin, but the amount of topography generated over the Herangi High can only have been a few hundred metres in elevation. (6) The Altonian (19-16 Ma) marked the start of the collapse of the eastern margin of Taranaki Basin that lead during the Middle Miocene to the eastward retrogradation of the continental margin wedge into the King Country region. During the Late Miocene, from about 11 Ma, a thick shelf-slope continental margin wedge prograded northward into the King Country region and infilled it (Mt Messenger, Urenui, Kiore and Matemateaonga Formations). (7) During the Pliocene and Pleistocene the whole of central New Zealand, including the eastern margin of Taranaki Basin, became involved in long wavelength up-doming with 1-2 km erosion of much of the Neogene succession in the King Country region. This regionally elevated the Taranaki Fault play into which hydrocarbons may have migrated from the Northern Graben region.

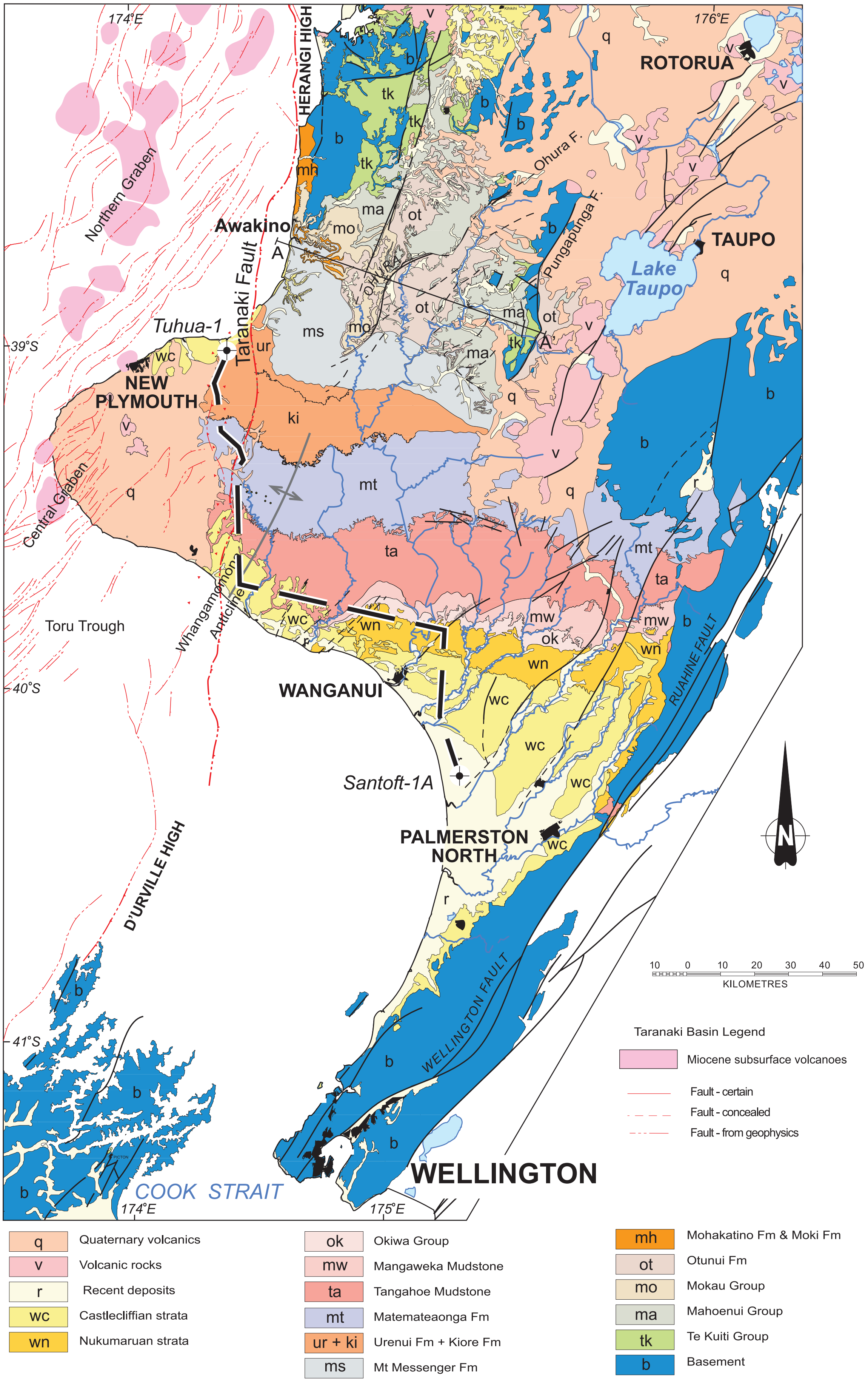


Figure 1. Simplified geological map of western North Island and parts of Taranaki Basin, showing the main stratigraphic units in the eastern Taranaki, King Country and Wanganui Basins (Fig.2). Figure compiled from authors' unpublished data, New Zealand Geological Survey (1972) and King and Thrasher (1996).

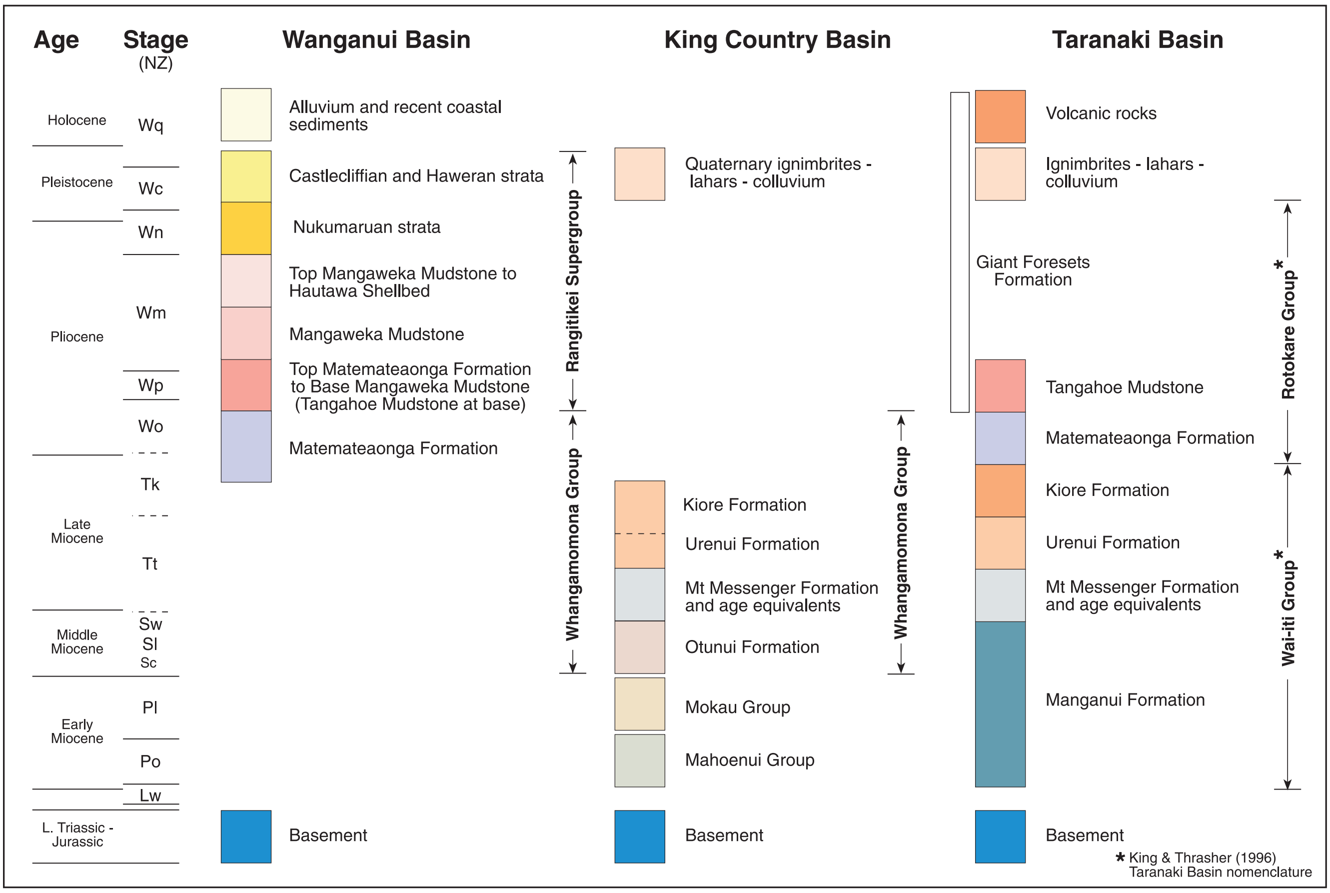


Figure 2. The major Neogene stratigraphic units in each of Taranaki, King Country and Wanganui Basins, and their age. The Moki and Mohakatino Formations, which occur within Manganui Formation in Taranaki Basin, are not distinguished separately.

Introduction

Taranaki Fault is the major structure along the eastern margin of Taranaki Basin (Fig. 1&2). It marks the boundary between basement, comprising Murihuku Terrane of Late Triassic and Jurassic age, and juxtaposed Late Cretaceous and Cenozoic sediments to the west making up the fill of Taranaki Basin. Taranaki Fault is regarded as a viable hydrocarbon play and numerous exploration holes have been drilled through the autochthonous Neogene succession and the tip of the underlying basement to test prospects in the Late Cretaceous-Paleogene sedimentary succession sealed beneath the overthrust block. Although some details about the character and age of Taranaki Fault are known (e.g. King and Thrasher 1996), many questions remain.

Characterisation of the nature and evolution of Taranaki Fault are the focus of a joint GNS-University of Waikato structural-stratigraphic objective within a broader research programme funded by The New Zealand Foundation for Research Science and Technology. This contribution brings together preliminary information pertaining to the origin of the fault and its vertical movement in the context of the stratigaphic development of the eastern margin of Taranaki Basin. Other studies focus on the detailed structure of the fault based upon industry-acquired seismic reflection data (Nicol et al. 2004), wide angle seismic surveys (Pecher et al., 2004), and magnetotelluric observations (Stagpoole et al. 2004).

Numerous questions surround the character and evolution of Taranaki Fault, including the following: (i) What was the nature of the eastern boundary of Taranaki Basin during the Late Cretaceous and Paleogene prior to Early Miocene emplacement of the overthrust block, including the relationship of the mid Cretaceous Taniwha Formation to the fault, and early rifting of Taranaki Basin; (ii) was basement overthrusting on the fault a single short-lived event, or did it occur over a longer interval; (iii) did substantial topography (e.g. a thrust belt) develop immediately within, or east of the fault zone during the early Miocene; (iv) to what extent did the Tongaporutu-Herangi structural high immediately east of the fault persist during the Middle and Late Miocene, thereby separating the Taranaki and King Country basins; and (v), to what extent has the fault zone been uplifted during the Pliocene and Pleistocene with exhumation of the Neogene stratigraphic cover?

In this paper we address these questions via the application of thermochronology to basement and by analysis of the Neogene cover sequences via stratigraphy and sedimentology. By necessity, our investigations have focused chiefly on the hanging-wall block in the Taranaki Peninsula through North Taranaki coastal region, and the Neogene succession in the King Country Basin. Basement samples for thermochronology have been obtained from

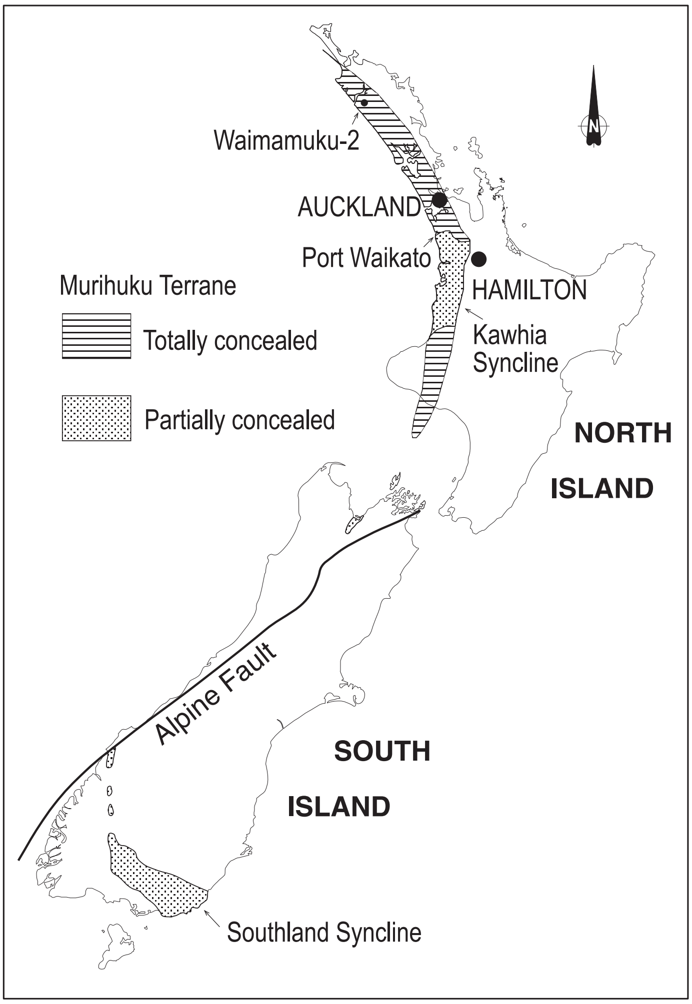


Figure 3. Map showing the distribution of the Murihiku Terrane in North and South Islands, New Zealand. Modified from Ballance & Campbell (1993, Fig.2) and Kamp and Liddell (2000).

outcrop in the Kawhia Syncline, which is a regional structure involving the Murihuku Terrane to the east of the fault, and from exploration holes intersecting the tip of the overthrust block. Much of the data will appear in subsequent papers and we explore results for the Port Waikato area here, after Kamp and Liddell (2000). A basin analysis of the King Country region in the context of our earlier work on Wanganui Basin (Kamp et al. 2002, in press) and in relation to the coastal North Taranaki stratigraphy (King et al. 1993), has provided new insights to the marked subsidence and uplift history of the hanging-wall block, which has implications for the timing of differential movement within the Taranaki Fault zone.

Geological Setting

Taranaki Fault forms the eastern margin of Taranaki Basin (Cope and Reed 1967). In broad terms it is an east-dipping low angle reverse fault that offsets basement by up to 6 km (King and Thrasher 1996). The fault, mapped at the top basement level, has a sinuous strike for about 250 km along central-western North Island, both on land and offshore, and lies entirely in the subsurface (Fig.1). Substantial reverse movement and juxtaposition of Triassic-Jurassic basement with the Late Cretaceous-Late Oligocene sedimentary succession in Taranaki Basin occurred during the Early Miocene (King and Thrasher 1996); there were subsequent movements of a lesser magnitude, particularly in the Taranaki Peninsula region and offshore to the south that probably continued into the Pliocene. Details of the fine structure of the fault zone are known from various hydrocarbon exploration studies, and are being systematically mapped by Nicol et al. (2004) along the length of the fault. In Taranaki Peninsula (Waihapa Field), for example, there are a series of reverse faults offsetting basement both west and east of the main trace that progressively offset basement up to the east and merge westward with the thin-skinned intra-basin deformation of the Tarata Thrust Zone (e.g. Bulte 1989; King and Thrasher 1996). A structural high involving basement, known as the Patea-Tongaporutu-Herangi High, parallels Taranaki Fault from a few, to 20 km to the east of it. This feature occurs mostly in the subsurface, but is emergent as the Herangi Range north of Awakino (Fig.1). Mapping of the Late Eocene-Oligocene coal measure and carbonate shelf succession of the Te Kuiti Group in the Waikato and northern King Country regions west of Herangi Range, shows clearly that this structural high was a paleogeographic feature at that time (Nelson 1978; Waterhouse and White 1994) and may have been slowly uplifting (Nelson et al. 1994). It is likely, and we develop further evidence below from the Early Miocene succession onlapping the eastern side of the Herangi Range, that the emplacement of the basement block into Taranaki Basin during the early Miocene was associated with *en echelon* reverse faulting in a zone east of the main trace of Taranaki Fault and within the high. Early Miocene crustal shortening by reverse faulting also occurred on faults in the King Country region (Crosdale 1993, Kamp et al. 2002) and the timing can be quite well constrained from the Miocene stratigraphy. The opportunity to establish these constraints arise because of a phase of very significant Pliocene-Pleistocene uplift and erosion that stripped off a Middle Miocene to Pliocene continental margin wedge, the Whangamomona Sequence (Group), and exposed the underlying Early Miocene successions (Mahoenui and Mokau Sequences/Groups) (Kamp et al. 2002, in press). In eastern Taranaki Peninsula and further to the east the Whangamomona Group is partially eroded and largely obscures the structure on basement (Fig.1). These beds, including those of mid-Pliocene age are mildly deformed by the Whangamomona Anticline east of Taranaki Fault.

A feature of the outcrop geology of central-western North Island is the absence of Cretaceous-Eocene beds east of Taranaki Fault, whereas thick successions of this age range occur immediately to the west of it. This may imply the occurrence of a proto-Taranaki Fault, albeit of a different character. To better understand the origin of the Taranaki Fault, and the evolution of the eastern margin of Taranaki Basin, we have applied the low temperature thermochronology technique of apatite fission track analysis to samples of Murihiku basement in various transects across the strike of the Kawhia Syncline. We consider below the results for the Port Waikato area.

Mid to Late Cretaceous transition from Kawhia Syncline and Te Ranga Basin to proto-Taranaki Fault bounded Taranaki Basin

The Kawhia Syncline is a regional synclinorium east of Taranaki Fault involving early-Middle Triassic to Late Jurassic basement (Ballance and Campbell 1993) classified as Murihiku Terrane. (Fig. 3). The youngest Murihiku rocks occur at Port Waikato where they are of Late Jurassic (Tithonian stage) age. However, the degree of induration of these beds and the vitrinite reflectance of thin coal seams they enclose (0.77%, Suggate 1990), suggest that they may have been formerly overlain by a thick sequence of younger beds (Ballance *et al.* 1980), necessarily of Cretaceous age.

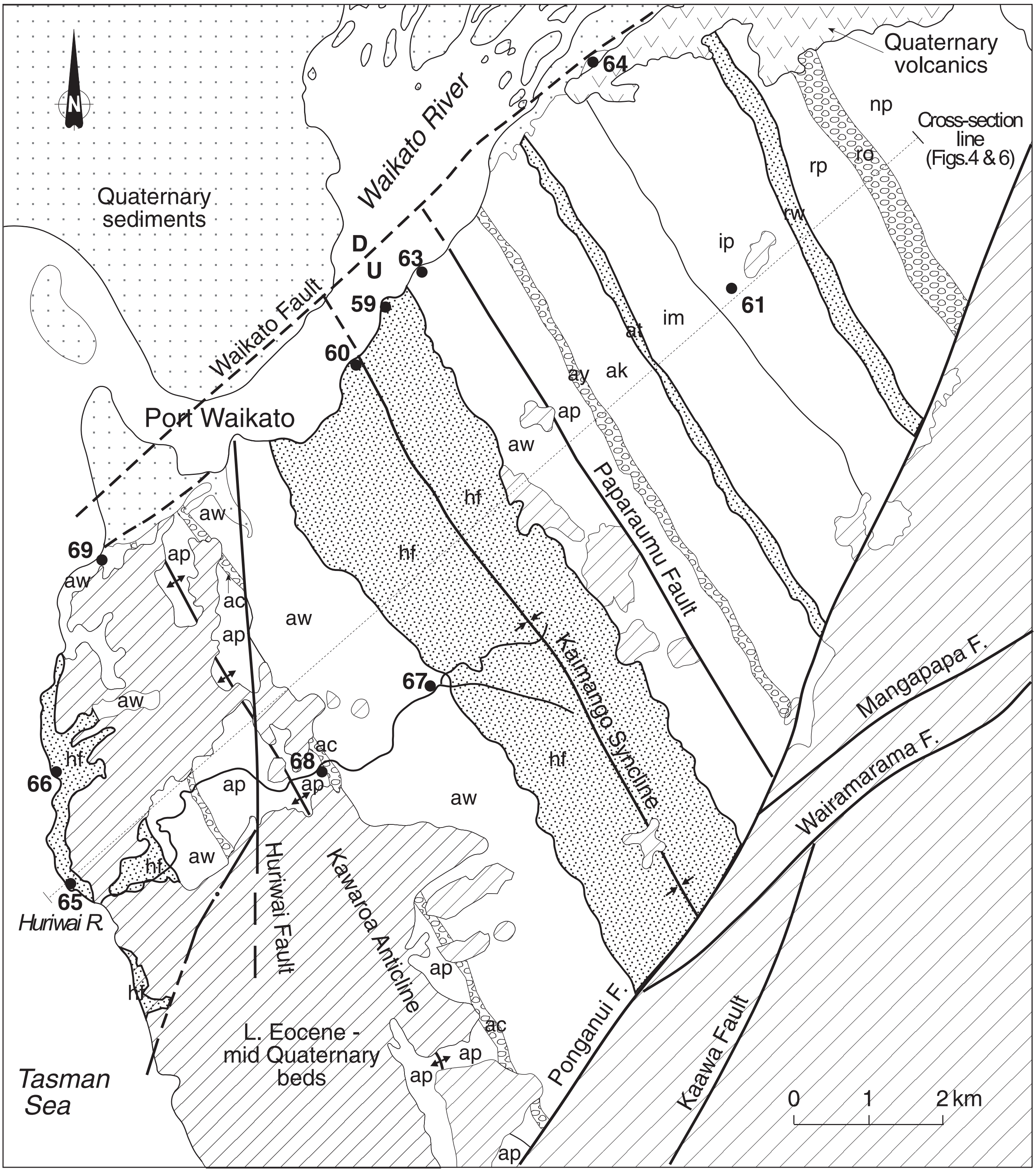


Figure 4. Simplified geological map of the Port Waikato area based on Waterhouse (1978) showing sample locations. Formation names (upsection) are abbreviated as follows: np, Pongawhakatiki Siltstone; ro, Ohautira Fm; rp, Putau Siltstone; rw, Wilson Sandstone; ip, Pakau Fm; im, Moewaka Fm; at, Takatahi Fm; ak, Kinohaku siltstone; ay, Waiharakeke Conglomerate; ap, Puti Siltstone; ac, Coleman Conglomerate; aw, Waikorea Siltstone; hf, Huriwai Measures. From Kamp and Liddell (2000).

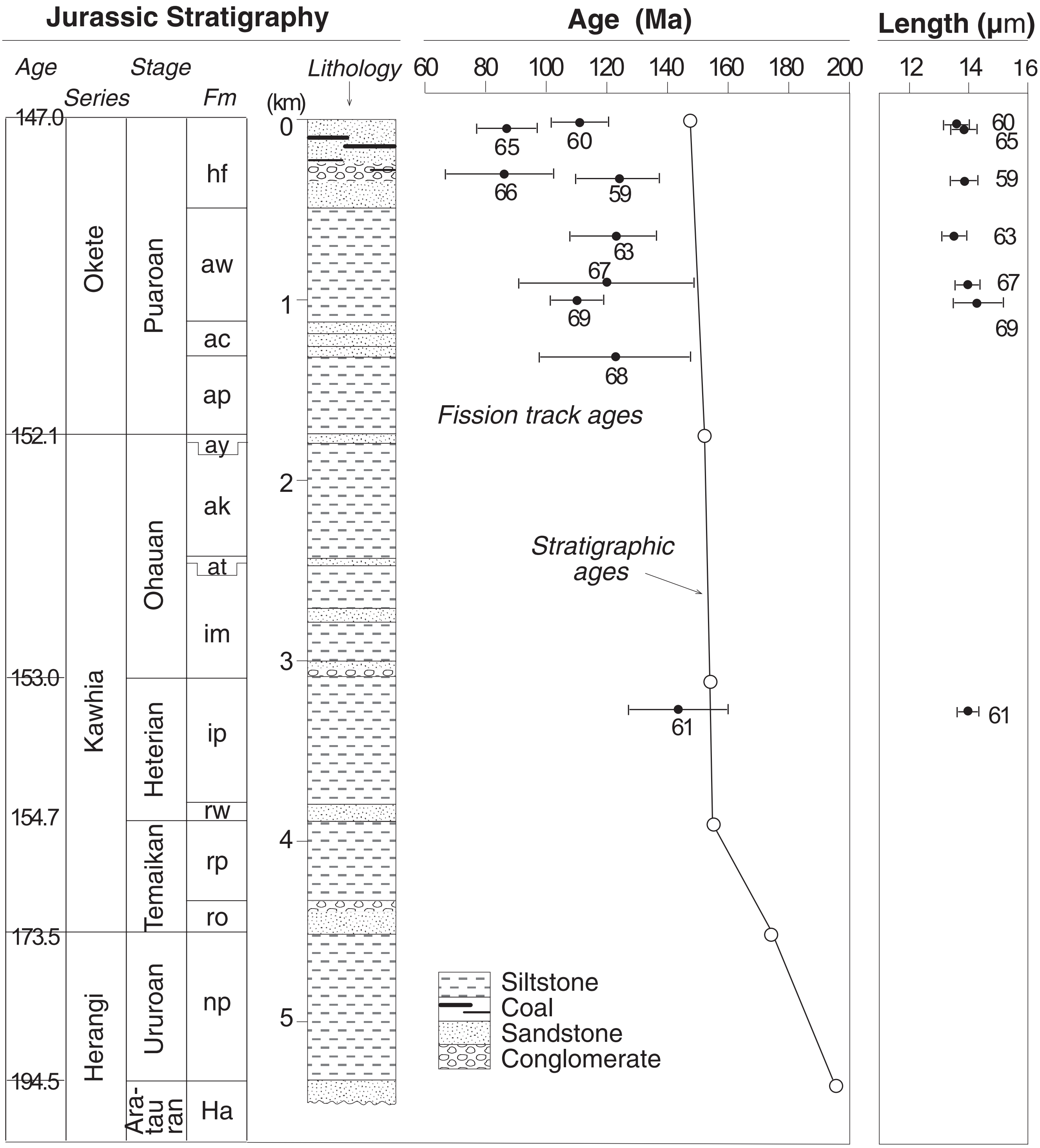


Figure 5. Stratigraphy of the Jurassic section in the Port Waikato area (from Waterhouse 1978), and sample mean fission track ages and track lengths. Sample numbers completed by prefix 9006-. Stratigraphic ages based on time scale in Harland et al. (1989). See caption to Fig. 4 for the full names of formations. From Kamp and Liddell (2000).

What was the relationship between these beds and the Cretaceous sediments that accumulated in Taranaki Basin immediately to the west? Based on fission track results, we suggest that the missing Cretaceous section across parts of the Kawhia Syncline correlates with the early-Late Cretaceous Taniwha Formation intersected in Te Ranga-1 east of Taranaki Fault and evident in seismic sections west of the fault (King and Thrasher 1996). Much of this succession accumulated between about 105 and 85 Ma and was displaced and inverted by formation of the Taranaki Fault at about 85 Ma.

The stratigraphy and structure of the Port Waikato region has been mapped in detail by Waterhouse (1978). The exposed basement comprises a thick (~5400 m) conformable Jurassic succession (Fig. 4) dominated by indurated siltstones with an intermediate volcanic provenance (Ballance 1988). The whole succession is essentially conformable, and although it forms the western limb of the Kawhia Syncline, is locally folded into a slightly asymmetrical anticline (Kawaroa) and syncline (Kaimango) pair that give the rocks dips of 20-50° with NNW strikes (Fig. 3). Because the Huriwai Measures are folded, the main deformation phase must have occurred after the Late

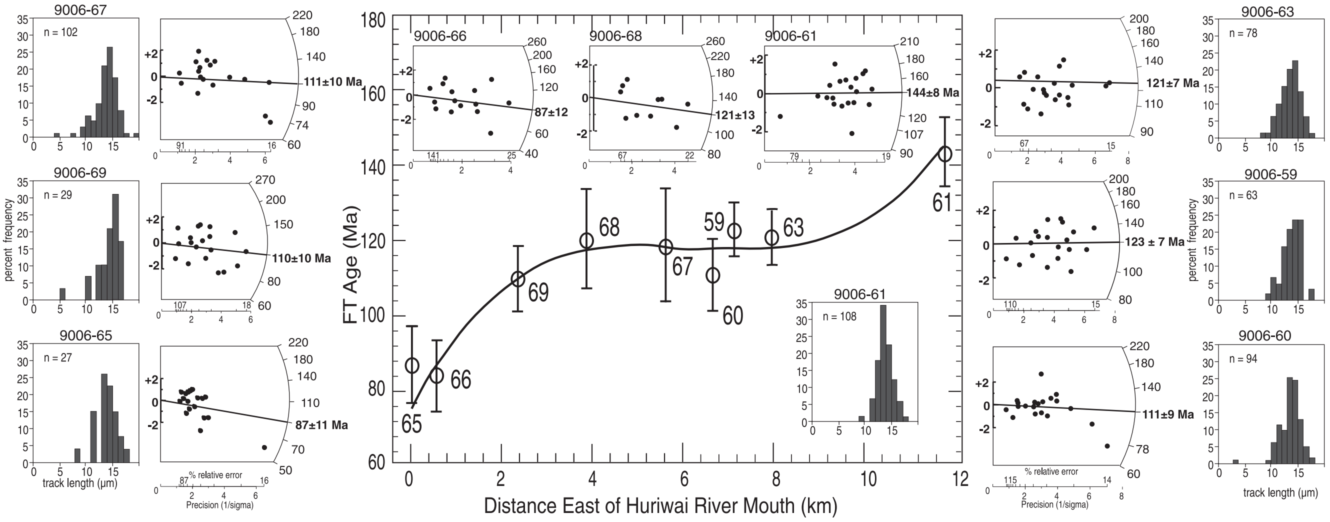


Figure 6. Plots showing the variations in mean fission track age (1 sigma error) along a transect shown in Fig. 4. Also shown are the radial plots and track length distributions for the samples for which lengths could be measured. From Kamp and Liddell (2000).

Jurassic; the only stratigraphic constraint on the minimum age of deformation is provided by the restricted occurrence of Late Eocene Waikato Coal Measures, which unconformably overlie an erosion surface cut across the basement folds (Fig. 4).

The Jurassic and Cenozoic successions are offset by several faults that have predominantly NE strikes with a secondary NNW striking mode (Fig. 4). Offsets are typically in the range 10-100 m. An exception is the Waikato Fault (Fig. 4), which is downthrown to the north. Hochstein and Nunns (1976) estimated from gravity modelling an offset of 2.7 km on this fault at Port Waikato, decreasing to 0.7 km near Tuakau along strike to the east. Because Jurassic formation boundaries and fold axes are not rotated at all by the Waikato Fault, it is reasonable to assume that the fault postdates the folding in the basement.

Apatite fission track thermochronology

Apatite fission track thermochronology is a method for obtaining thermal history information in sedimentary basins and basement provinces (Gallagher et al. 1997). As well as providing estimates of maximum palaeotemperature experienced by apatite-bearing rocks, the technique provides a direct estimate of the time at which a sedimentary section or basement sequence began cooling from its maximum paleotemperature. An understanding of the kinetics of annealing of fission tracks in apatite (e.g. Laslett et al. 1987), allows for forward modelling of the style of cooling, and in some cases of heating. The basis of the technique of analysis, principles of interpretation of fission track data, and the kinetic modelling procedure have been described in a series of papers (Gleadow et al. 1983, Green et al. 1986, 1989a, Gallagher 1995). The data supporting the results and interpretations represented here are reported in Kamp and Liddell (2000).

Results and interpretations reviewed

The sample apatite fission track ages from the Jurassic section at Port Waikato range from 87 ± 11 Ma to 144 ± 8 Ma. In Fig. 5 these ages and the associated sample mean track lengths are plotted against depth in a restored stratigraphic column from Waterhouse (1978), and against stratigraphic (depositional) age. There are no significant differences in mean lengths between samples, but all of the mean ages, except sample 61, are significantly less (outside 2 sigma ?error) than their respective depositional ages. This indicates that the apatite samples have undergone significant post-depositional annealing, and consequently their host rocks have experienced temperatures of about 70°C or higher, the temperature beyond which marked track shortening occurs. Sample 61 however, has a mean age that overlaps with its depositional age. Because this sample comes from a tuff horizon, most of the apatites in this sample would probably have been deposited with no inherited track density. That there has been minimal overall age reduction in this sample indicates that the host rocks have experienced maximum paleotemperatures of about 70°C since their deposition.

The pattern of mean fission track ages in relation to depth and depositional age in the stratigraphic pile (Fig. 5) is most unusual – the fission track ages decrease upwards in a fashion that appears to indicate that higher stratigraphic levels experienced higher paleotemperatures than lower stratigraphic levels. Usually, sample fission track ages decrease with increasing depth (Green *et al.* 1989*b*). Another unusual feature about the data illustrated in Fig. 5 is that there appear to be two trends in the data for the upper samples. Samples 9006-65, -66 and -69 come from the western limb of the Kawaroa Anticline, whereas samples 9006-60,-59 and –63 come from the eastern limb of the Kaimango Syncline located further to the east. In each of these sub-areas the FT ages decrease with higher stratigraphic levels in the Waikorea Siltstone and Huriwai Measures, but, importantly, the successively higher samples in each area also come from more western locations (Fig. 4). This implies that geographic

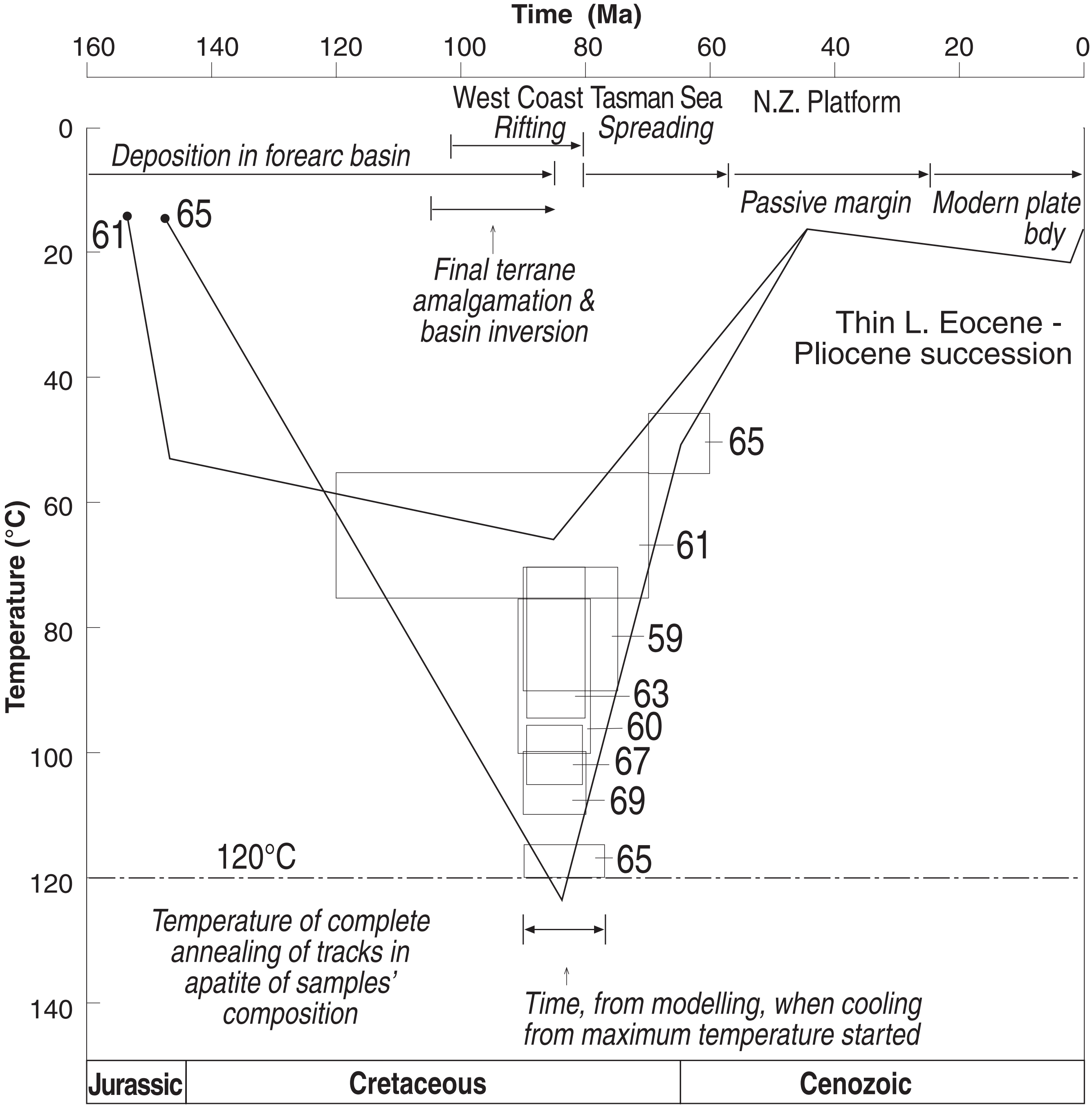


Figure 7. Plot of temperature versus time displaying the modelled thermal history of Port Waikato fission track samples. Also shown are the main tectonic phases in the region. From Kamp and Liddell (2000).

position exerts some control on the mean age and degree of annealing of the samples analysed.

In Fig. 6 the mean fission track ages and lengths are plotted against distance east of a line through the promontory just north of the Huriwai River mouth. There is a consistent reduction in the mean ages of samples from sites having increasing proximity to the modern coastline; samples successively closer to the modern coastline experienced progressively higher paleotemperatures in the past. This east-west pattern of age reduction is identical to that found in exhumed tilted annealing zones.

Sample 9006-61 is inferred to have been heated and annealed only mildly, as indicated by a peaked unimodal length distribution (Fig. 6), the occurrence of only one 9-10 µm track, the sample mean length (14 µm) being about 1 µm less than expected at ambient surface temperatures. In addition, one of the single grain ages has an age (90±20 Ma) significantly less than the stratigraphic age of the tuff horizon. These data are consistent with heating to a maximum temperature of about 70°C.

Samples 9006-63, -59 and -60 have broader length distributions than sample 9006-61, as indicated also by the larger length standard deviation values and in particular by these samples having a greater number of tracks between 9 and 13 µm. The single grain ages in each of these three samples have two to three grains with ages of 80-85 Ma, which are significantly less than the stratigraphic age. The

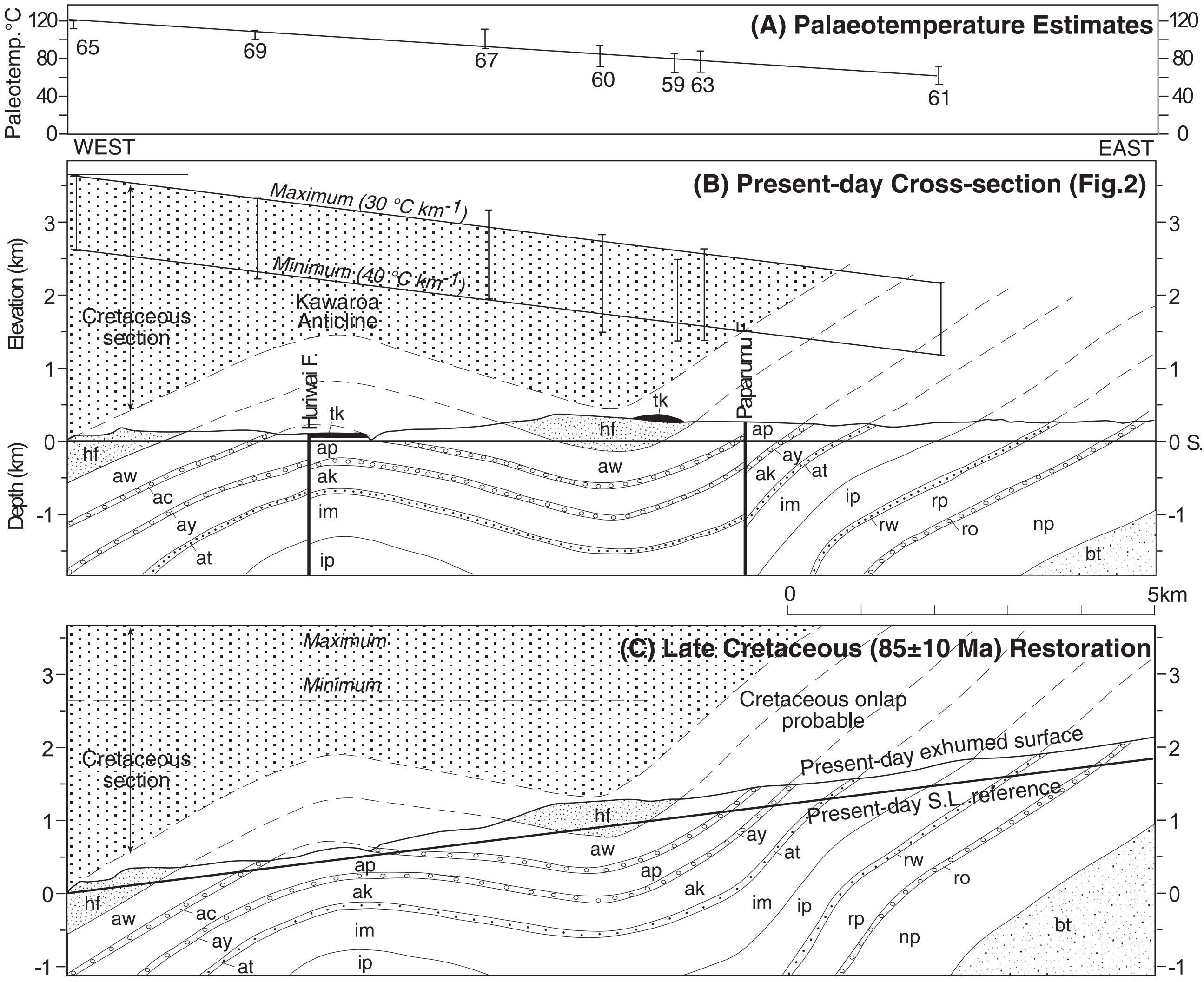


Figure 8. Composite figure showing in (A) the variation in maximum paleotemperature (2 sigma error) across the field area for modelled sample data; in (B) a structural cross-section for the line shown in Fig. 4, and maximum and minimum estimates of the amount of Cretaceous section that once overlay the Jurassic section; and in (C) a Late Cretaceous (85±10 Ma) palinspastic structural restoration of the field area, highlighting the amount of Late Cretaceous - early Cenozoic tilting that probably occurred as a result of extensional faulting accommodated on the Taranaki Fault or a coast-parallel fault. From Kamp and Liddell (2000).

rest of the grains have ages that overlap individually within 2 µm with their respective sample stratigraphic ages. Samples 9006-67 and -69 are slightly more heavily annealed than the preceding samples as indicated by the appearance of a proportion of short tracks between 4 and 10 µm in length, which is reflected also in an increase in the length standard deviation. In both of these samples there are many grains with individual ages, which trend to ~110 Ma in radial plots for sample 9006-67, and to ~82 Ma in sample 9006-69, statistically less than their respective depositional ages. It is difficult to estimate qualitatively the maximum temperatures experienced by samples 9006-67 to -69, largely because of the number of (long) tracks that have been added since the host rocks cooled from their maximum temperatures. Nevertheless these samples attained temperatures in the past at those corresponding to middle to lower parts (70-100°C) of an apatite annealing zone. The fission track parameters for sample 9006-65 and -66 show that they were close to having been totally overprinted and reached temperatures near the base of an apatite annealing zone having been heated to temperatures in the range 110-120°C.

Modelling of thermal history

The apatite fission track data reported above have been quantitatively modelled in a forward manner, as described by Green et al. (1989*a*) and Gallagher (1995), to estimate the likely time-temperature history experienced by the sample host rocks (Kamp and Liddell 2000). The multi-compositional model (1992 version) used includes allowance for the effects of intergrain differences in measured Cl content.

The permissible modelled range of temperatures for each sample reached at the peak of heating are illustrated in Fig. 6 together with the time limits when maximum temperatures were experienced. The peak temperature for sample 9006-61, the stratigraphically oldest sample (Fig. 5), lay in the range 55° - 75°C, and could have been experienced anytime between 120 and 70 Ma. Based on the thickness distribution of Jurassic units (Waterhouse 1978), sample 9006-61 would have been buried 3.15 km by 147 Ma. This would have corresponded to a temperature of ~57°C, as the basin had a

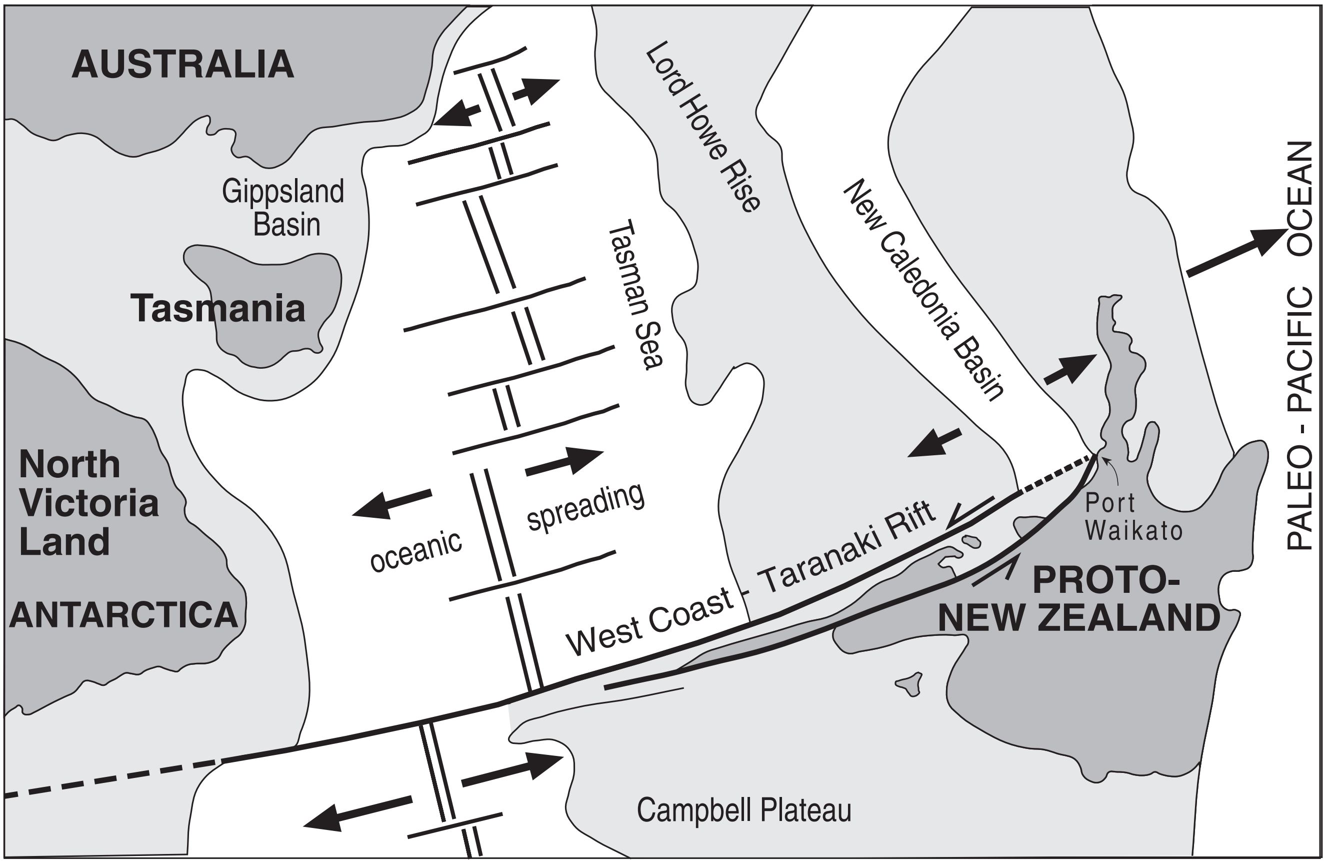


Figure 9. Sketch map showing the relative positions of New Zealand and its surrounding crustal blocks in relation to Australia and Antarctica and Tasman Sea spreading at about 60 Ma. Note the bounds of the oblique West coast-Taranaki Rift and the location of Port Waikato. Redrawn from King and Thrasher (1996, fig. 5.3).

very low geothermal gradient at that time of ~15°C/km (Black et al. 1993) due to lithospheric subduction. The timing when cooling started is poorly constrained by the modelling, but is likely to have occurred at the same time as the other samples.

Integrated modelling of the fission track and vitrinite reflectance data for sample 9006-65 indicate that it probably experienced peak temperatures of 110°C - 120°C between 90 and 77 Ma, and cooled through the range 55° to 45°C between 70 and 60 Ma (Fig. 7). The other samples experienced

Figure 10. Photograph of a tilted portion of the exhumed Late Cretaceous-Late Eocene erosion surface cut across Late Jurassic basement strata in Huriwai Valley, Port Waikato. An outlier of the Te Kuiti Group occurs at the top of the exhumed erosion surface. The higher country to the right (east) may represent Late Cretaceous-Late Eocene paleotopography as it is developed over resistant sandstone of the Huriwai Measures. Photo: P.J.J.Kamp.

Figure11. Composite photograph of eastward dipping Te Kuiti, Mahoenui and Mokau Group strata on the southern side of Awakino River at Awakino Tunnel. Note the degree of change in dip within the Taumatamarie Formation, and the development of Black Creek Limestone Member, which thins to the east (left). The black Creek Limestone represents the progradation of a shelf environment into the basin across mudstone lithofacies that accumulated on a tilting continental slope. Photo: P.J.J.Kamp.

maximum temperatures within the limits 70° to 110°C between 80 and 90 Ma, except for sample 9006-59, which may have started cooling between 90 and 75 Ma. Importantly, the order of increasing peak paleotemperature is consistently the inverse of the stratigraphic order, which gives rise to the crossover of the thermal history paths shown in Fig. 7.

Mid-Cretaceous Taniwha Formation and age of the proto-Taranaki Fault

The preferred explanation of the paleotemperature pattern in the Port Waikato succession is that a differential thickness of Cretaceous section accumulated across the field area, and that between 45 and 85±10 Ma this section was uplifted and completely eroded. Fig. 8B gives minimum and maximum estimates of the thickness of Cretaceous section involved. The uncertainty in the thickness estimates result from the combination of the uncertainty in each of the modelled sample paleotemperatures, and the range of geothermal gradients (30° - 40°C/km) that could have existed at the time (85±10 Ma) maximum paleotemperatures were attained by the host rocks. The amount of section removed after 85 ± 10 Ma, and hence deposited between 147 and 85±10 Ma, reduced from west to east (Fig. 8B).

A Late Cretaceous palinspastic restoration of a cross-section through the field area (Fig. 8C) suggests that the Cretaceous

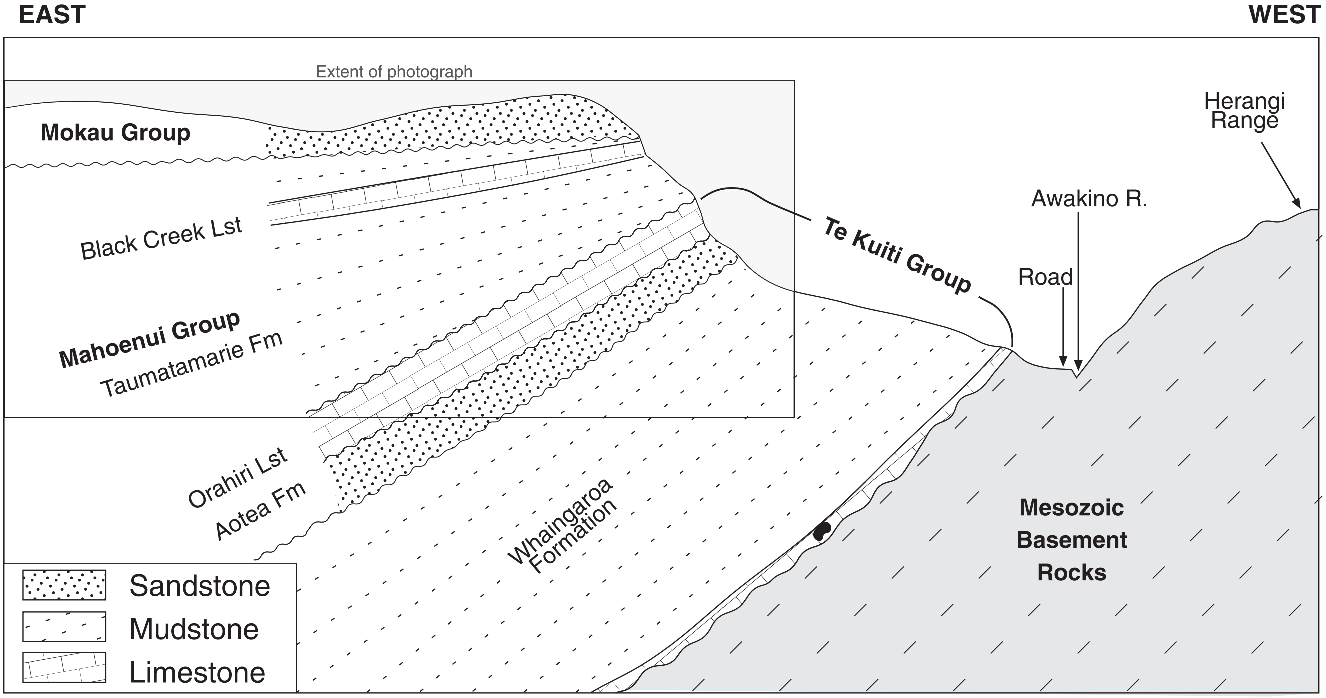


Figure 12. Sketch of the stratigraphy and structure evident in the Te Kuiti, Mahoenui and Mokau Group strata on the southern side of Awakino River at Awakino Tunnel, and their relationship to Mesozoic basement. Note how the dip decreases marginally upwards within the Te Kuiti Group, and significantly within the Mahoenui Group. Note also the extent of the photograph in Fig. 11.

depocentre occurred over the western part of the Kawhia Syncline, and that the basin would have extended to the west. The horizon from which sample 61 was obtained was not heated significantly through Cretaceous burial however. This implies that the eastern basin margin lay west of site 61 after 120 Ma. A question that arises is the timing of folding in relation to accumulation of the Cretaceous section. Apatite FT results for other transects in the Kawhia Syncline suggest that the compressive folding of Kawhia Syncline, arising from final amalgamation of the Murihiku and Waipapa terranes, had occurred by 105-100 Ma. Therefore part of the missing Cretaceous section may have accumulated between 105-100 and 85±10 Ma, and the Cretaceous section was probably sourced partly from erosion of the eastern margin of the Murihiku rocks uplifted as a result of terrane amalgamation. Lower parts of the Cretaceous sedimentary section were probably conformable with the underlying Late Jurassic beds, middle parts probably thinned on to the Kawaroa Anticline as it formed, and upper parts probably onlapped the eastern limb of the syncline.

Taniwha Formation of Ngaterian age (mid Cretaceous, 100–95 Ma) was encountered in the base of Te Ranga-1 and is regarded as part of a 2500 m thick unconformity-bounded succession above acoustic basement (Thrasher 1992). The Taniwha Formation is restricted to the northeast of Taranaki Basin, thickens eastward, and extends as a narrow band as far north as Auckland (King and Thrasher 1996) possibly forming part of sequence C2-B of Isaac et al. (1994). Taniwha Formation is tilted up to the east and is unconformably overlain by a thin veneer of North Cape Formation of Late Cretaceous age.

The age and geometry of the Taniwha Formation suggests that it is the other half of the Cretaceous succession reconstructed as having formerly occurred along the western Margin of the Kawhia Syncline (Fig 8). From the lithologies of this formation reported from Te Ranga-1, the Taniwha Formation has affinities with the Murihiku Terrane and may represent in lower parts a continuation of the original volcaniclastic provenance that characterizes the Murihiku

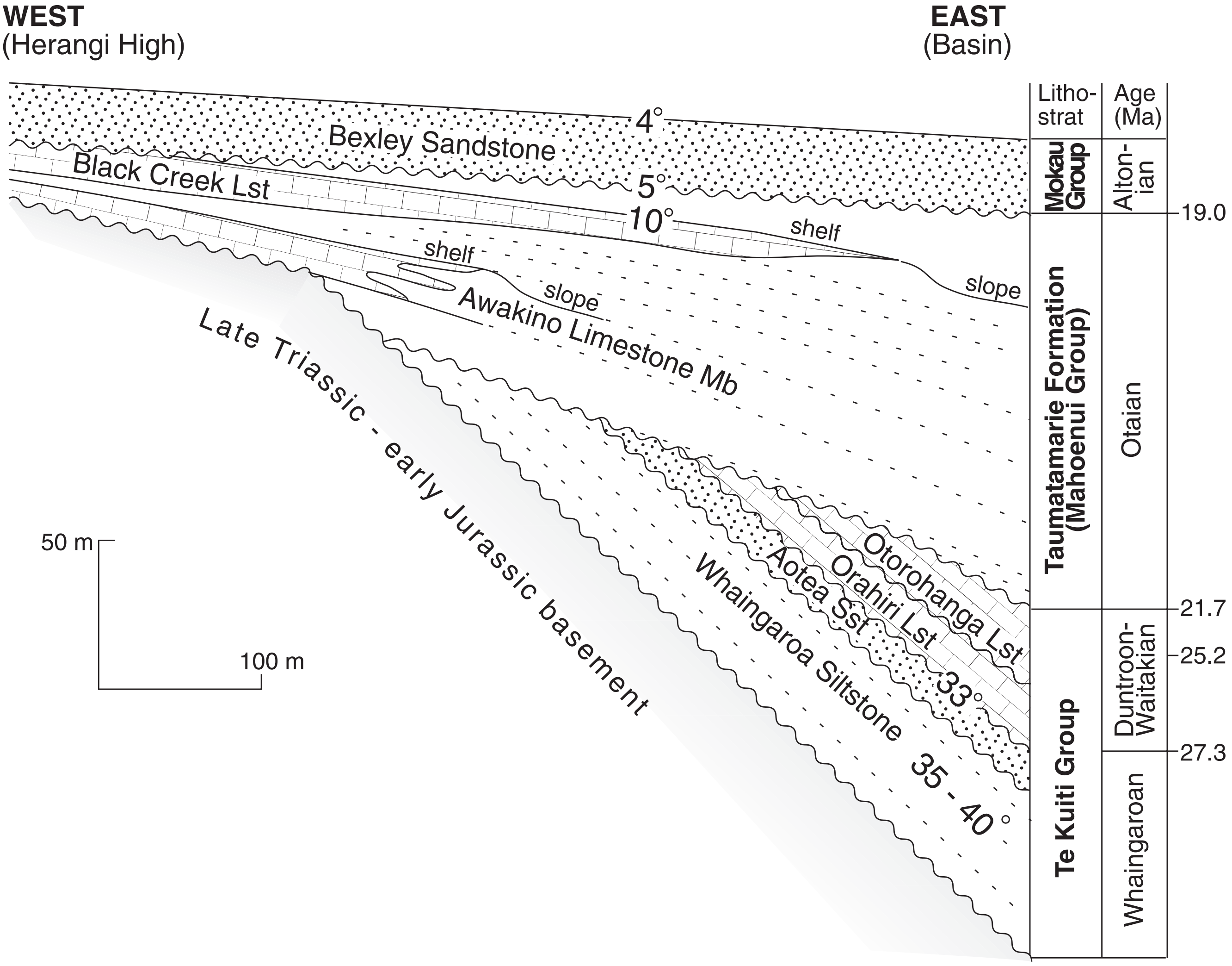


Figure 13. Sketch of the stratigraphy and structure in a west-east cross-section through Taumatamarie Trig on the eastern flank of the Herangi Range immediately north of Awakino Tunnel. Note how the Taumatamarie Formation onlaps an erosion surface cut across the Te Kuiti Group and oversteps on to basement. Note also the progradation of the depositional system within the Taumatamarie Formation as shown by the stepping out into the basin of the shelf-slope break at progressively higher stratigraphic levels. Numerical ages of the biostratigraphic stage boundaries are from the Institute of Geological & Nuclear Sciences WEB site.

Figure 14. Photograph north of Awakino Tunnel looking down the depositional dip (and paleoslope) of the Taumatamarie Formation with the development of the Black Creek Limestone Member near its top, which forms a prominent dipslope dipping away from the viewer. Photograph taken from a few hundred metres south of Taumatamarie Trig looking essentially down the cross-section illustrated in Fig. 13. Photo: P.J.J.Kamp.

basement, and in upper parts, comprise recycled Murihiku beds eroded especially from the eastern flank of Kawhia Syncline, uplifted as part of mid-Cretaceous deformation associated with amalgamation with Waipapa Terrane.

The inversion and erosion of the on land part of the Cretaceous succession represents a fundamental Late Cretaceous tectonic change from terrane amalgamation driven by plate convergence, to continental extension and formation of the Taranaki Rift-Transform Basin, with a new (proto-)Taranaki Fault marking the eastern margin of Taranaki Basin. The 85±10 Ma timing of the start of inversion coincides with the Haumurian age (base at 84.5 Ma) of the oldest Taranaki Basin sediments (King and Thrasher 1996). The eastward tilting of the Murihiku basement by about 5Ú (Fig. 8) was probably accommodated on a major fault, which would need to have been located west of Port Waikato, that is, west of the present coastline. The obvious structure is a northern continuation of Taranaki Fault, known to lie offshore (King and Thrasher 1992), or a related fault closer to Port Waikato. The Waikato Fault (Fig.4) may also have originated at this time as a transfer fault. It lies orthogonal to the axis of uplift/erosion and the Taranaki Fault, and defines the northern extent of Murihiku basement exposed at the surface. The tilting associated with the differential Late Cretaceous-Paleocene denudation across the Port Waikato area amounts to a vertical offset on the Waikato Fault at the intersection with the modern coastline of 1.4 km, which is about half of the total offset estimated by Hochstein and Nunns (1976) in that area, and is consistent with the pattern of decreasing vertical offset on this fault to the east. The eastward tilting of the Taniwha Formation in the offshore realm (Te Ranga-1) is part of the tilting of the Taranaki rift flank, analogous to the tilting reconstructed here for the Port Waikato region.

Figure 9, after King and Thrasher (1996), depicts the location of Port Waikato in relation to regional extensional tectonic features and structures active during the Late Cretaceous. Port Waikato lies at the intersection of the northern end of an oblique extensional transform system (West Coast-Taranaki Rift) through continental basement, which was probably colinear with a major oceanic transform in the Tasman Sea and the southern end of the New Caledonia Basin. The West Coast-Taranaki Rift –Transform was active from about 85 to 55 Ma (King and Thrasher 1996), coinciding with seafloor spreading in the Tasman Sea, and the tilting, uplift and erosion of Murihiku basement along central-western North Island.

Mid-Cretaceous Manganui Fault Displacement and Terrane Amalgamation

Manganui Fault is a substantial fault that has been regarded as part of the Early Miocene Taranaki Fault zone (King and Thrasher 1996). It strikes north-south in Manganui Valley within the Herangi Range north of Awakino. It is a steeply dipping, possibly reverse, fault within Murihiku Terrane that juxtaposes Lower to Middle Jurassic rocks to the west against Upper Triassic rocks to the east; that is, rocks to the east are upthrown (Happy 1971, Campbell and Raine 1989). From the offset in fossil zones and their stratigraphic thicknesses, there is an apparent minimum vertical throw of 5,500 m, probably of Cretaceous age (Campbell and Raine 1989).

Apatite FT data have been measured for a suite of samples through the Kawhia Syncline east of Awakino that help constrain the amount of displacement on the Manganui Fault and its timing. The apparent FT ages are all markedly younger than the stratigraphic ages of the sample host rocks and it is clear that there has been substantial erosion of Mesozoic stratigraphic section in the Awakino sample transect. This erosion can be partitioned into two episodes, one associated with final amalgamation of the Murihiku and Waipapa terranes at 105-100 Ma, and another that dates from about 85 Ma. The full geographic extent of the first (mid-Cretaceous) episode of exhumation is difficult to define due to a subsequent burial/thermal overprint that variably affects most sample host rocks. Samples from immediately east of the Manganui Fault however, show evidence from time-temperature forward modeling for significant cooling between 105 and 85 Ma, which we attribute to exhumation associated with crustal shortening and at least 4 km of reverse movement on Manganui Fault. A sample site from the transect on the far eastern limb of the Kawhia Syncline adjacent to the Waipa Fault (Murihiku-Waipapa terrane suture) also shows evidence for marked cooling and exhumation from the mid-Cretaceous. Apatite FT data for basement samples obtained from Pluto-1 and Pukearuhe-1, both located close to the Taranaki Fault, also suggest marked cooling and exhumation during the mid-Cretaceous; the basement section in Pukearuhe-1 even preserves the lower part of an apatite partial annealing zone fossilized by the exhumation that started around 105-100 Ma. Hence adjacent to the western and eastern faulted margins of the Murihiku Terrane, and within it (immediately east of Manganui Fault), there is evidence for four km or more of basement exhumation. Between these areas of uplift and erosion, modeling of the FT parameters seem to require heating from 105-85 Ma, followed by marked cooling between 85 and 75 Ma. We associate the heating with the accumulation of Late Cretaceous (late Moutuan or Ngaterian-Piripauan) sedimentary section (Taniwha Formation, as preserved in Te Ranga-1), and we associate the 85-75 Ma cooling with the erosion of Taniwha Formation and further Triassic-Jurassic section as the footwall block east of a normal Taranaki Fault was regionally uplifted and tilted eastward with formation of the Taranaki Rift-Transform basin from about 85 Ma (Haumurian Stage).

The new fission track data show that the Manganui Fault originated during the mid-Cretaceous, probably as a steeply dipping reverse fault associated with final Murihiku-Waipapa Terrane amalgamation. On the other hand, there seems to be no thermochronological evidence for significant displacement on Manganui Fault during the Late Cretaceous when it is likely that the Taranaki Fault first formed the eastern margin of Taranaki Basin as a normal fault, as detailed above from fission track data for the Port Waikato area (Kamp and Liddell 2000), and from the early stratigraphy and structure of the basin itself (King and Thrasher 1996). We show in the next section however, that Manganui Fault may have been part of the Taranaki Fault zone during the Late Oligocene-Early Miocene.

Late Oligocene – Early Miocene Taranaki Fault and Mobility of the Herangi High

There is no stratigraphic record on land central-western North Island of Late Cretaceous and Paleocene sediments, and from this it has been widely inferred to have been an interval of regional erosion west of Taranaki Basin, as detailed above, and the development of subdued topography (Fig.10) (Nelson 1978). A Late Eocene coal measure and transgressive shelf-marine carbonate succession (Te Kuiti Group) onlaps the erosion surface cut across basement (Nelson 1978, Edbrooke et al. 1994, Waterhouse and White 1996), indicating regional subsidence from about 36 Ma. A reassessment of the stratigraphy and chronology of the Te Kuiti Group is underway within the UOW research group, with a focus on the development of a sequence stratigraphic scheme and the identification of synsedimentary deformation, to compare with the Oligocene stratigraphic record in Taranaki Basin (King and Thrasher 1996, Hood et al. 2003 a,b,c).

Late Oligocene Deformation

The current understanding is that a structural high (Herangi High) persisted as a semi-continuous paleogeographic feature during the Oligocene from south of Awakino to Port Waikato. This appears to have been segmented by faults oblique and orthogonal to Taranaki Fault (e.g. Marakopa Fault), and breached by embayments in several places, some coinciding with modern West Coast harbours. By the Late Oligocene the Herangi High had been completely inundated in the north with accumulation over the top of it of outer shelf Carter Siltstone (Raglan Harbour to Port Waikato; Waterhouse and White 1996). The area around Awakino had a different late Oligocene history. Nelson et al. (1994) described a distinctive Te Kuiti Group succession at Awakino Tunnel on the eastern side of the Herangi Range where it is generally thick (300 m), has strong dips (40-30 degrees), exhibits an upsection decrease in the amount of dip (Fig.11&12), and the capping Orahiri Limestone includes several thick (up to 3 m) mass-emplaced units containing a variety of 1-10 cm-sized lithoclasts of older Te Kuiti Group rocks. Petrographic and oxygen and carbon stable isotope data of the lithoclasts suggest that the source deposits were cemented at relatively shallow subsurface burial depths (100-500 m) before being uplifted and eroded. The source for the lithoclasts probably corresponds to the narrow Herangi High between Awakino Tunnel and Taranaki Fault, but must have been submarine and accumulating Te Kuiti Group-equivalent calcareous facies during the Early Oligocene (Early Whaingaroan, 34.3-27.3 Ma). Inversion of this depocentre was accompanied by subtle synsedimentary eastward tilting

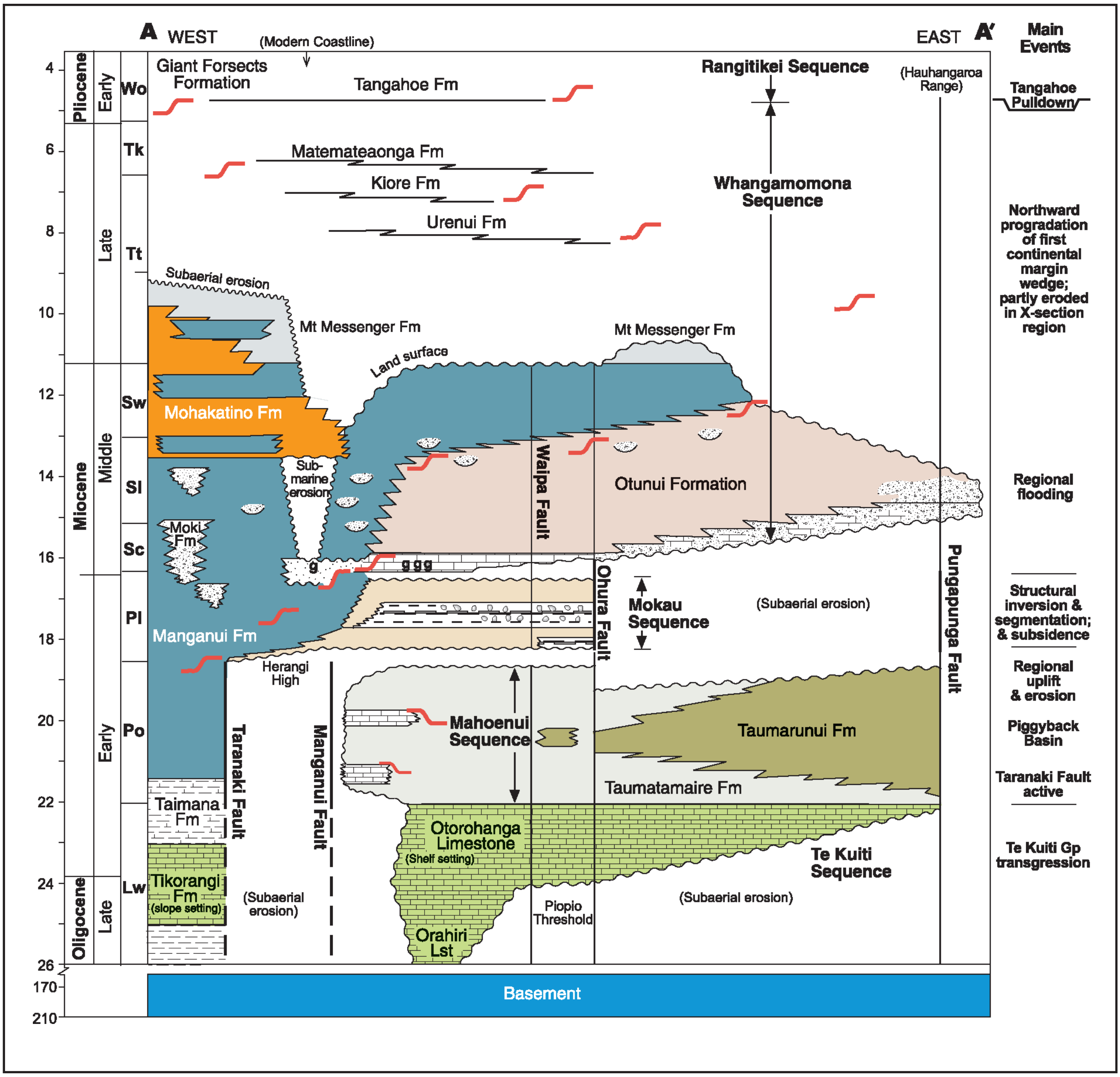
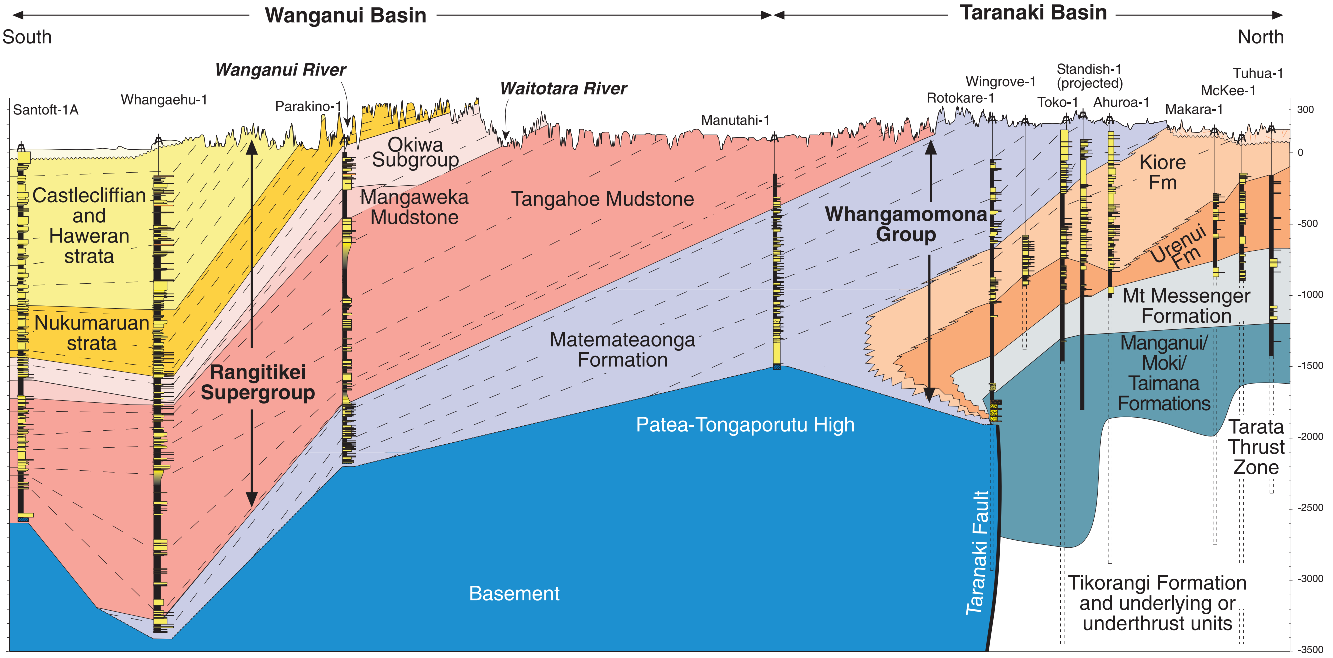


Figure 15. Chronostratigraphic panel representing the relationship between formations and 2nd order sequences of Cenozoic age cropping out in a cross-section between Awakino Heads in eastern Taranaki Basin and Waitui Saddle on the Hauhungaroa Range along the eastern margin of the King Country region (line of section A-A'on Fig.1). The Te Kuiti Sequence represents foundering of the New Zealand platform. The Mahoenui Sequence accumulated in a piggy back basin in response to overthrusting on the Taranaki Fault and reverse displacement on the Manganui Fault as the Australia - Pacific plate boundary formed as a through-going transform through eastern North Island. Note the Otaian migration of the shelf-slope break (shown in red) on to the Herangi High from the Mahoenui depocentre to the east. The Altonian Mokau Sequence accumulated in local depressions during inversion and segmentation in response to crustal shortening driven from the Alpine Fault sector of the plate boundary to the southeast. Regional flooding during the Middle Miocene reflects broad downwarping of the lithosphere and collapse of the eastern Taranaki Basin margin, with extension of Taranaki Basin into the King Country region north of Taranaki Peninsula. Note the retrogradation of the continental margin wedge to the east as marked by the inferred positions of the shelf-slope breaks. The Whangamomona Sequence represents the infilling of the King Country Basin, the sediments having been sourced from the Alpine Fault (Southern Alps) sector of the plate boundary zone. The lower part of the Rangitikei Sequence is projected northwards on to the cross-section, but it is unclear if the beds extended that far north.

Wanganui Basin to Taranaki Basin: Santoft-1A to Tuhua-1



Time-stratigraphic cross-section

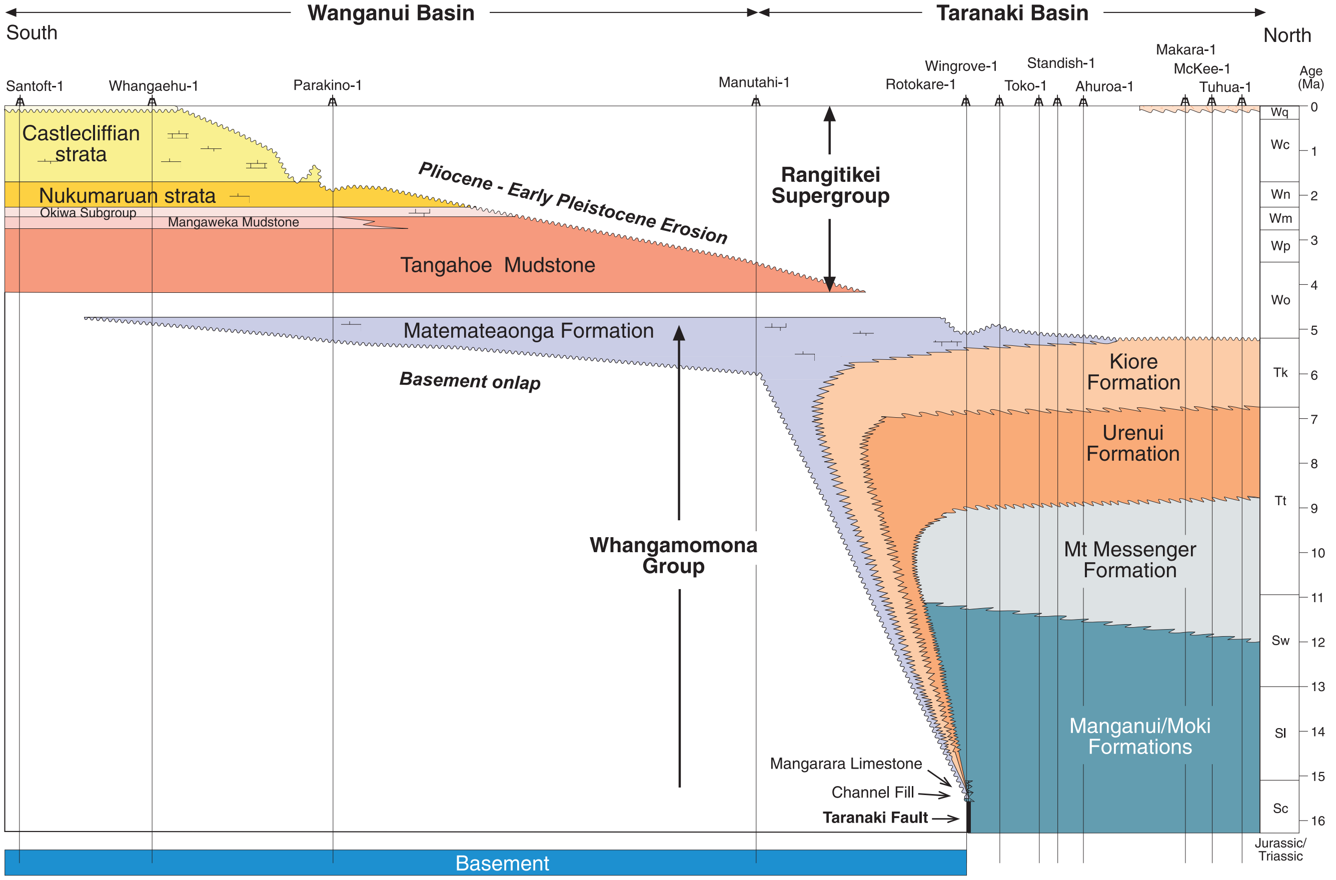


Figure 16. Wanganui Basin to Taranaki Basin (Santoft-1A to Tuhua-1) stratigraphic panel built up from well-to-well correlations. Also shown is the corresponding time-stratigraphic panel. Note the onlap of Whangamomona Group/Sequence across the Taranaki Fault from the Middle Miocene, which is younger than the onlap across this fault to the north in the vicinity of Awakino. See text for discussion.

of the Te Kuiti Group strata already deposited on the eastern flank of the Herangi High, contributing to the mass-emplacement of the lithoclast beds and the variable dips evident at Awakino Tunnel (Fig.12). A complementary Late Oligocene-earliest Miocene succession on the western flank of Herangi High is represented by the coarse bioclastic phases of the Tikorangi Formation, which were redeposited off a narrow shelf and into a foredeep in the vicinity of the Waihapa-Ngare oil field in Taranaki Peninsula (Hood et al. 2003a,b). Inversion of a depocentre and tilting of the southern part of the high began during the Late Whaingaroan around 30 Ma, concomitant with the onset of rapid subsidence along eastern Taranaki Basin, and continued through to the end of the Waitakian Stage (22 Ma, earliest Miocene), when erosion expanded on to the shelf at Awakino Tunnel, stripping out the Otorohanga Limestone, the topmost formation in the Te Kuiti Group. The stress regime and tectonic environment that drove this early uplift of the Herangi High remains speculative. It may have been compressive and represent the first indications of reverse movement on Taranaki Fault (Nelson et al. 1994, King and Thrasher 1996). Alternatively, as the Australia-Pacific finite pole of rotation was essentially along the eastern margin of Taranaki Basin during the Oligocene, the asymmetric basin subsidence and uplift of the neighbouring part of the high may reflect continuing normal faulting on a west dipping Taranaki Fault.

Miocene Deformation

In eastern Taranaki Basin the latest Oligocene (early Waitakian) Tikorangi Formation is offset by the Taranaki Fault. The oldest sediments overlying the basement overthrust block are late Otaian and more regionally Altonian in age (King and Thrasher 1996). This brackets the emplacement of the basement overthrust into Taranaki Basin and marked displacement on Taranaki Fault as lying between 23.8 (mid-Waitakian; Oligocene-Miocene boundary) and 19.0 Ma (Otaian-Altonian Stage boundary). This timing associates the reverse movement on Taranaki Fault with the Oligocene-Miocene boundary development of the Australia-Pacific plate boundary through eastern New Zealand (e.g. Kamp 1986, Cooper et al. 1987). Taranaki Fault as a pre-existing structure appears to have accommodated part of the compressive regional strain that developed across North Island at that time. Related questions are the extent to which topography developed along the eastern margin (i.e. was there a thrust belt) and how long did the reverse faulting continue?

These questions can be addressed from the stratigraphy and structure preserved on the eastern side of Herangi Range near Awakino Tunnel and from basin analysis of the King Country region more widely. On the southeastern flank of Herangi Range near Awakino Tunnel, the Te Kuiti Group is onlapped and overlapped on to basement by Early Miocene siliciclastic mudstone and sandstone of the Mahoenui and Mokau Groups, respectively (Fig.13). The Mahoenui Group is Otaian in age (22-19 Ma) and throughout the King Country region is either a bathyal massive mudstone facies (Taumatamarie Formation) or a flysch facies (Taumarunui Formation). The accumulation of this group and the dramatic change from carbonate to siliciclastic deposits reflects, sedimentologically, the uplift and erosion of basement in response to formation of the plate boundary. The regional thicknesses of this mudstone, stratigraphic thicknesses commonly exceeding 1000 m (Topping 1978), cannot be explained by erosion of the Herangi High alone, and the source probably lay closer to the plate boundary zone to the east.

Near Awakino Tunnel our mapping shows that the Taumatamarie Formation clearly onlaps an unconformity cut across the Te Kuiti Group, which it oversteps to onlap basement (Fig.13&14). The identification of onlap is facilitated by the occurrence of at least two limestone units (Awakino Limestone Member; Black Creek Limestone Member), which together with thin calc-flysch beds and other subtle lithological variations, identify sufficient bedding within Taumatamarie Formation to establish (i) a pattern and timing of marked synsedimentary tilting of the basin margin, and (ii) a progradational shelf-slope depositional geometry within the Mahoenui Group north of Awakino Tunnel. We interpret the absence of Otorohanga Limestone at Awakino Tunnel as due to subsequent erosion when the basin margin lay a short distance to the east (we note the presence of Otorohanga Limestone at Raroa Station and Bexley Station along strike to the north and south, respectively). The basin margin then subsided differentially during accumulation of Taumatamarie Formation, as indicated by the fanning of dips from 30-5 degrees (Figs 12&13). The hinge line about which the underlying basement block rotated cannot have been located more than a few hundred metres to a km to the west of the eroded onlap margin where the formation thickness projects to zero. The Manganui Fault lies 3 km to the west of the eroded onlap margin and has the appropriate strike to have acted as the structure controlling the rotation of the block carrying the differentially tilted Taumatamarie Formation. We infer that the Manganui Fault was a high-angle reverse fault at this time, upthrown to the east, with several hundred to 1000 m of displacement, which adds to the Mid-Cretaceous reverse displacement of about four km (see above).

As the Taumatamarie Formation beds onlapping the Te Kuiti Group are very fine grained and the expected neritic facies are very thin to absent, we infer that the initial reverse movement on the Manganui Fault was rapid, perhaps quickly developing some hundred metres of topography as a narrow ridge. Reverse faulting and uplift evidently continued through the Otaian (22-19 Ma). Concurrent with the tilting, the Taumatamarie Formation beds developed an eastward directed progradational shelf-slope depositional geometry. This is evident from the greater extent of the Black Creek Limestone compared with the Awakino Limestone. In Fig.13 we show approximately where the shelf-slope break lay at various stages. The narrow shelf and limited progradation through several million years of Taumatamarie Formation accumulation probably reflects the effective bypassing in suspension of the fine-grained sediments sourced from the contemporaneous Herangi High, and the excess accommodation available in the Mahoenui depocentre.

The unconformable contact of the Taumatamarie Formation and Bexley Sandstone is marked by the development of metres of relief formed by channel erosion in a subaerial environment, and was followed by the accumulation of conglomerate in the channels and a sheets of well sorted nonmarine to innershelf sandstone facies. The Bexley Sandstone maintains very similar lithological character and an unconformable relationship with Mahoenui Group over wide areas in the King Country Basin. These features imply a change in the pattern of deformation near the Otaian-Altonian boundary from reverse movement on the Manganui Fault, and probably the Taranaki Fault, to more regional uplift and the inversion of the Mahoenui depocentre in the King Country region, as detailed below.

To conclude, the stratigraphy and structure of the Early Miocene successions near Awakino Tunnel on the eastern flank of the Herangi High teach us several aspects about the evolution of the eastern margin of Taranaki Basin. (i) There was mobility of the Herangi High during the whole of the Otaian (22-19 Ma). (ii) The Manganui Fault was an active reverse fault during the Otaian about which the basement block to the east rotated. We infer that reverse, possibly thrust, movement also occurred on the Taranaki Fault during the whole of the Otaian. (iii) In a simple sense the basement blocks east of Manganui Fault, together with another to the west bounded by Taranaki Fault, may be described as forming a thrust belt of a thick-skinned type, but the amount of topography generated can only have amounted to several hundred metres, being higher east of Manganui Fault than in the block to the west. This crustal thickening seems to be limited to the Awakino-Kawhia area, there being no evidence for it north of Kawhia Harbour. (iv) Near the Otaian-Altonian boundary at 19 Ma, the whole of the Herangi High started to subside as Altonian sediments onlapped and overtopped it both from the west and east.

Late-Early Miocene – Middle Miocene Collapse of Eastern Taranaki Basin Margin and Eastward Retrogradation of the Continental Margin Wedge

The youngest parts of the Mahoenui Group in King Country Basin are late Otaian to possibly earliest Altonian in age (Topping, 1978). No regressive deposits are associated with this predominantly bathyal succession, even though its unconformable contact with the overlying Mokau Group and Otunui Formation formed through subarial erosion. This emphasizes the regional nature of an initial uplift phase that seems to have involved inversion of the whole of the Mahoenui depocentre (Fig.15). Throughout most of the Altonian (19-16 Ma) the King Country region was segmented by reverse movement on the Ohura (e.g. Crosdale 1993) and Pungapunga Faults into three zones, one between Taranaki and Ohura Faults, where Mokau Group accumulated, another between Ohura and Pungapunga Faults, where Mahoenui Group was partially eroded, and a third east of Pungapunga Fault where Mahoenui Group was completely eroded (Fig.15). The magnitude of uplift and erosion driven by crustal shortening clearly increased towards the southeast and in the direction of the contemporary plate boundary. The Ohura and Pungapunga Faults are younger in age and have more easterly strikes than Taranaki Fault, which could reflect a changing geometry of the plate boundary zone and a shift to the south in the locus of crustal shortening away from the northern part of Taranaki Fault; reverse movement probably continued on the Taranaki Peninsula sector of the Taranaki Fault, thereby maintaining the juxtaposition of basement against early-Middle Miocene sediments (Fig. 16), and on the Tarata Thrust Zone. Hence we infer that between the Otaian and Altonian there was an easterly change in the orientation of the stress field with the result that the compressive strain that had been accommodated partly on the Taranaki and Manganui Faults during the Otaian, shifted southeastward to the Ohura and Pungapunga Faults during the Altonian. Consequently, the eastern boundary of the northern part of Taranaki Basin shifted into the northern part of the King Country region to lie along the Ohura Fault (Fig.15), but Taranaki Fault persisted into the Middle Miocene as the reverse faulted margin of Taranaki Basin in the Taranaki Peninsula region due to its closer proximity to the plate boundary zone.

Mokau Group accumulated during the Altonian to a thickness of about 260 m northwest of Ohura Fault (Fig.15). This group comprises three main units: (i) a 60 m-thick lower transgressive shoreface sandstone (Bexley Sandstone); (ii) a 120 m-thick middle unit of coal measures, fluvial conglomerate and shoreface sandstone, and (iii) an upper 80 m-thick unit of regressive shoreface to innermost shelf sandstone (Waingarara Sandstone) (Vonk 1999). Concurrently, to the west of the Herangi High, transgressive shoreface facies (Bexley Sandstone) onlapped the top of the block of basement overthrust into Taranaki Basin on Taranaki Fault during the Otaian (Fig. 13). This was followed by the accumulation of Manganui Formation mudstone, initially as a shelfal deposit, but by the late Altonian as a mid bathyal succession (King et al. 1993). Moki Formation accumulated as submarine channel and fan deposits within slope to basin Manganui Formation facies (King and Thrasher 1996) west of the modern coastline. Hence a complete coastal plain-shoreface-shelf-slope-basin floor linked depositional system developed along the eastern margin of Taranaki Basin during the Altonian. This depositional system formed over a narrow belt some 35 km wide. We show in red in Fig.15 the approximate positions of the shelf-slope break during the Altonian and infer that this break migrated slowly inland (retrogressed). The system had a strong aggradational component during the Altonian and a surprisingly narrow shelf, which will have been controlled by the balance between the rate of subsidence of the underlying basement block and by the rate of sediment flux. Sediments would have been sourced from the erosion of the Mahoenui Group, much of which would have bypassed the neritic zone to accumulate as the Manganui Formation, and from the basement being uplifted and eroded from the plate boundary zone further to the southeast. Mapping at the southern end of the Herangi Range shows that the earlier (Oligocene-earliest Miocene) structural high in the area was completely buried by Altonian sediments and was likely to have exerted minimal, if any, paleogeographic control upon sedimentation.

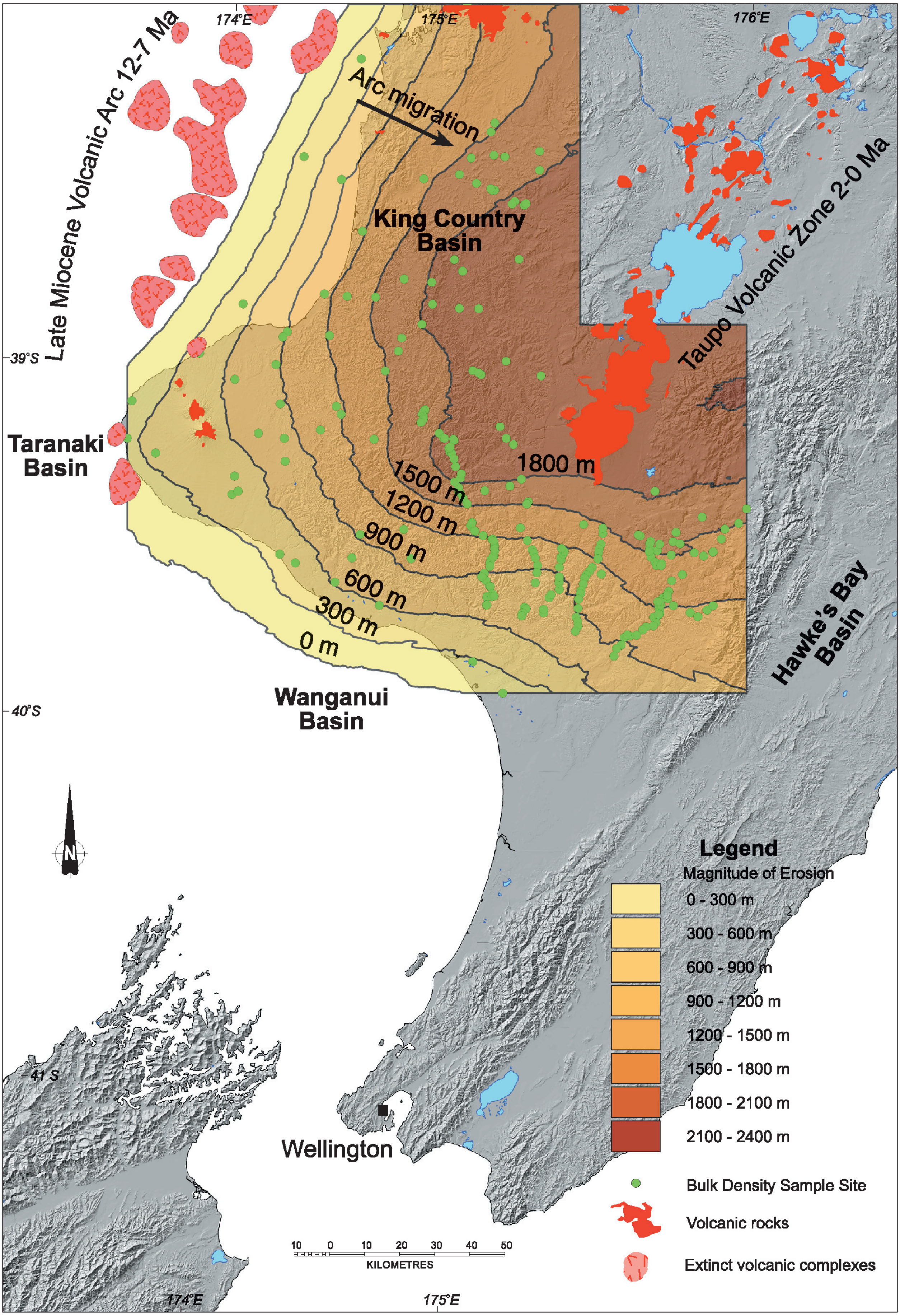


Figure 17. Map showing the magnitude in 300 m contours and pattern of Pliocene-Pleistocene erosion over central North Island derived from mudstone bulk density data. See text for discussion.

The Altonian interval marked the start of the collapse (marked subsidence) of the eastern margin of Taranaki Basin between Kawhia Harbour and Taranaki Peninsula, a process that probably started earlier during the Late Oligocene in the area north of Kawhia, as noted above. This collapse accelerated during the early-Middle Miocene leading at the end of the Middle Miocene to the development of a basin floor at bathyal depths over the eastern Taranaki margin and the King Country region. During the Clifdenian, reverse displacement on the Ohura and Pungapunga Faults ceased, associated with foundering and flooding of the King Country region in response to emplacement of the subducted slab of Pacific plate beneath the region (Kamp 1999). The basal stratigraphic unit is the Mangarara Member (of the Otunui Formation), which over most of the King Country is a transgressive shellbed. The Otunui Formation is a 100-200 m-thick sandstone to calcareous sandy siltstone, containing a variety of facies typical of an onlapping shoreline through shelf and upper slope succession, including glauconite-rich units (Gerritsen 1994, Cartwright 2003, Evans 2003). It passes gradationally upwards into massive siltstone facies of the Manganui Formation. Channelised redeposited sandstone deposits occur within the upper parts of the Otunui Formation and near the transition zone to Manganui Formation. Within 10-50 m of the base of the Manganui Formation the mass-emplaced (sandy debris flows) sandstone beds become more broadly channelised and are inferred to be part of the Mt Messenger Formation; thicker bedded sandstone units analogous to those exposed in the North Taranaki coastal section (King et al. 1993) occur at slightly higher stratigraphic levels in the southern King Country region and indicate that lower slope to basin floor environments developed there.

Critical new stratigraphic and sedimentological observations have been made in the Awakino-Mohakatino region in Middle Miocene outcrop sections near the modern coastline. These pertain to the Mangarara Sandstone (Member, in our work) and its relationship to the underlying and overlying beds. The Mangarara Sandstone comprises a Clifdenian (16-15 Ma), variably calcareous (slightly calcareous to limestone composition) glauconitic sandstone, which in all of the western river catchments accumulated as mass-emplaced beds on a continental slope. It is closely associated with thick-bedded well sorted sandstone beds that accumulated as channelised sandy debris flows, which we assign to Moki Formation, as described from other parts of Taranaki Basin by de Bock (1994) and King and Thrasher (1996). The mechanism(s) of emplacement and the continental slope environment of deposition of the Mangarara Sandstone are common to the Mangarara Sandstone and Moki Formation, which differ only in carbonate content. The Mangarara Sandstone facies, which are rich in *Amphistegina* and rhodoliths (calcareous red algal balls), were sourced from areas of carbonate accumulation on the contemporary shelf to the east in the King Country region (Fig.15), whereas the sandstone facies of the Moki Formation were transported across the shelf and upper slope from a shoreface in the southeast, where the sandstone had been well sorted by wave action. The sandstone beds of the Moki Formation, encased in background siltstone facies of the Manganui Formation, persist through the Middle Miocene section, whereas the Mangarara Sandstone beds accumulated only during the Clifdenian. We attribute this to the smothering of areas of shelf carbonate production by higher accumulation rates of terrigenous sediment as basin subsidence developed. The Moki and Manganui facies pass gradationally upwards into Mt Messenger Formation (Ferry Sandstone Member), which is identified by the first occurrence of mass-emplaced thick-bedded sandstone beds, whose geometry, by contrast with the stratigraphically lower channelised Moki Formation beds, indicate more widespread distribution as basin floor fans. The Mohakatino Formation comprises richly volcaniclastic sandstone sourced from andesitic volcanoes of Middle to Late Miocene age in northern Taranaki Basin. This formation occurs onshore but strongly volcaniclastic facies are restricted to coastal sections (King et al. 1993). These sediments occur as either airfall units, or dominantly as mass-emplaced beds. We suggest that the later could only be transported east of Taranaki Fault once the margin had subsided to bathyal basin floor depths (Fig.15). Moreover, the restriction of their occurrence to the vicinity of the modern coastline reflects the northwesterly paleoslope of the retrograding continental margin during the late-Middle Miocene.

The sum of the depositional facies and formational distribution of the Middle Miocene units in the eastern Taranaki and King Country regions, in the context of those for the older (Altonian) and younger formations (Late Miocene-Pliocene) (Kamp et al. 2002), indicate that between about 18 and 11 Ma (late Waiauan) there was marked subsidence to bathyal (1000 m) basin floor environments of what had been land at about 19 Ma along the eastern margin of Taranaki Basin and in the King Country region (Fig.15). This subsidence, in the absence of an oversupply of sediment, lead to a southeastward retrogradation of the continental margin that previously (in the Otaian) had been pinned to the Taranaki Fault, and a concomitant expansion of Taranaki Basin eastward into the King Country region. At about 12 Ma when higher rates of uplift and erosion developed on the plate boundary zone and the rates of sediment flux correspondingly increased, a continental margin wedge comprising Mt Messenger, Urenui, Kiore and Matemateaonga Formations started to prograde northward into this basin (Kamp et al. 2002, Vonk et al. 2002) (Fig.15). There are no indications that any paleogeographic barriers separated the Taranaki Basin proper from the King Country region north of Taranaki Peninsula. There have been suggestions in the past that the unconformity at the base of the Mangarara Formation in the section at Awakino Heads formed through subearial erosion and may indicate a Middle Miocene uplift phase; rather, we regard this unconformity as having formed through submarine canyon erosion on the contemporary slope, which cutout part of the underlying Manganui Formation. We illustrate in Fig.15 the Altonian-Lillburnian retrogradation of the continental margin and its subsequent (Waiauan - early Opoitian) progradation via red markings representing successive positions of the shelf-slope break.

The late-Early through Middle Miocene collapse of the eastern Taranaki Basin margin and of the King Country region, followed the successive cessation of reverse movement on four main faults, whose earlier movement had acted to thicken the crust. Reverse displacement on the Taranaki and Manganui Faults stopped at the end of the Otaian (Fig.15). Reverse movement was then taken up on the Ohura and Pungapunga Faults, but ended at the end of the Altonian. The flooding of the King Country region was not associated with faulting and appears to be part of a broad crustal downwarp driven below from the mantle and probably associated with the emplacement of the subducted slab of Pacific plate (Kamp 1999). Through the later parts of the Middle Miocene this downwarp started to affect the basement east of Taranaki Fault in Taranaki Peninsula, leading to onlap of the Whangamomona Sequence (Fig.16). This marked the end of most movement on the Taranaki Fault in the peninsula sector, although there are indications from our mapping that the paleogeographic effects of the highstanding hanging wall and neighbouring Tarata Thrust Zone still affected sedimentation patterns during Late Miocene accumulation of the Matemateaonga Formation. During the early Pliocene the Wanganui Basin subsided rapidly as a southward migration of the mantle-driven crustal downwarp that affected the more northern areas during the Middle Miocene. The overall pattern we have outlined of Early Miocene crustal thickening as expressed by overthrusting on the Taranaki and related faults, the southeastward retreat of reverse faulting, retrogradation of the continental margin and finally regional uplift, as we outline in the next section, is one repeated southwards through western North Island during the Neogene (Kamp 1999). It is the lithospheric response to changes in the configuration of the Australia-Pacific plate boundary zone and in particular the southward migration of the continent-continent oblique transform (Alpine Fault) sector and its replacement by an ocean-continent convergent margin (Hikurangi margin).

Pliocene-Pleistocene Uplift, Exhumation and Tilting along the Eastern Taranaki Basin Margin

Pliocene-Pleistocene uplift and erosion has completely inverted the Middle Miocene to Early Pliocene basin which formed along the eastern margin of Taranaki Basin and the King Country region. The outcrop pattern of the formations (Fig.1) reflect long wavelength up-doming of central North Island and associated erosion of weakly lithified mudstone and associated lithologies. Fig.17 is a map showing the magnitude and pattern of erosion calculated by kriging of site estimates of the amount of erosion determined chiefly from analysis of the bulk density of mudstone cores. There are two sets of bulk density data underpinning the map, including a DSIR dataset obtained during the 1960s for regional gravity mapping (Reilly 1965), made available by IGNS, and a second data set collected as part of this study, which concentrated on high density sampling in the main river valleys of Wanganui Basin (Fig.17). The laboratory methods used for the determination of bulk density of core samples followed standard soil and rock mechanics methods (Franklin et al. 1979). Estimation of the amount of erosion for individual sites from the bulk density data was made by reference to a porosity-depth relationship determined by Armstrong et al. (1998) for calibration well sites in Taranaki Basin that are currently at maximum burial depths and have not experienced any uplift and erosion. The statistically fitted surface through the combined dataset also included the erosion estimates made by Armstrong et al. (1998) for some hydrocarbon well sites along the eastern margin of Taranaki Basin.

Two features about the erosion pattern that indicate it fundamentally originates from long wavelength up-doming of central North Island are the very close match between the orientation of the erosion contours (Fig.17) and the strike of the major stratigraphic units (Fig. 1). Moreover, the coincidence of these geological signals with the contours of a positive isostatic anomaly on the regional gravity map (Reilly 1965), together with the long wavelength of the mild deformation of the surface expressed as rock uplift and erosion, point to the involvement of upper mantle processes in the origin of the uplift. Note on Fig. 17 how the uplift appears to be centred on or northwest of the Taupo Volcanic Zone, which is a Pleistocene volcanic arc. Its predecessor andesitic volcanic arc was located in northern Taranaki Basin until the latest Miocene, and during the Pliocene shifted southeastward, probably as a result of steepening of the dip of the subducted slab. Part of the broad doming and erosion of central North Island predated the outbreak of Taupo Volcanic Zone volcanism since Late Pliocene andesite volcanoes (Puerora and Titiraupunga) rest on basement, requiring prior erosion of Miocene beds.

The Pliocene-Pleistocene uplift and erosion affected the whole of the eastern Taranaki Basin margin with erosion extending offshore to the edge of the Northern Graben. The area of Miocene formations offshore in North Taranaki Bight truncated by erosion is known as the Manganui Platform (King and Thrasher 1996). East-west seismic sections across this platform clearly show westward tilting of the underlying strata. They are also cut by northeast-southwest normal faults, which are part of a set that occur across the whole of western North Island northwest of the Taupo Volcanic Zone (Fig.1). During the Pleistocene the Manganui Platform has subsided as part of this back arc extension and there has been further planation of the Miocene formations by wave processes. Between Awakino and Kawhia the Pliocene-Pleistocene erosion phase has exhumed basement in the Herangi Range. There seems to be no structural evidence suggesting differential uplift of the range. We think that the erosion has merely uncovered the relief that developed by crustal shortening during the early Miocene (Otaian) and was onlapped and buried during the late-Early Miocene (Altonian).

In Eastern Taranaki Peninsula the Whangamomona Anticline mildly deforms Late Miocene and mid Pliocene beds (Matemateaonga Formation, Tangahoe Mudstone) (Fig.1&2). The axis of the anticline and both of its flanks are cut by numerous northeast-southwest striking normal faults. The anticline axis trends oblique to Taranaki Fault, but is subparallel to the modern plate boundary zone located to the east. We infer from these observations that the anticline probably formed during the Late Pliocene-earliest Pleistocene as a far-field manifestation of crustal shortening originating from compression across the plate boundary. The normal faults that cut the Whangamomona Anticline reflect the Pleistocene development of extension broadly across central-western North Island in association with formation and evolution of the Taupo Volcanic Zone.

Conclusions and Implications for the Taranaki Fault Play

Based on application of apatite fission track thermochronology and basin analysis of Neogene successions in the King Country region, we have synthesized an evolution of the Taranaki Fault and the eastern margin of Taranaki Basin between Taranaki Peninsula and Port Waikato. Aside from the North Taranaki coastal section, the stratigraphy and sedimentology of the King Country region have not previously been factored into the evolution of the eastern margin of Taranaki Basin. In doing so we make the following conclusions that may be useful in assessing the viability of the Taranaki Fault play.

1. Taniwha Formation, intersected in Te Ranga-1 and evident in seismic reflection lines as a narrow depositional belt east of Taranaki Fault, was formerly extensive across the western half of the Kawhia Syncline between Port Waikato and Awakino. This formation has a primary and detrital volcanic provenance, having been partly sourced from Murihiku Terrane.
2. Taranaki Fault first formed as a normal fault during the Late Cretaceous around 85±10 Ma, and formed the eastern boundary of the Taranaki Rift-Transform basin. Uplift and tilting of the footwall block on the eastern side of this fault resulted in the near complete erosion of the Taniwha Formation by the Late Eocene and Early Oligocene, when Te Kuiti Group onlapped basement forming a remnant structural high east of the fault. Waikato Fault was active during the Late Cretaceous as a transfer fault.
3. Manganui Fault formed as a steeply east dipping reverse fault and accommodated about four km of displacement during the mid Cretaceous concurrent with amalgamation of the Murihiku and Waipapa Terranes and folding of the Kawhia Syncline.
4. Uplift and erosion, involving inversion of Early Oligocene deposits, occurred along the Herangi High during the Late Oligocene. This may have been associated with initial reverse movement on Taranaki Fault, or it may have been a continuation of normal fault displacement associated with proto plate boundary development through eastern New Zealand.
5. During the Early Miocene (Otaian) the Taranaki Fault accommodated the westward transport of Murihiku basement into the eastern margin of Taranaki Basin, where it truncated and overrode the Late Cretaceous to Late Oligocene sedimentary succession (King and Thrasher 1996). Concurrently, the Manganui Fault moved as a reverse fault, enabling the rotation of a basement block to the east. The movement on the Taranaki and Manganui Faults represents the development of a type of thick-skinned thrust belt, but the amount of topography generated over this structural high can only have been a few hundred metres in elevation. This crustal thickening extended from Awakino to Kawhia Harbour, and seismic studies suggest similar development south to Taranaki Peninsula. We infer active movement on these faults and mobility of the Herangi High throughout the Otaian (22-19 Ma).
6. The Altonian (19-16 Ma) marked the start of the collapse (marked subsidence) of the eastern margin of Taranaki Basin that lead during the Middle Miocene to the eastward retrogradation of the continental margin wedge into the King Country region. During the Altonian the Taranaki and Manganui Faults were inactive north of Awakino, and reverse movement was transferred to the southeast on the Ohura and Pungapunga Faults. During the Clifdenian (16-15 Ma) these faults became inactive and the King Country region subsided as a broad crustal downwarp (driven from the mantle), and through into the Lillburnian (15-13 Ma) was flooded, forming a continental shelf environment. During the later part of the Lillburnian and Waiauan (13-11 Ma) the King Country region subsided to bathyal basin floor depths. During the Late Miocene, from about 11 Ma, a thick shelf-slope continental margin wedge prograded northward into the King Country region and infilled it (Mt Messenger, Urenui, Kiore and Matemateaonga Formations).
7. During the Pliocene and Pleistocene the whole of central New Zealand, including the eastern margin of Taranaki Basin, became involved in long wavelength up-doming with 1-2 km erosion of much of the Neogene succession in the King Country region.
8. Taranaki Fault started out during the Late Cretaceous as a normal fault. During the Late Oligocene to earliest Miocene this fault was modified by km-scale westward transport of the basement footwall into Taranaki Basin; the eastern margin of the basin therefore became the hanging-wall. Marked Middle and Late Miocene regional subsidence by 1-2 km of the hanging-wall block (and Taranaki Fault) would have contributed to maturity of the mid and Late Cretaceous successions beneath the fault. Late (Pliocene-Pleistocene) rebound and erosion of much of the Neogene succession over the eastern margin has created a regional structural high from Taranaki Peninsula to Kawhia Harbour, with westward tilting of the beds from deeper in the basin (Northern Graben) forming ideal migration paths.

References

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 103, 30,269-30: 282.

Ballance, P.F. 1988. The Huriwai braidplain delta of New Zealand: a late Jurassic, coarse-grained, volcanic-fed depositional system in a Gondwana forearc basin. In: Nemec, W. & Steel, R.J. (eds) Fan Deltas: Sedimentology and Tectonic Settings. Blackie and Son, 430-444.

Ballance, P.F., Heming, R.F. and Sameshima, T. 1980. Petrography of the youngest known Murihiku Supergroup, New Zealand. In: Cresswell, M.M. & Vella, P. (eds) Gondwana Five. A.A. Balkema, Rotterdam, 161-166.

Ballance, P.F. and Campbell, J.D. 1993. A Murihiku arc-related basin of New Zealand (Triassic-Jurasic). In: Ballance, P.F. (ed.) South Pacific Sedimentary Basins. Elsevier, Amsterdam, 21-33.

Black, P.M., Clark, A.S.B. and Hawke, A.A. 1993. Diagenesis and very low-grade metamorphism of volcaniclastic sandstones from contrasting geodynamic environments, North Island, New Zealand: the Murihiku and Waipapa terranes. Journal of Metamorphic Geology, 11, 429-435.

Bulte, G. 1989. Styles of compressional wrench faulting, Taranaki Basin, New Zealand. *In:* Proceedings of the 7th Offshore South East Asia Conference, Singapore, February 1988, 79-91.

Campbell, H.J. and Raine, J.I. 1989. Biostratigraphic evidence for the Manganui Fault, near Awakino, southwest Auckland. Journal of the Royal Society of New Zealand 19, 43-53.

Cartwright, S. J. 2003. Cenozoic geological evolution of the central-eastern King Country Basin, North Island. MSc Thesis, University of Waikato, Hamilton, New Zealand. 214 p.

Cooper, A.F., Barreiro, B.A., Kimbrough, D.L. and Mattinson, J.M. 1987. Lamprophyre dyke intrusion and age of the Alpine fault, New Zealand. Geology 15, 941-944.

Cope, R.N. and Reed, J.J. 1967. The Cretaceous paleogeography of the Taranaki-Cook Strait area. Australasian Institute of Mining and Mettalurgy proceedings 222, 63-72.

Crosdale, P. J. 1993. Regression-related coal-bearing sequences in the Neogene of New Zealand: relation to the developing Alpine fault transform. *In*: Ballance, P.F. (ed) South Pacific sedimentary basins, *Sedimentary Basins of the World 2*. Elsevier. Pp.279-293.

De Bock, J.F. 1994. Moki Formation, a Miocene reservoir sequence, its facies' distribution and source in offshore Southern Taranaki Basin. 1994 New Zealand Petroleum Conference Proceedings, The Publicity Unit, Crown Minerals operations Group, Energy and Resources Division, Ministry of Commerce. Pp. 155-167.

Edbrooke, S. W., Sykes, R., Pocknall, D.T. 1994. Geology of the Waikato Coal Measures, Waikato Coal Region, New Zealand. Institute of Geological and Nuclear Sciences Monograph 6, 236 p. Lower Hutt, New Zealand. Institute of Geological & Nuclear Sciences Ltd.

Evans, T.P.H. 2003. Stratigraphy and sedimentology of Early to Middle Miocene strata, western Taumarunui region, King Country Basin. MSc thesis, University of Waikato, Hamilton.

Franklin, I. A., Volger, U. W., Szlavin, J., Edmond, J. M., Bieniawski, Z. T. 1979. Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake-Durability Index properties. International Journal of Rock Mechanics and Mining Sciences and Geomechanics, *16*: 141-156.

Gallagher, K. 1995. Evolving temperature histories from apatite fission track data. Earth and Planetary Science Letters, 136, 421-35.

Gallagher, K., Brown, R and Johnson, C. 1997. Fission track analysis and its applications to geological problems. Annual Review of Earth and Planetary Sciences, 26, 519-72.

Gerritsen, S.W. 1994. The regional stratigraphy and sedimentology of the Miocene sequence in the Ohura-Taumarunui region. MSc thesis, University of Waikato, Hamilton.

Gleadow, A.J.W., Duddy, I.R. and Lovering, J.F. 1983. Fission Track analysis: a new tool for the evaluation of thermal histories and hydrocarbon potential. Australasian Petroleum Exploration Association Journal, 23, 93-102.

Green, P.F., Duddy, I.R., Gleadow, A.J.W., Tingate, P.R. and Laslett, G.H. 1986. Thermal annealing of fission tracks in apatite 1: A qualitative description. Chemical Geology (Isotope Geoscience Section), 59, 237-253.

Green, P.F., Duddy, I.R., Laslett, G.M., Hegarty, K.A. Gleadow, M.J.W. and Lovering, J.F. 1989a. Thermal annealing of fission tracks in apatite 4: Quantitative modelling techniques and extension to geological timescales. Chemical Geology (Isotope Geoscience Section), 59, 237-253.

Green, P.F., Duddy, I.R., Gleadow, A.J.W. and Lovering. 1989b. Apatite fission track analysis as a paleotemperature indicator for hydrocarbon exploration. In: Naeser, N.D. & McCullogh, T. (eds) Thermal history of sedimentary basins - methods and case histories. Springer-Verlag, New York, 181-195.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. and Smith, D.G. 1989. A geologic time scale. Cambridge University Press, Cambridge.

Happy, A.J. 1971: Tertiary geology of the Awakino area, North Taranaki. MSc Thesis, University of Auckland, New Zealand.

Hochstein, M.P. and Nunns, A.G. 1976. Gravity measurements across the Waikato Fault, North Island, New Zealand. New Zealand Journal of Geology and Geophysics, 19, 347-358.

Hood, S.D., Nelson, C.S. and Kamp, P.J.J.: 2003a. Lithostratigraphy and depositional episodes of the Oligocene carbonate-rich Tikorangi Formation, Taranaki Basin, New Zealand. New Zealand Journal of Geology and Geophysics 46, 363-386.

Hood, S.D., Nelson, C.S. and Kamp, P.J.J.: 2003b. Petrogenesis of diachronous mixed siliciclastic-carbonate megafacies in the cool-water Oligocene Tikorangi Formation, Taranaki Basin, New Zealand. New Zealand Journal of Geology and Geophysics 46, 387-405.

Hood, S.D., Nelson, C.S. and Kamp, P.J.J.: 2003c. Modification of fracture porosity by multiphase vein mineralization in an Oligocene nontropical carbonate reservoir, Taranaki Basin, New Zealand. American Association of Petroleum Geologists Bulletin 87, No10, 1575-1597.

Isaac, M.J., Herzer, R.H., Brook, F.J. and Hayward, B.W. 1994. Cretaceous and Cenozoic sedimentary basins of Northland, New Zealand. New Zealand Institute of Geological and Nuclear Sciences Monograph 8.

Kamp, P. J. J. 1986. The mid-Cenozoic Challenger Rift System of western New Zealand and its implications for the age of Alpine Fault inception. Geological Society of America Bulletin 97: 255-281.

Kamp, P. J. J. 1999. Tracking crustal processes by FT thermochronology in a forearc high (Hikurangi margin, New Zealand) involving Cretaceous subduction termination and mid-Cenozoic subduction initiation. Tectonophysics 307: 313-343.

Kamp, P. J. J. and Liddell, I. J. 2000. Thermochronology of northern Murihiku Terrane, New Zealand, derived from apatite FT analysis. Journal of the Geological Society, London 157: 345-354.

Kamp, P. J. J., Vonk, A. J., Bland, K. J. et al., 2002. Megasequence architecture of Taranaki-Wanganui-King Country Basins and Neogene progradation of two continental margin wedges across western New Zealand. 2002 New Zealand Petroleum Conference Proceedings, Ministry of Economic Development, Wellington. Pp. 464-481.

Kamp, P.J.J., Vonk, A.J. et al. in press. Stratigrahic architecture, neogene megasequences and exhumation of Wanganui, King Country and eastern Taranaki Basins. New Zealand Journal of geology and geophysics.

King, P.R. and Thrasher, G.P. 1992. Post-Eocene development of the Taranaki Basin, New Zealand. In, Watkins, J.S., Zhiqiang, F. & McMillen, K.J. (eds) Geology and Geophysics of continental margins. The American Association of Petroleum Geologists Memoir, 53, 93-118.

King, P.R. and Thrasher, G.P. 1996. Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. New Zealand Institute of Geological and Nuclear Sciences Monograph, 13.

King, P. R., Scott, G. H. and Robinson, P. H. 1993. Description, correlation and depositional history of Miocene Sediments outcropping along the North Taranaki coast. Institute of Geological and Nuclear Sciences Monograph 5, 199 p. Institute of Geological & Nuclear Sciences Ltd, Lower Hutt.

Laslett, G.M., Green, P.F., Duddy, I.R. and Gleadow, A.J.W. 1987. Thermal annealing of fission tracks in apatite 2: A quantitative analysis. Chemical Geology (Isotope Geoscience Section), 65, 1-13.

Nelson, C.S. 1978. Stratigraphy and paleontology of the Te Kuiti Group, Waitomo County, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 21: 223-243.

Nelson, C.S., Kamp, P. J. J. and 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: 269-285.

New Zealand Geological Survey 1972. North Island (1st Ed.) " Geological map of New Zealand 1: 1,000,000." Department of Scientific and Industrial Research, Wellington, New Zealand.

Nicol, A., Maslen, G. and Stagpoole, V. 2004: Petroleum potential of the Taranaki fault play – a new structural interpretation. 2004 New Zealand Petroleum Conference Proceedings (this volume).

Pecher, I., Maslen, G.,and Stagpoole, V. 2004. Wide angle seismic surveys – the solution for imaging beneath the Taranaki Fault. 2004 New Zealand Petroleum Conference Proceedings (this volume).

Reilly, W. I. 1965. Gravity map of New Zealand 1:4,000,000. Bouger and Isostatic Anomalies (1st ed.), Department of scientific and Industrial Research, Wellington.

Stagpoole, V., Dravitski, S., Ingham, M., Bennie, S., and Bibby, H 2004. Structure of the Taranaki Fault from the interpretation of magnetotelluric observations. 2004 New Zealand Petroleum Conference Proceedings (this volume).

Suggate, R.P. 1990. Coal ranks in Permian-Lower Cretaceous rocks of New Zealand. New Zealand Journal of Geology and Geophysics, 33, 163-172.

Thrasher, G.P. 1992. Late Cretaceous source rocks of Taranaki basin. 1991 New Zealand Petroleum Conference Proceedings, The Publicity Unit, Crown Minerals operations Group, Energy and Resources Division, Ministry of Commerce. Pp. 147-154.

Topping, R. M. 1978. Foraminifera from the Mahoenui Group, North Wanganui Basin. PhD Thesis, University of Auckland, New Zealand. 300 p.

Vonk, A.J. 1999. Stratigraphic architecture and sedimentology of the Early Miocene Mokau Group, North Wanganui Basin, Western North Island, New Zealand. MSc (Tech) Thesis, University of Waikato, Hamilton, New Zealand.

Vonk, A. J., Kamp, P. J. J. and Hendy, A. W. 2002. Outcrop to subcrop correlations of Late Miocene-Pliocene strata, Taranaki Peninsula. 2002 New Zealand Petroleum Conference Proceedings, Auckland 24-27 February, 2002. Ministry of Economic Development, Wellington. Pp. 234-255.

Waterhouse, B.C. 1978. Sheet N51 Onewhero (1st ed.). Geological map of New Zealand 1:63 360 Map (1 sheet) and notes (32p). N.Z. Department of Scientific and Industrial Research, Wellington.

Waterhouse, B.C., White, PJ. 1994. Geology of the Raglan-Kawhia area, scale 1:50 000. Institute of Geological & Nuclear Sciences geological map 13. 48p., 1 sheet. Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited.

Acknowledgements

We thank the Directors of Geotrack International Pty Ltd for access to apatite fission track modeling software. We thank Betty-Ann Kamp for cartographic assistance. We acknowledge the New Zealand Foundation for Research Science and Technology (Contract UOWX0301) and University of Waikato for research funding.

Authors

PETER KAMP is Professor of Earth Sciences in the Department of Earth Sciences at The University of Waikato and leader of the FRST-funded sedimentary basins research programme. He has MSc and PhD degrees. Research activities include basin analysis, fission track and U-Th/He thermochronology and thermochronometry applied to sedimentary basins and basement provinces in New Zealand and the Asia-Pacific region.

ADAM VONK is a post-graduate student in the Department of Earth Sciences at The University of Waikato. Adam has an MSc(Technology) (Hons) degree including a thesis on the stratigraphy and sedimentology of the Early Miocene Mokau Group in King Country Basin. He is currently undertaking a PhD degree on the Mid-Miocene to Early Pliocene evolution of the central-western North Island continental margin. Adam holds a FRST Enterprise Doctoral Scholarship.

CAMPBELL NELSON received a B.Sc (honours) degree from Victoria University of Wellington, and a PhD degree from the University of Auckland. He is a founding staff member of the Department of Earth Sciences at The University of Waikato and was Chairman from 1988 to 1996 and has been Professor of Earth Sciences from 1991. His research interests are in sedimentary and marine geology and stratigraphy and Cenozoic paleoceanography and paleoclimatology of the southwest Pacific region. He is Past President of the Geological Society of New Zealand and was elected a fellow of the Royal Society of New Zealand in 1994.

ROCHELLE HANSEN holds an MSc (Hons), which involved a thesis on the stratigraphy, sedimentology and paleomagnetism of the Mount Messenger Formation. She has recently completed a PhD degree (University of Waikato) on the characterisation and evolution of the Giant Foresets Formation, northern Taranaki Basin, and is currently a post doctoral research fellow, involved in seismic mapping of Taranaki Basin.

ANAND TRIPATHI holds BSc (Hons) and MSc degrees from M.S.University of Baroda, Baroda-India, and has worked for 12 years for Oil and Natural Gas Corporation Ltd, India, most recently with the Basin Group, Western Onshore Exploration Asset. He is currently undertaking research towards a PhD thesis on the sequence stratigraphy of the Te Kuiti Group in central-western North Island and comparisons with the Oligocene succession in northern Taranaki Basin.

STEVEN HOOD is a postdoctoral research research fellow and gained his PhD degree from the University of Waikato. His thesis involved an investigation of the subsurface Tikorangi Formation fracture reservoir in Taranaki Basin. His research interests are focussed on petrology, paragenesis, and petroleum geology of coolwater carbonates and associated siliciclastics, especially in New Zealand.

MELODY NGATAI is currently competing an MSc degree in the Department of Earth Sciences at the University of Waikato, Hamilton, New Zealand. Her thesis topic involves the stratigraphy and sedimentology of the Neogene succession in Mohakatino Valley, Taranaki Basin.

AUSTIN HENDY has particular interests in macrofossil diversity, paleoecology and taphofacies characteristics. He is currently undertaking research towards a PhD in the Department of Geology, University of Cincinatti, USA. He has an MSc degree from the University of Waikato, Hamilton, New Zealand.