

# Neogene thermal history of Opoutama-1, Hawke's Bay Basin: implications for hydrocarbon prospectivity

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## Abstract

Northern Hawke's Bay comprises two sedimentary depocentres, one north of Wairoa containing Middle Miocene Tunanui Formation with a depositional axis oriented northwest-southeast, 90° to the trend of the modern plate boundary zone, and another south of Wairoa containing mainly Late Miocene to Early Pleistocene section uplifted along the axial ranges to form the northeast-southwest striking Hawke's Bay Monocline. Northwest directed shortening since the Late Miocene (Kapitean), driven by the growth of an accretionary prism offshore to the southeast, has folded the Tunanui Formation in the northern depocentre into a series of anticlines and synclines, which have been drilled in the search for petroleum resources.

Apatite fission track (FT) analysis has been applied to samples from Opoutama-1 to establish the thermal history of the more northern depocentre. The porosity of samples of mudstone sequences from the flanks of folds have been determined to independently estimate from an established porosity-depth relationship the amount of section eroded from the surface. Restoration of this section enables the paleogeothermal gradient to be estimated for the host rocks in Opoutama-1 (16°C/km; possible range 11-18°C/km) for the Late Miocene (Kapitean) peak in burial. It is argued that the subnormal geothermal gradient developed during the Middle Miocene when the northern depocentre formed parallel to the contemporary plate boundary, and in response to the cooling effect of emplacement of the subducted slab beneath the basin. This timing is supported by Neogene plate reconstructions of New Zealand that incorporate the extent of the subducted slab of Pacific plate lithosphere. An effect of the cooling of the basin concurrent with its subsidence and sedimentation would be reduction in the rate of hydrocarbon generation and expulsion from possible source rocks at depth in the basin, compared with Taranaki basin which has a more normal thermal regime.

## Introduction

The Hawke's Bay region contains a Neogene sedimentary succession 3-4 km thick regionally (Field & Uruski 1997), reaching 7 km thickness at the northern end of the Wairoa Syncline (Figs 1,2). This overlies a Late Cretaceous-Paleogene succession about 1 km thick (Field & Uruski 1997), which in turn overlies basement comprising a Late Jurassic-Early Cretaceous accretionary complex (Mortimer 1995). The sedimentary cover sequences have been the focus of hydrocarbon exploration activity, with drilling having been undertaken during the 1920s, 1960s, 1980s and late 1990s (Davies et al. 2000; Frederick et al. 2000). As a result of the latest phase of drilling gas resources have been discovered near Wairoa.

The purpose of this study has been to investigate the thermal history of Hawke's Bay Basin to help assess its hydrocarbon prospectivity. This has been undertaken chiefly by

application of apatite fission track thermochronology (e.g. Green et al. 1989a). Samples for analysis have been sourced from curated core and unwashed cuttings originating from selected hydrocarbon exploration holes relating to past drilling. A key well section investigated has been Opoutama-1, located east of Wairoa in part of the basin with prominent anticlines that reflect inversion of the basin succession (Fig. 2). Other well sections investigated include Ruakituri-1, Hawke Bay-1, Te Hoe-1 and Taradale-1, the results of which are reported in Kamp & Xu submitted).

## Geological setting

In the region north and east of Wairoa the rocks at the surface are mainly of Middle and Late Miocene age and have been deformed into a series of northeast-southwest striking anticlines and synclines (Fig. 2A&B). These structures parallel the trend of the plate boundary zone. The structural level and age of the sediments exposed at the surface in the core of

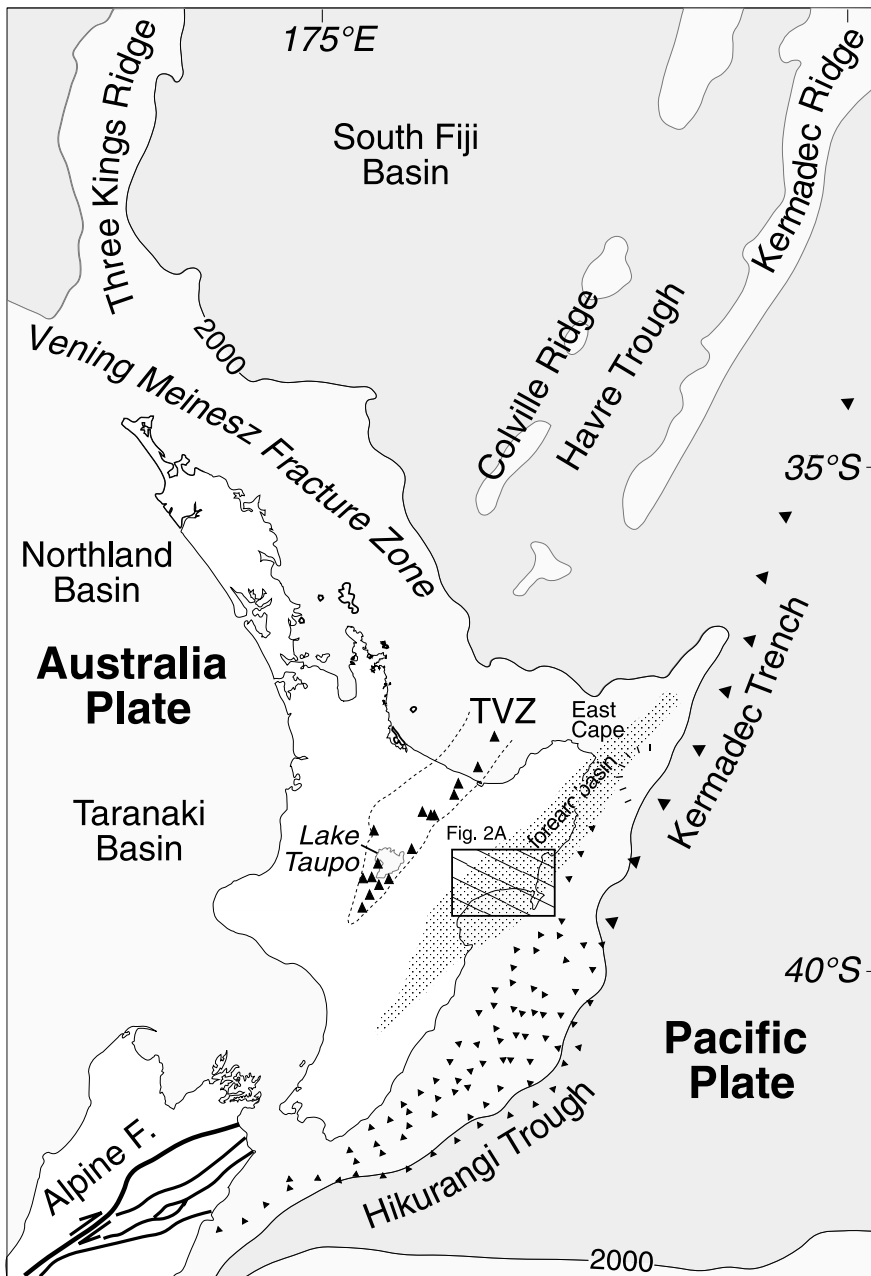


Figure 1: Map of North Island New Zealand showing the generalised extent of the forearc basin in the East Coast region in relation to other features of the modern plate boundary zone, and the location of Fig 2A.

the anticlines increases eastward across the region towards Mahia Peninsula but are no older than Middle Miocene. Late Cretaceous and Paleogene sediments are however exposed in a small fault-bounded zone on eastern Mahia Peninsula (Kingma 1965; Francis 1993)(Fig.2A), probably representing the most inboard thrust zone of the modern accretionary wedge (Lewis & Pettinga 1993). This indicates that deformation of the Neogene basin sediments north and east of Wairoa, which accumulated in a forearc basin, has been driven by the growth and imbrication of the accretionary wedge, with consequent foreshortening in the forearc region. The distribution and facies characteristics of Pliocene limestone sheets north and west of Wairoa (Beu 1995) suggests that most of the shortening and deformation onshore has occurred since the Early Pliocene.

The Middle Miocene section now inverted north and east of Wairoa accumulated in a basin with a depositional axis oriented at right angles to the present structural grain and to the trend of the plate boundary zone. An isopach map of the prominent Middle Miocene Tunanui Sandstone cropping out between Lake Waikaremoana and Mahia Peninsula, shows a depositional axis oriented WNW-ESE (Davies et al. 2000) (Fig. 3). Significantly, Tunanui Sandstone thins dramatically to the southwest. A combination of surface and subsurface stratigraphy of units above and below the Tunanui Sandstone suggests that through the Early and Middle Miocene a broad structural high or platform, at times exposed and at other times forming a shelf environment, existed to the southwest of the depositional axis. During the middle Altonian (Early Miocene) until the Early Tongaporutuan (early-Late Miocene) parts of this platform accumulated cool water shelf carbonates (Davies et al. 2000). The present northeast-southwest structural grain in Northern Hawke's Bay seems to date from the Late Miocene (Tongaporutuan) at about 10 Ma. From that time the modern forearc basin formed, evident in the monocline structure and outcrop pattern southwest of Wairoa (Wairoa Syncline), involving rapid subsidence to bathyal depths followed by infilling to shelf depths during the Pliocene. A thick Late Miocene to Early Pliocene sedimentary section also accumulated over the region north and east of Wairoa

where the Middle Miocene rocks are thickest. The structural shortening and associated erosion that has affected this area since the Early Pliocene has stripped Late Miocene-Early Pliocene section off the cores of the anticlines, but these rocks are still present in the flanking synclines (Francis 1993).

## Methods

### Apatite fission track thermochronology

Apatite fission track thermochronology is a method of obtaining thermal history information in sedimentary basins and basement provinces. As well as providing estimates of maximum paleotemperatures experienced by apatite-bearing rocks, usually achieved through burial, the technique provides a direct estimate of the time at which a sedimentary section or basement sequence began cooling from its maximum paleotemperature, usually via denudation. The basis of the technique, principles of interpretation and kinetic modelling have been described in a series of papers (Gleadow

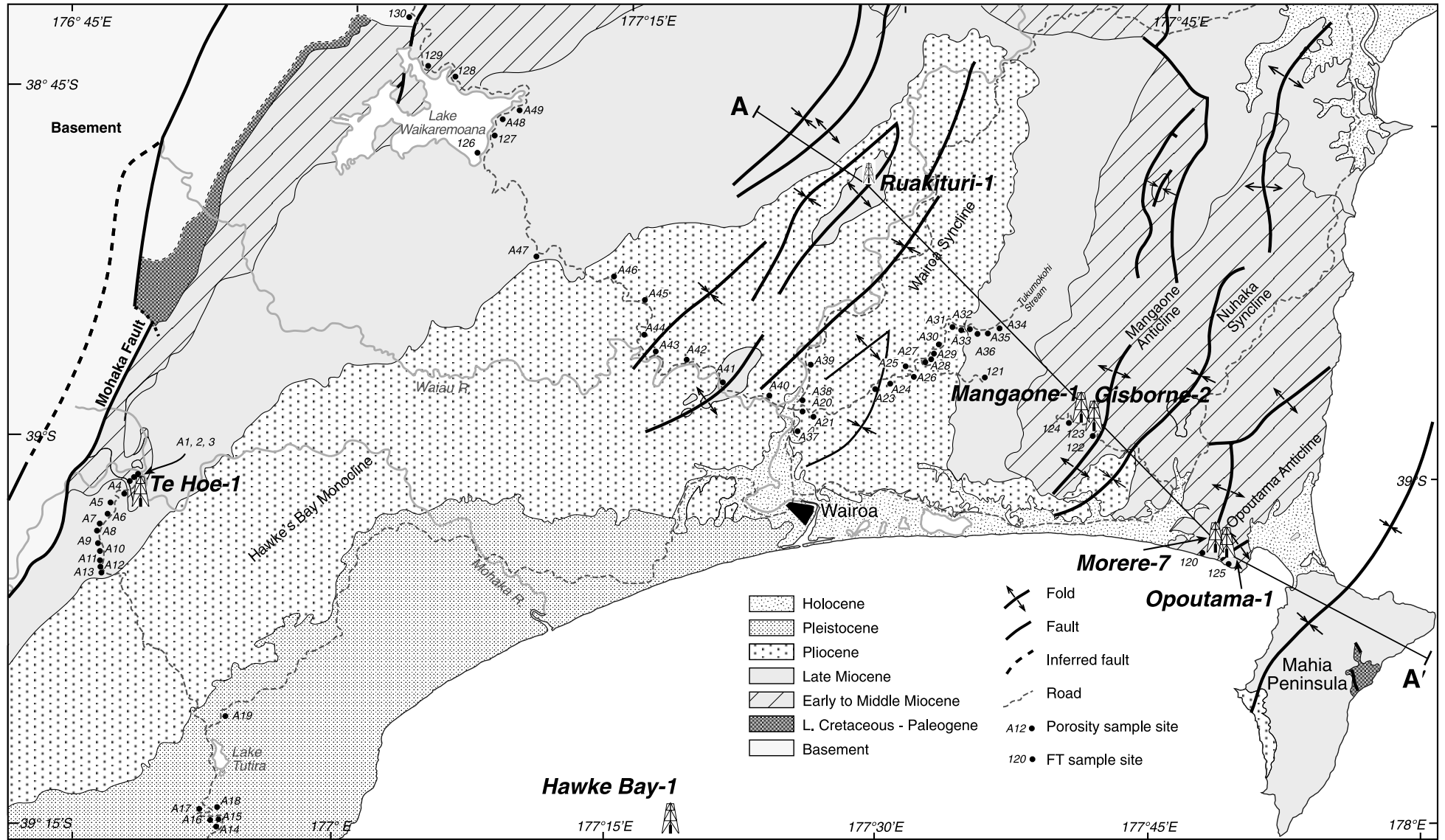


Figure 2A: Map of the generalised geology of Northern Hawke's Bay simplified from Grindley (1960) and Mazengarb (2001). Note the location of "A" series samples for which porosity and burial depths are reported (Table 3), and outcrop fission track samples 121-130 (Table 2).

et al. 1986; Green et al. 1986; Laslett et al. 1987; Duddy et al. 1988; Green et al 1989a; Gallagher et al. 1998). Examples of the application of the technique in sedimentary basins include Green et al. 1989b and Kamp & Green (1990).

In this study standard procedures were followed (e.g. Green 1985) in processing apatites for fission track analysis. Samples of core and unwashed cuttings from Opoutama-1 exploration hole were obtained from the Ministry of Economic Development core store, were processed, of which 6 yielded apatite (Table 1).

(Francis 1993) (Fig. 2A) in middle Miocene (Lillburnian) Tunanui Formation, which extended to 265 m depth in the hole. Tunanui Formation comprises medium to very thick-bedded redeposited feldspathic litharenite with thin siltstone interbeds. This is underlain by Early and early-Middle Miocene siltstone (460.5-716.4 m below KB), 343 m of glauconitic calcareous siltstone (Oligocene Weber Formation, base at 1059.2 m KB) and 410 m of green and grey siltstone (Eocene Wanstead Formation, base at 1469.1 m KB). This in turn overlies Paleocene - latest Cretaceous Whangai Formation (1469.1-2203.7 m KB) comprised of grey-green and dark grey argillaceous mudstone with

Table 1. Fission Track Sample Details, Opoutama-1, Hawke's Bay

Lab No.	Sample type	Depth (m)	Depositional Age (NZ Stages)	Unit
Opoutama-1				
9101-4	cuttings	201-265	Sc	Tunanui Fm
9101-5	core	1902-1904	Mp	Whangai Fm
9101-6	core	2337-2339	Mp	
9801-91	core	3197-3198	Ra	
9801-93	core	3378-3379	Ra	
9101-7	core	3527-3528	Ra	
9801-94	core	3654-3655	Ra	

Apatite concentrates were separated using standard magnetic and heavy liquid techniques. These concentrates were prepared for irradiation in the nuclear reactor at Oregon State University following the procedures outlined by Green (1985) and Kamp et al.(1989). The external detector method (Gleadow 1981) has been used exclusively throughout this study and fission track ages were determined using the zeta calibration method (Hurford & Green 1982; Green 1985). Fission track ages were calculated as central ages (Galbraith & Green 1991). Confined track lengths in apatite sample mounts were measured using a digitizing tablet connected to a computer, superimposed on the microscope field of view via a projection tube. Tracks can be measured with a precision  $\pm 0.2$  microns with this system. Tracks were measured using the recommendations of Laslett et al (1982).

abundant carbonaceous fragments. The lowermost 1454 m of the hole (to 3657.6 m KB) intersected Late Cretaceous siltstone and sandstone beds.

Fig. 2B shows a northwest-southeast oriented cross-section (A-A'), redrawn from Mazengarb (2001), through the structurally inverted zone of northern Hawke's Bay that intersects Opoutama-1 and other wells. A substantial section of post-Middle Miocene sediments have clearly been eroded from the crest of Mangaone and Opoutama Anticlines. Some constraints on the amount (about 3000 m) and timing (latest Miocene - Pleistocene) of this erosion are available from the younger rocks preserved on the western flank of the Mangaone Anticline (Tukumokohi Stream) and within the Nuhaka Syncline (Fig. 2A). Tunanui Sandstone, of which 265 m occurs in the uppermost part of the drill hole, has a total thickness of about 1500 m in the vicinity of Opoutama-1, based on measurements of its thickness in the flanks of the anticlines and in adjacent wells (Fig. 3)(Francis 1993; Davies et al. 2000). Overlying formations (Tangihau Mudstone, Makaretu Sandstone and Pindari Mudstone) of Waiuan and

## Results and interpretations

### Opoutama-1

Opoutama-1 was drilled in 1967 to a total depth of 3657.6 m (Fig. 4). It was located near the crest of Opoutama Anticline

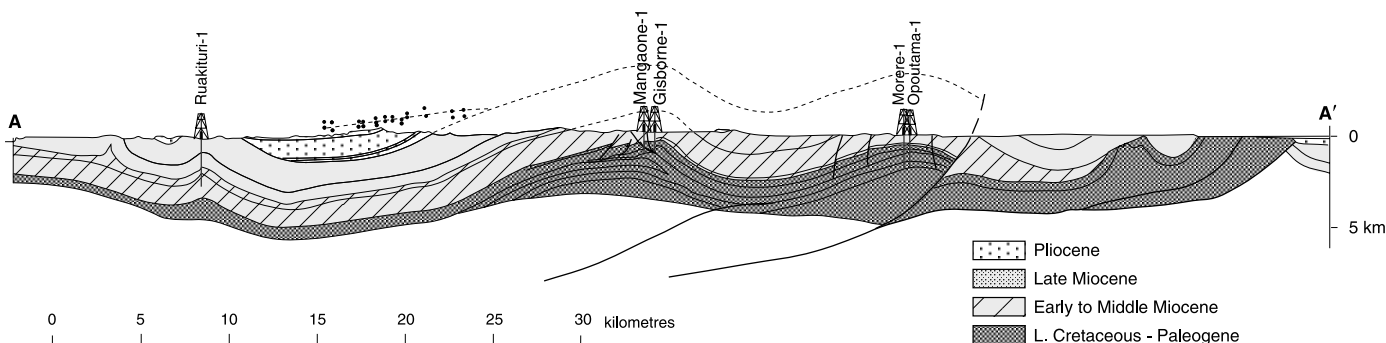


Figure 2B: Cross-section showing the generalised subsurface structure (note age units) of Northern Hawke's Bay see figure 2A for location. (from Mazengarb 2001)

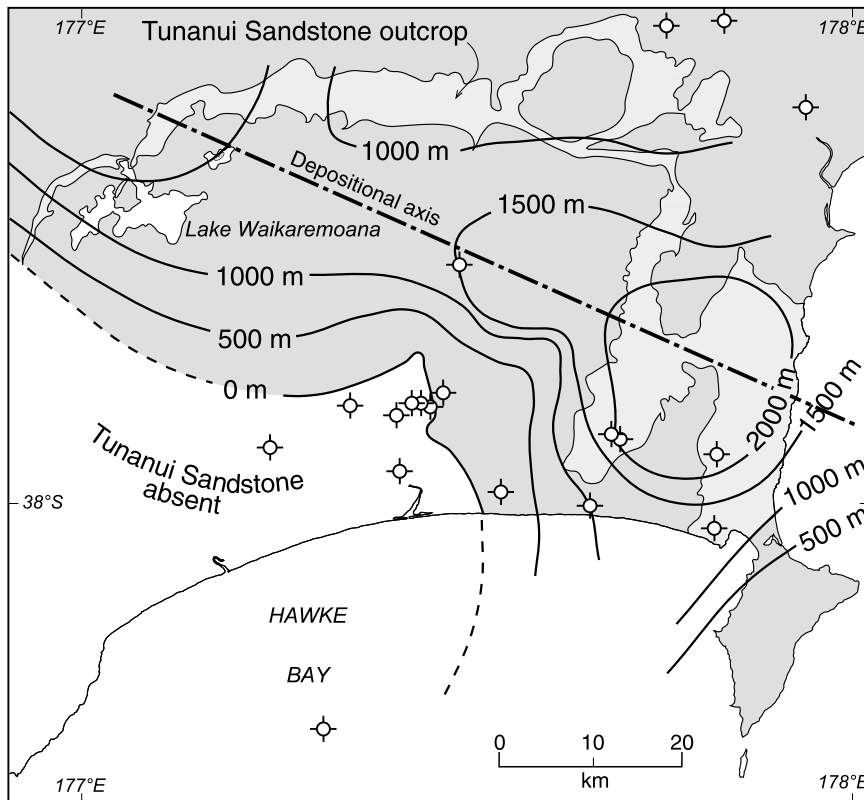


Figure 3: Map redrawn from Davies et al (2000) showing the thickness distribution (in metres) of the Middle Miocene Tunanui Formation in Northern Hawke's Bay. Note the orientation of the depositional axis some 90° to the strike of the modern plate boundary zone. Location of exploration well sites shown but not named.

Early Tongaporutuan age comprise about 750-1000 m of section (Francis 1993; Davies et al. 2000). In the intensively sampled Tukumokohi Stream section (Fig. 2A) on the western flank of the Mangaone Anticline, sediments of early-Late Tongaporutuan age (c 9.5-8.0 Ma) are not recorded (M.Crundwell personal communication 2000), probably due to non deposition, and this is assumed to have affected the Opoutama-1 site as well. This is followed on the western flank of Mangaone Anticline by 1500-2000 m of Poha Formation (Late Tongaporutuan), comprised chiefly of siltstone and fine silty sandstone. In the axis of Nuhaka Syncline (Fig. 2A) the Waiauan-Tongaporutuan beds are mapped as Makaretu Sandstone and Morere Mudstone, of which about 1000 m of sediments, lithologically similar to Tangihau Mudstone to Poha Formation, are preserved (Francis 1993). Given the thickness of Late Miocene (Waiauan-Tongaporutuan) section west of Mangaone Anticline (2250-3000 m), we estimate a conservative 1500 m of mudstone accumulated in the vicinity of Opoutama-1 during this time (13-6.5 Ma), of which about 1 km is preserved in the Nuhaka Syncline.

As latest Miocene and Pliocene rocks are not preserved over the Opoutama Anticline, the burial and uplift history for this interval in the well site area needs to be inferred from the stratigraphy in the west flank of Mangaone Anticline, where rocks of this age occur. In that area most of the Lower Kapitean (6.5-5.5 Ma) is missing in an angular unconformity of 2.5°

evident in Tukumokohi Stream (Wright & Vella 1986). This probably reflects early (submarine) development of the Mangaone and Opoutama folds. This unconformity is overlain by a Pliocene succession about 1000 m thick, but it is possible that these beds overlapped the crest of the Mangaone and Opoutama antiforms without adding to their burial. In the Nuhaka Syncline Early Pliocene Opoiti Limestone unconformably overlies Miocene mudstone and is in turn unconformably overlain by Middle Pliocene Tahaenui Limestone. While this indicates some Pliocene inner to mid shelf deposition in the vicinity of Opoutama-1, and significant erosion during the latest Miocene (Kapitean Stage) and late-Early Pliocene, there is no certainty that any latest Miocene and Pliocene sediments accumulated over the crest of Opoutama Anticline. Therefore in reconstructing the geohistory for Opoutama-1 we take the conservative approach of having burial end during the Early Kapitean at about 6 Ma, when uplift

of the structure started.

### Mudstone porosity data

Fig. 2B shows the locations of sites on the western flank of the Mangaone Anticline for which mudstone porosity values were determined and the amount of burial calculated (Kamp & Xu, submitted). The porosity values decrease and the amount of eroded section increases towards the crest of the anticline, although a few values have lower porosity values that appear out of sequence. Data for the stratigraphically deepest sample (A34) implies about 1600 m of sediments accumulated over the top of this site, which is about mid way in the Poha formation. This could have comprised 750-1000 m of Late Miocene Poha Formation, and 600-850 m of Pliocene Wairoa Formation. As the Wairoa Formation is about 1000 m thick to the west, there is probably some thinning by onlap on to the anticline, which suggests that it was growing as a submarine ridge during the Pliocene. Data for samples near Frasertown in the axis of the Wairoa Syncline imply erosion estimates between 660 m and about 1300 m. This variation is probably real, reflecting local structure, and suggests that considerable late Pliocene sediment accumulated in the Wairoa Syncline.

### Opoutama-1 geohistory

Fig. 5 is a geohistory plot reconstructed for Opoutama-1 based on the stratigraphic and structural constraints outlined above. The Late Cretaceous to early-Middle Miocene burial history is based on the stratigraphy intersected in the exploration hole. For the rest of the Middle Miocene section and for younger strata the history is calculated from the stratigraphy preserved in the western flank of the Mangaone Anticline and within the Nuhaka Syncline, as modified and inferred above for the crest of Opoutama Anticline. Conservative estimates have been taken of the amount of

# Opoutama-1

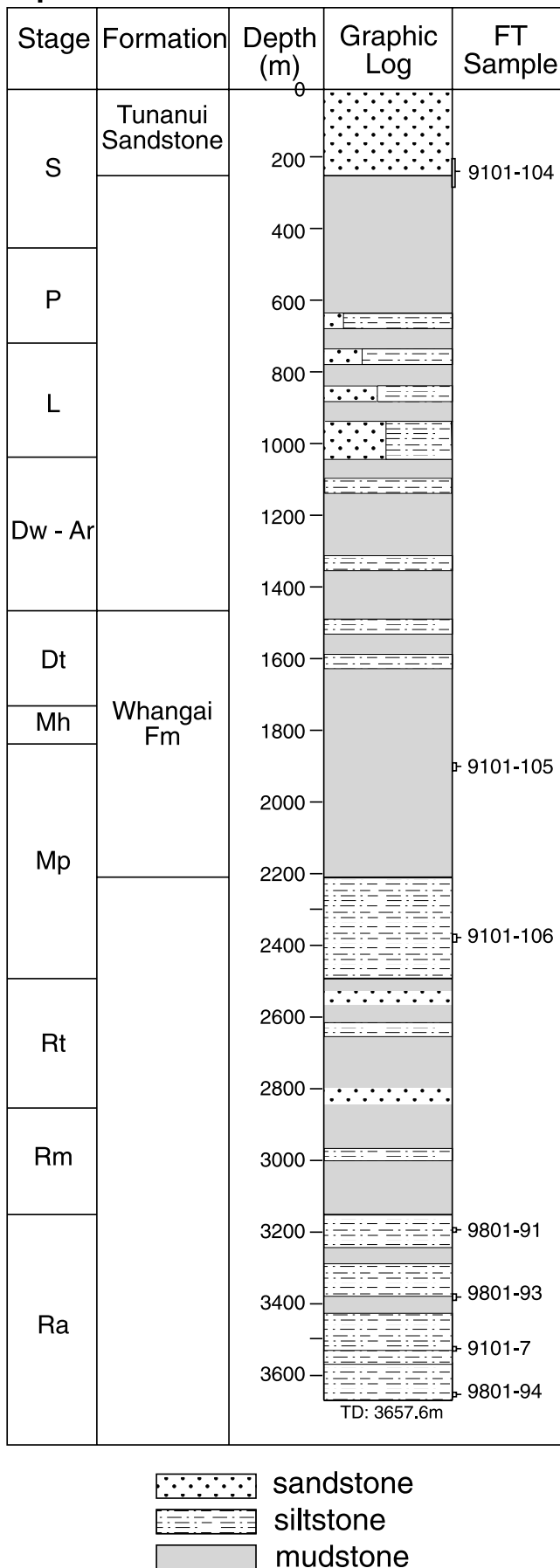


Figure 4: Stratigraphic logs for named well sections in Hawke's Bay showing the stratigraphic position of fission track samples.

Middle and Late Miocene section that accumulated in the vicinity of Opoutama-1, amounting to a total of 3000 m, compared with 4500-5300 m preserved within the Mangaone Anticline. This is because of some uncertainty surrounding the exact timing of initial formation of the Opoutama antiform/anticline (inferred to be 6 Ma), and the possibility of onlap having occurred on to the precursory submarine ridge through the latest Miocene, with minimal, if any, burial after 6 Ma.

### Thermochronological data

Fission track data (FT) have been obtained from six stratigraphic horizons at different levels in Opoutama-1 (Table 2)(Fig. 4, 6). Table 2 summarises the FT age and length data. Fig. 6 shows in (a) the central ages for sample host rocks in relation to the stratigraphic ages down the hole, and below this the individual single grain ages on radial plots. Central ages increase down the well to a maximum of  $63.5 \pm 6.6$  Ma at 2338 m KB, and then decrease to  $20.5 \pm 3.9$  Ma at 3655 m KB. In all except sample 9101-4 the central ages are less than the respective stratigraphic ages indicating significant partial annealing in the basin for the section between about 1000 m KB to TD at 3658 m. Sample 9101-4 shows a wide spread in the single grain ages, all being older than the 15 Ma depositional age, and the sample has a comparatively long mean track length of  $13.18 \pm 0.24$  microns. We interpret these parameters as being dominated by provenance characteristics, with minimal indication of annealing having occurred within the basin.

Several features about the FT data between 1000 and 3658 m in the hole suggest that they belong to one fossil partial annealing zone (PAZ). The mean track lengths decrease down the hole from 9101-5 to 9101-7 together with a reduction in the central ages (Fig. 6). The radial plots show that in all samples there is a reasonable spread in ages, even in the lowermost sample, consistent with the effects of partial annealing. The down-hole decrease in mean track lengths is indicative of increased annealing due to exposure to higher temperatures in the past. Samples between 9101-5 and 9801-94 currently reside at temperatures in the well in the range 68-90°C. This corresponds to the upper (cooler) half of an apatite PAZ. The degree of age and length reduction evident in the lowermost four samples is more than might be expected at 68-90°C and qualitatively would be consistent with former exposure to temperatures in the lower part of an apatite PAZ (e.g. Green et al. 1989b). This would imply cooling of the sedimentary succession in the past from more elevated temperatures.

A remarkable feature of the FT data is the stratigraphic extent of the PAZ in Opoutama-1. At a minimum this extends from sample 9101-5 (1903 m) to 9801-94 (3654 m), a height of 1751 m. The lowermost sample with age and length data (9101-7) is clearly not reset as the mean length is  $11.58 \pm 0.44$  microns. From regional stratigraphic considerations cooling started around 6 Ma, which would be the expected reset apatite FT age. As such an age is not observed, the base of the fossil PAZ lies some distance below the TD of the hole (3658 m). The upper limit of the fossil PAZ is more difficult to identify. Significant age and length reduction occurs at a

temperature of 70°C at geological time scales of annealing. As the apatite grains that entered the basin during the late Cretaceous-Paleogene would have been derived from terrigenous sources, the grains would have had an inherited age component, and significant annealing would be required to reduce the apparent age to the depositional age (the crossover point lies at 1200 m depth KB, Fig. 6). Hence the 70°C paleo-isotherm would lie no lower in the hole than 1000 m KB. A more reasonable minimum stratigraphic extent of the apatite PAZ is therefore 2654 m (3654-1000 m KB). This information constrains the paleogeothermal gradient prior to c.6 Ma as having been about 15°C/km ((110°-70°C)/2.65 km). Currently the gradient is about 22°C based on corrected bottom hole temperatures (Field & Uruski 1997).

### Paleotemperature modelling

Forward modelling, constrained by the stratigraphy in the hole and by the regional stratigraphy, as summarised above, enable quantitative limits to be potentially placed on the maximum temperatures experienced by sample horizons, an approach described by Green et al. (1989b) and Gallagher (1995). The purpose of modelling the paleotemperatures in this study has been to resolve the paleogeothermal gradient more precisely at different levels in the drilled section. It was not undertaken to estimate the amount of section eroded from the well site, which is the more typical application and requires the gradient to be known or assumed (e.g. Kamp & Green 1990). Modelling by the monte carlo method was undertaken using Monte trax software developed by Gallagher (1995), based on the kinetic understanding of annealing made by Laslett et al. (1987) and Duddy et al. (1988). The laboratory-scale annealing experiments of Laslett et al. (1987) were made on Durango apatite, which has a uniform chlorine content of 0.41 wt%. Chlorine content is known to influence FT annealing in apatite (Green et al. 1986). The chlorine contents of apatites in Opoutama-1 samples were not measured in this study. They are likely however, to exhibit a range of compositions, not dissimilar to those in the Otway Group (Green et al. 1986), based on measurements of greywacke basement reported by Tippett & Kamp (1993) and Kamp (1999) that are likely to have sourced the successions in Opoutama-1. A surface temperature of 10°C was used in all calculations. The Monte trax model works by predicting FT ages and lengths for given time-temperature histories, which are compared statistically with the observed FT age and length data. An advantage of this approach is that constraints from the stratigraphy of the hole can be incorporated in the modelling. By modelling a series of samples stratigraphically separated in the one hole, the results are more robust and the errors can be reduced. The errors are likely to have a range of about 10°C.

An independent check on the temperatures modelled from the FT data are provided by modelling of vitrinite reflectance (VR) data available for Opoutama-1 (Jackson 1982). The VR data were modelled using the Burnham & Sweeney (1989) formulation via the thermal history framework of the fission track model. Evolution of VR and FT annealing of fission tracks in apatite have essentially identical kinetics; that is, they respond to the temperature-time conditions to which they are exposed in a similar way regardless of heating

**Table 2. Apatite Fission Track Data for Opoutama-1 (Hawke's Bay Basin) Samples**

Sample Number	Number of crystals	Spontaneous $\rho_s$	$N_s$	Induced $\rho_i$	$N_i$	$P(\chi^2)$ %	$\rho_s/\rho_i \pm 1\sigma$	$\rho_d$	$N_d$	Age (Ma) $\pm 1\sigma$	Mean Track Length $\pm 1\sigma$ ( $\mu\text{m}$ )	Standard Deviation ( $\mu\text{m}$ )	Number of Lengths
9101-4	20	0.171	72	1.349	567	59.8		1.513	3591	<b>33.4</b> $\pm$ <b>4.3</b>	13.18 $\pm$ 0.24	2.49	110
9101-5	15	0.799	122	3.822	584	60.9		1.520	3608	<b>55.1</b> $\pm$ <b>5.6</b>	12.03 $\pm$ 0.28	1.77	40
9101-6	20	0.817	121	3.410	505	98.7		1.527	3625	<b>63.5</b> $\pm$ <b>6.6</b>	11.89 $\pm$ 0.15	1.54	111
9101-7	20	0.324	36	3.197	355	100.0		1.278	3031	<b>22.6</b> $\pm$ <b>4.0</b>	11.11 $\pm$ 0.63	1.99	10
9801-91	30	2.220	114	1.839	944	31.2		1.326	3145	<b>27.5</b> $\pm$ <b>3.0</b>	11.20 $\pm$ 0.66	2.20	11
9801-93	30	0.197	128	1.530	993	1.9	0.127 $\pm$ 0.025	1.334	3165	<b>30.7</b> $\pm$ <b>4.2</b>	11.58 $\pm$ 0.44	1.07	6
9801-94	30	0.093	31	1.039	347	86.9		1.340	3178	<b>20.5</b> $\pm$ <b>3.9</b>	14.24		1

Track densities ( $\rho$ ) are  $\times 10^6$  tracks  $\text{cm}^{-2}$ . All analyses are by the External Detector Method using 0.5 for the  $4\pi/2\pi$  geometry correction factor. Apatite ages calculated using dosimeter glass SRM 612 and zeta-612 =  $343.5 \pm 4.5 (\pm 1\sigma)$ .  $P(\chi^2)$  is the probability of obtaining  $\chi^2$  value for  $\nu$  degrees of freedom (where  $\nu$  is the number of crystals - 1) [Galbraith, 1981]; pooled  $\rho_s/\rho_i$  ratio is used to calculate age and uncertainty where  $P(\chi^2) > 5\%$ ; mean  $\rho_s/\rho_i$  ratio is reported for samples where  $P(\chi^2) < 5\%$  and for which Central ages (Galbraith & Green, 1990) are calculated.

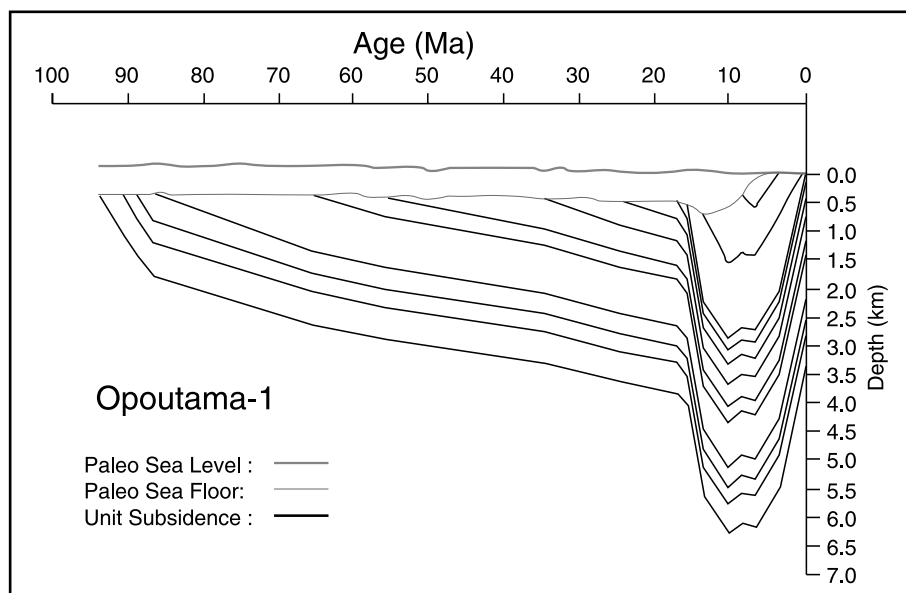


Figure 5: Geohistory plot for Opoutama-1. Note the marked basin formation from 15 Ma, corresponding to accumulation of the Tunanui Formation, and the Late Miocene (Kapitean) inversion of the basin in the vicinity of the well.

rate (Duddy et al. 1991). Total annealing of fission tracks in apatite of Durango composition coincides with a constant Ro% value of 0.7%, for heating times typical of sedimentary basins ( $10^5$  -  $10^7$ ) (Arne & Zentilli 1994).

Fig. 6 shows the model input time-temperature histories (average run) for each of the samples and along side the observed and predicted FT parameters. Because the majority of the depositional history (Late Cretaceous, c.93 Ma, to early-Middle Miocene, c.15 Ma) is recorded as rock section in the hole, and it is reasonably well dated biostratigraphically, there is good control on this part of the thermal history. The uncertainties in the period of heating up to 15 Ma for each sample arises from the assumed geothermal gradient value adopted for this part of the history ( $27^\circ\text{C}/\text{km}$ ) and the chlorine contents of the apatites. Because the maximum temperatures were reached after 15 Ma, the uncertainty in the geothermal gradient will not greatly influence the estimation of maximum temperature. For the post 15 Ma thermal history, the only constraints imposed on the modelling were the timing when maximum temperatures were experienced (6 Ma), and the proportion of Middle versus Late Miocene section, both argued above from the regional geology. In each of the samples the observed and predicted FT parameters compare very closely with each other (Fig. 6). In the lower three samples the discrepancies between the observed and predicted track lengths reflect the limitation of observing few short horizontally-confined tracks in samples with low track densities, and in these cases the validity of the modelling is based on comparison of the observed and predicted FT ages.

The modelled VR values with their possible range of error are plotted on Fig. 6 together with the BP set of VR data. The modelled values lie within the spread in the data. The comparisons are sufficiently close to support the maximum temperatures derived for each horizon from modelling of the FT data.

## Paleogeothermal gradient

The maximum paleotemperatures modelled for each FT sample horizon enable the geothermal gradient to be calculated across the stratigraphic section encountered in Opoutama-1. Fig. 7 illustrates the most likely value ( $16^\circ\text{C}/\text{km}$ ) and the possible upper ( $18^\circ\text{C}/\text{km}$ ) and lower limits ( $11^\circ\text{C}/\text{km}$ ) permissible for an error range of  $10^\circ\text{C}$  associated with the modelled maximum paleotemperatures for each of the FT samples. The value of  $16^\circ\text{C}/\text{km}$  compares well with the approximate c. $15^\circ\text{C}$  estimate made earlier from the extent of the fossil apatite PAZ in the well section. A gradient of  $16^\circ\text{C}/\text{km}$  implies a maximum paleotemperature of

$57 \pm 5^\circ\text{C}$  for the base of the Tunanui Sandstone at 265 m KB in the hole. For 3000 m of Middle and Late Miocene section that formerly overlay this horizon, and a surface temperature of  $10^\circ\text{C}$  at the peak of burial (6 Ma), the gradient would have been about  $15.7^\circ\text{C}/\text{km}$ . This estimate is well within the error range estimated for the succession in the hole (Fig.7).

A question that arises from identification of the subnormal Late Miocene geothermal gradient is the timing of its development. This cannot be uniquely resolved from the FT modelling, but the FT data require it to have occurred by 6 Ma, when maximum paleotemperatures were experienced. The optimum modelling result for the Opoutama-1 samples, particularly the lower three, incorporated a decrease in geothermal gradient at c.15 Ma from c. $27^\circ\text{C}/\text{km}$  to c. $16^\circ\text{C}/\text{km}$ , although a later timing is also possible. A change in gradient around 15 Ma would coincide with the start of deposition of the Middle Miocene Tunanui Sandstone, which accumulated in a bathyal environment. Comparison of the geohistory plot for Opoutama-1 (Fig. 5) with the optimum time-temperatures histories for each sample (Fig. 6), visualises that the scale of burial from 15-10 Ma is not matched by a comparable increase in maximum paleotemperature. Fig. 7 shows more explicitly for two datums (15 Ma & 6 Ma) the scale of the shift in geothermal gradient emerging from the paleotemperature modelling.

The magnitude of the decrease in geothermal gradient is more pronounced and longer lived than can be explained by the transient cooling effects associated with the deposition of cold sediments at the sea floor. It probably has a more fundamental tectonic origin as discussed below.

## Discussion and implications

### Controls on Neogene thermal history

Interpretation and modelling of apatite FT data for Opoutama-1 suggest that the geothermal gradient at the peak of burial during the latest Miocene was about  $16^\circ\text{C}/\text{km}$ . The modelling framework incorporated a gradient value of  $27^\circ\text{C}/\text{km}$  through the Late Cretaceous-early Neogene, and it was assumed that the low gradient value started to develop at

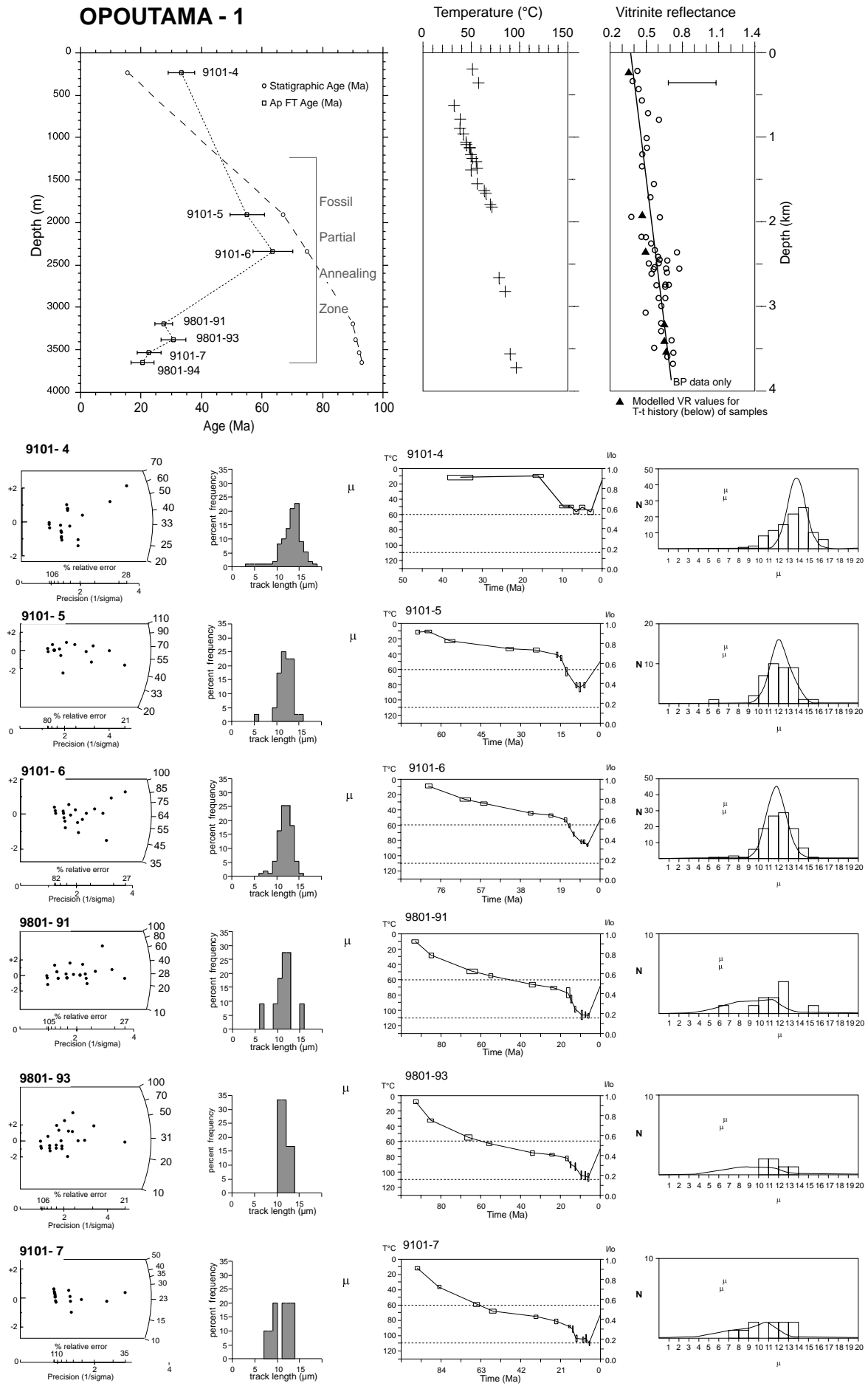


Figure 6: Summary of the fission track, vitrinite reflectance and modern formation temperature data for Oputama-1. Also shown are the fission track data and the modelled temperature–time paths followed by the sample host rock horizons analysed in the well.

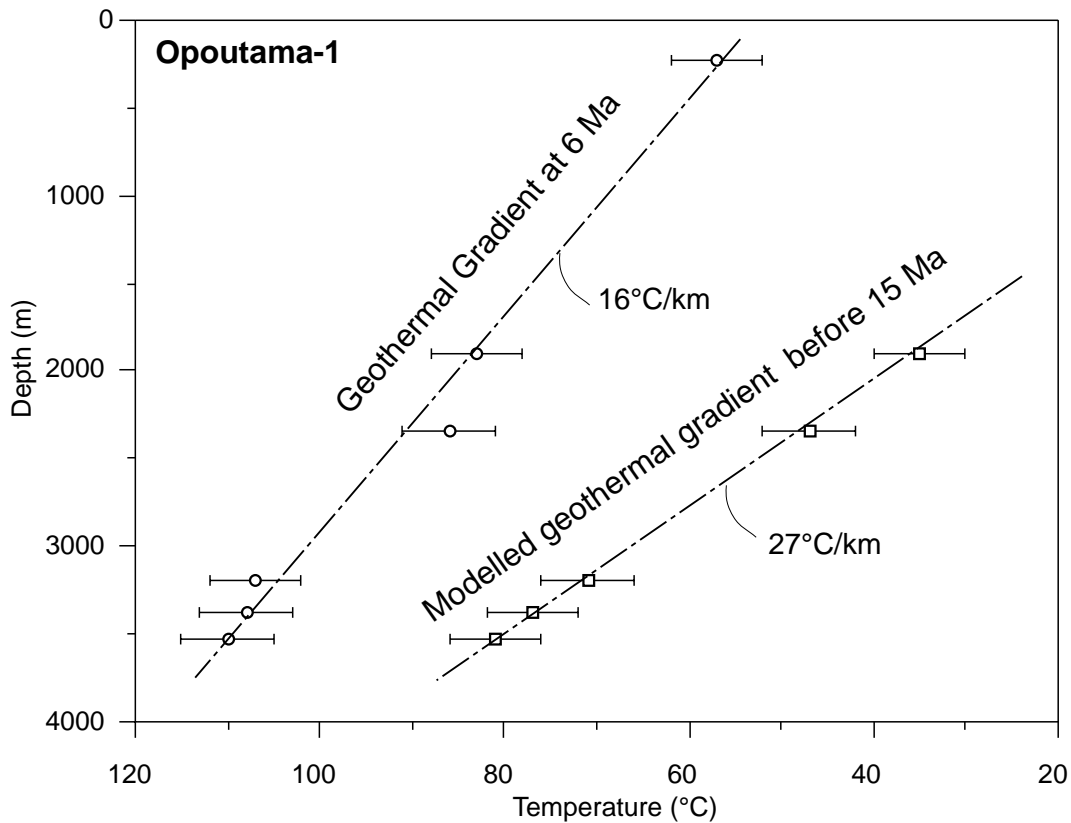


Figure 7: Graph showing the estimated geothermal gradients for the succession in Opoutama-1 for pre-15 Ma and c. 6 Ma. The gradients have been determined from the modelled temperature-time values in Opoutama-1 given the stratigraphic distance between sample horizons.

about 15 Ma, coinciding with deposition of the Middle Miocene Tunanui Sandstone. There is poor control in the modelling over the geothermal gradient prior to 6 Ma when the peak temperatures occurred because the FT parameters and VR values respond chiefly to the maximum paleotemperatures and the cooling history experienced by the succession in the basin. Nevertheless, a geothermal gradient of 16°C/km throughout the well section is very low although not atypical of forearc regions (Dumitru 1988) and requires explanation. The results for Te Hoe-1, which suggested a slightly higher value of 18°C/km for the same period (Kamp & Xu, submitted) support the results for Opoutama-1, and imply that the low gradient was of regional significance.

We seek explanation for the Middle to Late Miocene development in northern Hawke's Bay of a low geothermal gradient in the tectonic evolution of the modern plate boundary zone through eastern North Island. The most recent synthesis of the evolution of the Australia-Pacific plate boundary zone through New Zealand is that of King (2000). One of the uncertainties in any tectonic model of this type is the pre-plate boundary configuration of the crustal blocks, particularly of Eastern North Island. We extend this model by estimating the position through the Neogene of the slab of Pacific plate subducted at the convergent plate boundary along the northern and eastern margins of New Zealand. This was done by tracking towards the southwest, away from the contemporary trench, the unfolded position of the leading edge of the slab, assuming no relative movement between

this oceanic part of the Pacific plate and the continental part (Chatham Rise, Canterbury-Otago, Campbell Plateau) concurrently being displaced on the Alpine Fault (Fig. 8). This assumption is reasonable as the present position of the leading edge of the subducted slab is located correctly in the model beneath Westport (Fig. 8D), as suggested by the modern extent of Benioff Zone seismicity (Reyners et al. 1998). Figure 8 shows the extent of the unfolded slab for four datums, but note in B and D that the position of the leading edge is also shown for 18 and 10 Ma.

A feature shown by these tectonic reconstructions is that the subducted slab became established beneath northern Hawke's Bay around 18 Ma depending on the paleo-position of the East Coast Block (Fig. 8). This just preceded the development and rapid subsidence of the northwest-southeast oriented basin in which the thick Tunanui Sandstone accumulated (Figs 3&5), and with the decrease in geothermal gradient to subnormal values in Opoutama-1 (Fig. 7). We suggest therefore that the emplacement of the slab geodynamically pulled down the crust, thereby forming the sedimentary basin. The concomitant decrease in geothermal gradient resulted from the cooling effect on the over-riding Australia plate of the cold subducted Pacific Ocean crust and the transient effect of cold sediments entering the basin. We draw an analogy here with the subnormal geothermal gradient in the Great Valley sequence in California, which resulted in the Late Cretaceous-Paleogene from shallow subduction of Farralon plate (Dumitru 1988; et al, 1990). The tectonic pull-down that

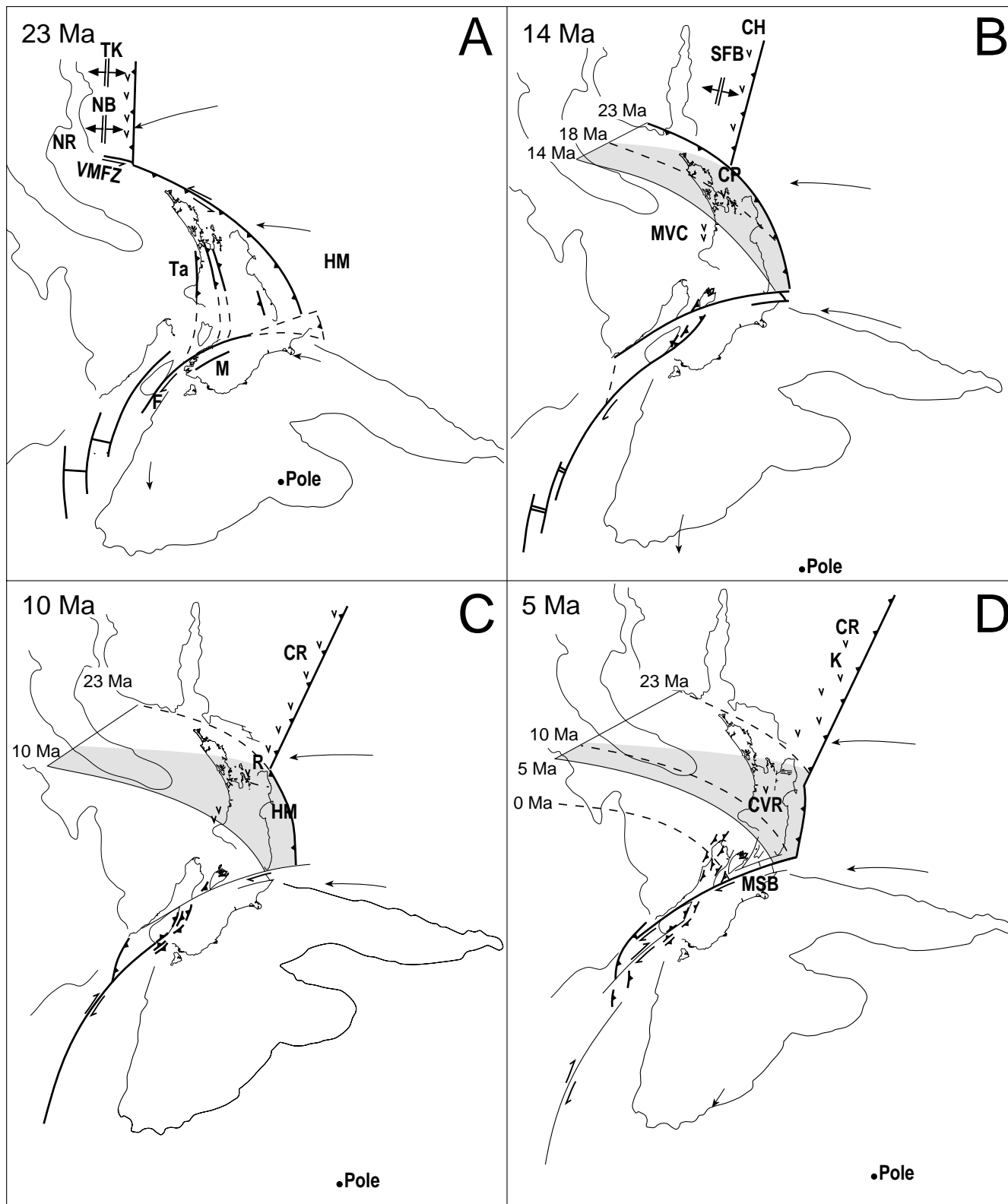


Figure 8: Plate tectonic reconstructions of New Zealand through the Neogene, modified from King (2000) by adding the unfolded extent of the subducted slab of Pacific oceanic lithosphere, located assuming no relative movement between this slab and the continental part of the Pacific plate southeast of the Alpine Fault in South Island. In this figure the position of the slab is shown relative to the palinspastic position of the modern coastline of North Island according to the King (2000) model.

formed the Tunanui depocentre is a Middle Miocene expression of a North Island wide Neogene pattern of basin formation and migration associated with the leading edge of the subducted slab. We emphasise that the apparent timing of emplacement of the subducted slab beneath northern Hawke's Bay, which provides a mechanism for formation of the basin and its low geothermal gradient, is independent of the FT data and its interpretation, which also suggest a decrease in gradient during the Middle to Late Miocene.

### Implications for hydrocarbon generation

Eastern North Island is generally regarded as an under-explored area in terms of hydrocarbon prospectivity. The level of maturity, the timing when peak levels were achieved and the relationship between this timing and that of trap formation, are important elements amongst others in assessment of the hydrocarbon prospectivity of the region. The data presented, modelled and interpreted above impact on these issues and can help move understanding forward for northern Hawke's Bay. First we discuss uncertainties in the interpretations.

A critical observation is that samples (801-91, -93, -94 & 9101-7) from deep in Opoutama-1 retain Late Oligocene-early Miocene apatite FT ages. Together with FT data for horizons higher in the well, all indications are that horizons at the base of the well succession have not experienced temperatures above about 110°C at any time during the Neogene. The FT data do not preclude higher temperatures having been experienced by the Late Cretaceous formations low in the well section during the Paleogene, or earlier, because the FT ages do not record back that far. We return to this point below. The results of paleotemperature modelling are consistent with the peak temperatures occurring during the latest Miocene (c.6 Ma), but this is not necessarily a unique result. As summarised early in this paper, the regional stratigraphy and structure points to the peak burial having occurred during the latest Miocene. Usually, peak burial coincides reasonably closely with peak temperatures, any variation being due to the transient effects associated with the deposition of cold sediments and adjustments in thermal conductivity. If peak temperatures were experienced before the Neogene, which we strictly cannot preclude, the temperatures reached in older formations must have exceeded 110°C and hydrocarbons could have been evolved, given source beds of sufficient quality. Under this scenario it is difficult to predict what type of traps would have initially captured the fluids, at what time this might have occurred and where they may now be located. The alternative scenario is that peak burial and heating of potential source beds, particularly of the Waipawa Black Shale, occurred during the latest Miocene, preceding the structural inversion of the basin, which formed the folds that are commonly regarded as the hydrocarbon traps. In this scenario there is an issue of timing: the heating phase will mostly have preceded the trap formation, although the transient effects noted above may have delayed peak generation until after the folds started to form, as it appears that there was a rapid transition from basin subsidence and sedimentation to inversion of the basin.

Useful analogies can be drawn between Hawke's Bay Basin and Taranaki Basin, although, inevitably, appreciation of the differences between basin evolutions are important in designing an effective exploration strategy for the east Coast region. One similarity lies in the thickness and volume of deep-water Miocene sediments deposited in the two basins. The Tunanui Sandstone is of similar age, facies and depositional environment to the Moki Sandstone (de Bock 1991), Miocene bathyal mudstones (Waingaromia Mudstone, Tangihau Mudstone, Pindari Mudstone and Poha Formation; Francis 1993 and Davies et al. 2000) are similar to the Manganui Formation (King and Thrasher 1996), and latest Miocene through Plio-Pleistocene sediments are analogous to the Giant Foresets Formation in Taranaki Basin. Essentially, both basins have accumulated very thick successions sourced from basement eroded from other parts of the plate boundary zone, which prograded into the basins to form an overall regressive continental margin wedge. The accumulation of this thick sediment wedge caused the burial and maturation of Paleocene units such as the Waipawa Black Shale in Hawke's Bay, just as it buried and matured the Kupe Formation in Taranaki Basin. One difference though, identified here, is that the emplacement of the cold Pacific plate slab impinged upon the thermal regime of Hawke's Bay Basin and setup a subnormal geothermal gradient, which will have retarded, relative to Taranaki Basin, the rate and volume of hydrocarbons evolved from the source beds. Despite the thickness of Miocene sediments deposited in Hawke's Bay Basin the heating resulting from burial was partly counteracted by the low geothermal gradient and was not as dramatic as in Taranaki Basin (Armstrong et al. 1996).

## Conclusions

A thick (2 km) succession of Middle Miocene sediments (Tunanui Formation) accumulated in northern Hawke's Bay, Eastern North Island, in a depocentre oriented northwest-southeast, some 90° to the trend of the modern plate boundary zone (Fig. 1&3). During the latest Miocene the depocentre started to invert as a consequence of shortening driven by northwest-directed imbrication within a growing accretionary prism developing offshore to the southeast. This resulted in the formation of a series of northeast-southwest trending anticlines and synclines (Fig. 2), with deeper structural levels exposed across this zone to the southeast. Many of these folds have been drilled in the search for petroleum resources.

Fission Track (FT) data are reported, modelled and interpreted for Opoutama-1 in northern Hawke's basin. A thick fossil apatite FT partial annealing zone has been identified in this section between 1300 m KB and TD at 3658 m (Fig. 6). Together with paleotemperature modelling of six samples for which the stratigraphic separation are known, we infer a subnormal geothermal gradient of about 16°C/km throughout the well section at the peak of burial during the Late Miocene. Fission track data for Te Hoe-1 suggest a gradient value of about 18-20°C/km (Kamp & Xu, submitted), which is probably within error for the Opoutama-1 result, and indicates that the low gradient was a basin-wide phenomena.

We attribute the development of a subnormal geothermal gradient within Hawke's Bay Basin to the emplacement of the cold slab of Pacific plate beneath the region from 18-15 Ma. We have extended the tectonic model of King (2000) by tracking the unfolded position of the leading edge of the slab, assuming no relative movement between this part of the oceanic plate and the continental part being displaced on the Alpine Fault. The transit of the leading edge of the slab beneath northern Hawke's Bay coincided with the development of a subnormal gradient and the rapid subsidence of the Tūnānui depocentre, which we attribute to some type of dynamic coupling.

The implications of this work for hydrocarbon prospectivity of the basin are that maximum Neogene paleotemperatures were experienced during the Late Miocene immediately before basin inversion started and the structural traps started to form. The evolution of Hawke's Bay Basin has some similarities with Taranaki Basin: both received thick fills of Miocene sediments sourced from the plate boundary zone to the south that forced the progradation of continental margins. A difference however is that the emplacement of the cold slab of Pacific plate beneath Hawke's Bay from the Middle Miocene setup a subnormal geothermal gradient in the crust. This counteracted the effect of increasing temperature experienced by source beds normally achieved by burial. This may have retarded the timing and volume of hydrocarbons generated in the basin, by comparison with the history in Taranaki Basin.

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