HYDROCARBON PROSPECTIVITY OF TARANAKI BASIN WELL SEQUENCES ASSESSED BY APATITE FISSION TRACK ANALYSIS

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Apatite Fission Track Analysis (AFTA) has been applied to samples from four hydrocarbon well sections to study the thermal and tectonic history, and hydrocarbon prospectivity, of the southern part of the Taranaki basin (New Zealand). Samples from three of the wells (Fresne-1, North Tasman-1, Surville-1) show that the successions were exposed to higher temperatures in the past, through deeper burial. Cooling from elevated paleotemperatures was effected by Late Miocene uplift and erosion, of 3.0 ± 0.3 km of section in Fresne-1, and ≤2.0 ± 0.5 and 1.0 ± 0.3 km in Surville-1 and North Tasman-1, respectively. AFTA indicates geothermal gradient values in the past (mid-Miocene) were very similar to present values. In the fourth well (Kupe-1), all formations are currently at their maximum temperatures since deposition.

AFTA provides unique constraints on the timing of hydrocarbon generation in relation to that of trap formation. The proposed source rocks in Fresne-1 passed through the oil formation window (100-150°C) and into the zone of gas production (150-220°C) during the mid-Miocene, prior to the formation of potential trapping structures. Those in North Tasman-1 just passed into the oil formation zone about the same time, and source rocks in Surville-1 have probably never been heated enough to produce oil. AFTA indicate considerable prospectivity remains in the region of Kupe-1, where generation would have occurred after trap formation, leading to the accumulation of hydrocarbons discovered in subsequent wells.

INTRODUCTION

Apatite Fission Track Analysis is a new inorganic technique for analysis of low temperature thermal histories, especially those of the magnitude found in sedimentary basins (e.g. Green et al., 1989a). It is based upon measurement under an optical microscope at high magnification (1250 x) of fission track density and track length distributions in apatite grains separated from host rocks or unwashed cuttings. A latent fission track is a linear zone of atomic damage that results from the spontaneous fission of trace amounts of ^{238}U usually incorporated into apatites at crystallisation. The areal density of spontaneous fission tracks, made visible by acid etching of polished internal grain surfaces, is a function of both uranium content and time; by application of an external mica detector to measure the uranium content (via thermal neutron irradiation) and normalising to geological time using a scale determined by age standards (e.g. Hurford and Green, 1982), fission track ages can be determined for individual grains.

AFTA has the potential to reconstruct the variation in paleotemperature in sedimentary basins over the temperature range required for the generation of hydrocarbons (Gleadow et al., 1983). This arises because the latent tracks in apatite are unstable and anneal (shorten) at temperatures of 20-130°C over time-scales of 10^6 Ma. Consequently, with increasing depth (and temperature) in a stratigraphic succession, the fission track parameters of mean confined track length and sample mean age show a progressive reduction, also reflected in track length distributions and single grain age distributions (Green *et al.*, 1989a). Apatites from host rocks that have undergone different thermal histories (i.e., different temperature - time paths) therefore show different AFTA parameters. This arises because (i) all tracks have a similar length (~16 μm) when produced (Gleadow *et al.*, 1986), (ii) the ultimate length of a track is controlled largely by the maximum temperature that it has experienced (Duddy *et al.*, 1988; Green *et al.*, 1989b), and (iii) new tracks are progressively added to a sample through time. Hence the distribution of confined tracks, which controls the age, contains a complete record of the temperature experienced below about 130°C because each track has experienced a different part of the total thermal history. A particular advantage of AFTA as an exploration tool in the assessment of paleothermal histories, over organically based maturation indicators or fluid inclusion techniques, is the simultaneous provision of information about both the intensity and timing of heating, as we highlight in subsequent sections.

In this study we assess the thermo-tectonic history of four well sequences in the Taranaki basin by application of AFTA. Extended discussion of the results of this study are presented elsewhere (Kamp and Green, in press). This study particularly illustrates the usefulness of AFTA in constraining the timing of hydrocarbon generation in relation to trap formation, which appears to have played a key role in the formation of significant hydrocarbon accumulations in the southern part of the Taranaki Basin.

GEOLOGICAL SETTING: TARANAKI BASIN

The Taranaki basin is one of several late Cretaceous-Cenozoic basins developed upon New Zealand-wide Paleozoic-early Cretaceous basement. It lies mainly offshore beneath the modern continental shelf and slope bordering western North Island, but occurs onshore in northernmost South Island, and the Taranaki Peninsula (North Island). For details of the structure and stratigraphy of the Taranaki basin, see McBeath (1977), Pilaar and Wakefield (1978), Knox (1982), Palmer (1985) and King and Robinson (1988). One of the wells studied (Kupe-1) is located in the Southern Taranaki Graben, and the other three (Fresne-1, North Tasman-1, Surville-1) lie in the Southern Zone, on the southeast margin of the Western Platform (Fig. 1).

APATITE FISSION TRACK ANALYSIS

Several early studies of basement rock sequences (e.g. Wagner, 1968; Naeser and Dodge, 1969) showed that apatite fission track ages are commonly thermally reset, which lead to the conclusion that fission tracks in apatite are unstable at temperatures as low as 100°C (Naeser and Faul 1969; Wagner and Reimer, 1971). Subsequently, analysis of samples from exploration well sequences where formation temperatures could be measured, revealed changes in fission track parameters, notably reduction in fission track age and track length, at increasing temperature in the range 10-150°C (Naeser 1979; Gleadow *et al.*, 1983). The thermally activated processes that progressively anneal the latent radiation damage in the apatite crystal lattice are not completely understood, but empirical observations (Green *et al.*, 1986) show that the net effect of annealing is to reduce the etchable length of each track. A reduction in etchable length is manifest in a reduction in fission track age (density) because the probability of a track intersecting a randomly polished surface depends on the etchable track length (Laslett *et al.*, 1984; Green, 1988).

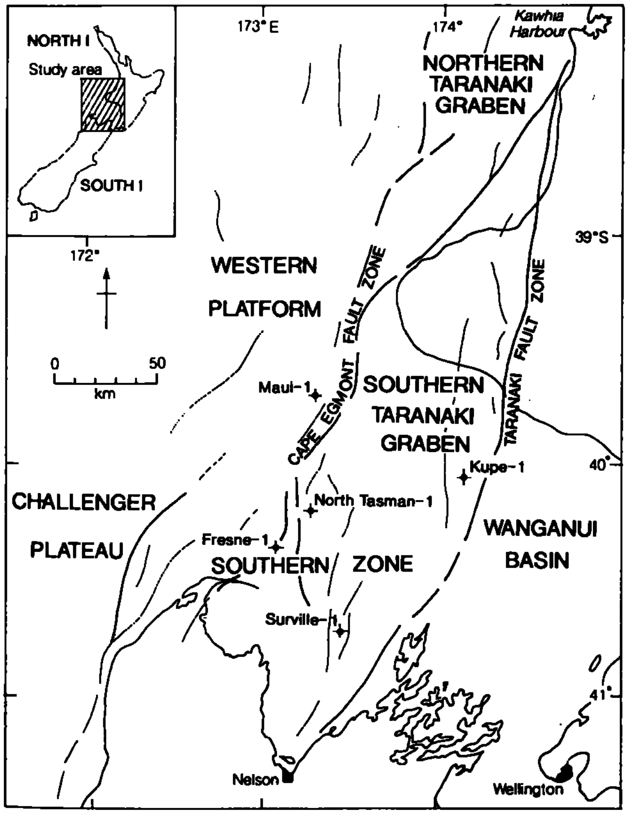

Fig. 1: Location of Taranaki basin and main structural elements. Shown are positions of hydrocarbon exploration wells considered in this study. Figure modified from King and Robinson (1988, Fig. 1).

AFTA routinely involves the determination of fission track ages for 20 grains of apatite, and also a track length distribution for each sample (normally for 100 tracks). Track length data are derived from horizontally confined tracks, a subset of the total tracks, that lie parallel to the etched surface and totally within the crystal, and have been etched by acid that has passed down an intersecting crack or other track. Such confined tracks provide the most direct measure of the distribution of etchable track lengths in an apatite grain, although it is biased against shorter tracks because of their lower probability of intersecting an acid transmitting conduit (Laslett *et al.*, 1982).

The kinetics of fission track annealing for apatite have been established from a series of laboratory experiments (Green *et al.*, 1986; Laslett *et al.*, 1987; Duddy *et al.*, 1988; Green *et al.*, 1989b). Comparisons between the laboratory data and data obtained from simple geological situations have revealed the interplay of temperature and time on the kinetics of annealing. For example, in the laboratory, tracks are totally annealed after one hour at a temperature of c. 360°C (Green *et al.*, 1986), whereas in a geological setting for timescales of 10-40 Ma, tracks are totally annealed at c. 125°C (Gleadow *et al.*, 1983). Superimposed upon the controls of temperature and time on annealing is apatite composition, specifically the Cl/(F + Cl) ratio (Green *et al.*, 1986); in a sample containing a range of apatite compositions, those grains richest in fluorapatite will anneal at a slightly faster rate than more chlorapatite rich grains. At temperature of 90-100°C, and time scales of 10 Ma or more, these differences will be maximised, as shown by distributions of single grain ages and track lengths (Green *et al.*, 1989b) and, in sequence with other samples, can be very diagnostic of the temperatures attained by the rocks.

Thermal history interpretations are based on a quantitative treatment of annealing achieved by forward computer modelling (Green *et al.* 1989b) of track shortening and age evolution through likely thermal histories, derived from burial histories, for an average apatite composition (Cl/(Cl + F) ca. 0.1). The predictions of this procedure agree with observations of fission track annealing in apatites of the appropriate composition in samples from selected wells in the Otway basin (Gleadow *et al.*, 1983; Green *et al.*, 1989b), while data from these wells and experiments in progress afford the means of extending model prediction to other compositions. The uncertainty in predicted track length values is of the order of 0.25 - 0.5 μm, which is considered equivalent to an uncertainty in the absolute paleotemperature estimates quoted in this paper of ± ca. 10°C. Errors due to likely variation in apatite composition are generally less than this figure.

SAMPLE DETAILS

Four to eight samples were obtained from nearly equally spaced depth intervals within each of the four hydrocarbon wells investigated. Sample details including depth, formation name, stratigraphic age and apatite yield are summarised in Kamp and Green (in press), where full details of experimental procedures are given. All samples were splits obtained from curated unwashed well cutting samples from sand-dominated intervals, each of 300 g, retrieved at 3 m spacing during drilling. Each fission track sample comprised about 1 kg of well cuttings, which had necessarily to be obtained from samples ranging over up to about 50 m of section.

RESULTS AND INTERPRETATIONS

Fresne-1

The variation of fission track age versus sample depth in Fresne-1 shows a rapid decrease, from values much greater than stratigraphic age in shallower samples to values much less than stratigraphic age in deeper samples (Fig. 2). In sample 8694-7 individual grains have ages from 44 to 123 Ma, with no grains significantly younger than the stratigraphic age of ~53 Ma. Thus the age data for this sample show no direct evidence of annealing since deposition. In 8694-8 a small number of the grains counted have ages significantly less than the stratigraphic age of ~59 Ma, indicating this sample has experienced temperatures during burial high enough to severely anneal the more sensitive apatite compositions (those richer in fluorine). Samples 8694-9 and 10 have both undergone severe annealing as all but one grain in each sample have fission track ages significantly younger than the stratigraphic ages of ~66 and ~68 Ma, respectively. The four deepest samples give similar age data to those in 8694-10 and have been severely annealed.

The rapid decrease in fission track age (and increasing degree of annealing) with depth in Fresne-1 takes place at temperatures less than 50°C, at which appreciable annealing would not be expected. This pattern shows therefore that the sedimentary sequence has been subjected to higher paleotemperatures at some time in the past. The distinct inflection in the pattern of fission track age versus depth shown in Fig. 2B suggests that the samples span the transition from partial to total annealing of tracks formed prior to attainment of maximum paleotemperatures through the section. All samples below 8694-10 (except 8694-12) would have been totally annealed prior to cooling. This interpretation is supported by the track length data (Fig. 2B) and *corrected ages* discussed below. In 8694-12, a single grain which gave an age of 107 Ma may represent an unusually retentive composition and has had a large effect on the mean age (18.3 ± 5.4 Ma) of the grains counted. Contamination or caving may also explain the presence of this grain.

The AFTA data allow an independent estimate of the timing of cooling from maximum paleotemperatures by *correction* of the measured fission track ages, which provides an estimate of the time over which the tracks have been retained. Using the relationship between track length and fission track age reduction reported by Green (1988), corrected fission track ages have been calculated for all samples from Fresne-1. In samples that have been only partially annealed, age correction can severely underestimate the true time over which tracks have been retained. However, in the three samples considered to have been totally annealed (8694-11, 13 and 14), corrected ages are between 8 and 12 Ma, giving the best estimate available of the timing of cooling in this well.

In principle, the elevated paleotemperatures could have been produced by either greater depth of burial followed by uplift and erosion, with a thermal gradient close to the present value, or by a period of higher thermal gradient, or by a combination of both. There are two unconformities in the Fresne-1 succession. One is defined by early Tertiary beds, extends from ca. 52-29 Ma; the other lies in the Miocene section (ca. 15.5-2 Ma), and Knox (1982) considered from seismic profiles that at least 2000 m of late Miocene-Pliocene section had been removed by uplift and erosion at this level. The observation (above) from fission track ages that cooling took place in the late Miocene, is consistent with cooling being due to uplift and erosion associated with development of the late Miocene unconformity.

The quantitative treatment of fission track annealing in apatite described in an earlier section has been used to derive estimates of maximum paleotemperature for each sample. These have been derived from the burial histories appropriate to each sample, with additional burial between 15.5 and 12 Ma, prior to uplift starting about 12 Ma, with the thermal gradient equal to the present value of ~28°C/km throughout the history. This procedure requires adjustment of the amount of section deposited between 15.5 and 12 Ma, and subsequently removed by uplift and erosion, to match the observed data. The difference between estimated maximum paleotemperature and present temperature in each of the upper four samples is very consistent at ~80°C, while the deeper samples allow only lower limits on the difference, as they were totally annealed. This consistency suggests that the assumption of a constant geothermal gradient through time is valid, and that the observed cooling was due to uplift and erosion of ~3.0 km during the late Miocene-Pliocene. The uncertainty of ~10°C in the estimated paleotemperatures, combined with other factors, suggests an uncertainty of 0.3 km in this estimate.

Kupe-1

Sample mean fission track ages in samples from Kupe-1 show a progressive increase with depth in contrast to the pattern for Fresne-1 (Fig. 3). In each sample, mean fission track age is significantly older than the stratigraphic age (Fig. 3), and therefore the samples are interpreted to have undergone much less annealing than those in Fresne-1.

The three shallowest samples, with Pliocene-Pleistocene stratigraphic ages, have very similar apatite fission track age data. In each sample there is a significant spread of individual grain ages from a few to ~100 Ma, none being significantly less than the stratigraphic ages, of 1.2, 2.8 and 4.5 Ma, while mean ages are much older, in the range 41-44 Ma. These samples are part of a 2.15 km section deposited apparently without significant stratigraphic breaks during the last 5 Ma. Over this time scale, and at temperatures of ~60°C or less, little annealing would be expected, and the AFTA data from these samples including track length distributions can be interpreted as characteristic of the provenance terrains of the sediments.

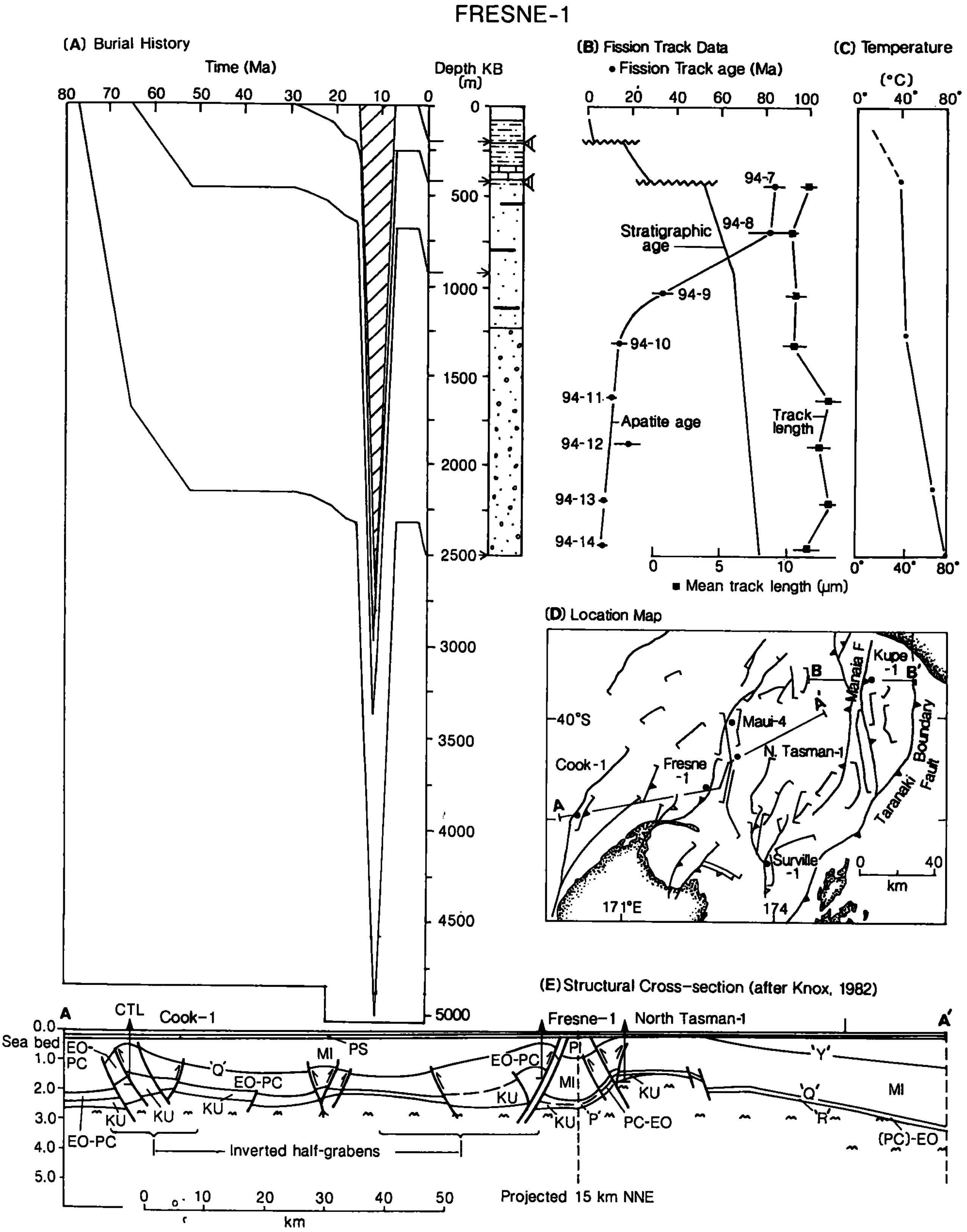

Fig. 2 Composite figure showing compaction-corrected burial history of selected horizons (A), fission track data (mean age and track length) (B), present formation temperatures (C), location map (D) and structural setting (E) of Fresne-1. See Fig. 4 for map and lithology symbols, and Fig. 7 for age of seismic horizons. The first two numbers (86) of sample numbers have been left off this and subsequent figures. Error bars are ± one standard deviation of mean values.

In sample 8694-4, which comes from below the Miocene-Pliocene unconformity, a large spread of single grain ages is present, from 22.9 ± 6.9 Ma to 164.2 ± 102.9 Ma. As none of these ages are less than the stratigraphic age (~15 Ma), and the sample mean age (87.4 ± 7.4 Ma) and length (11.75 ± 0.23 µm) are both larger than for the immediately overlying sample (8694-3), the AFTA data for 8694-4 are also best interpreted as characteristic of provenance areas.

Similar interpretations of the dominance of provenance control can be made about the data from the two deepest samples, 8694-5 and 6, which also show significant spreads of single grain ages, with mean ages of 125.1 ± 17.2 Ma and 136.9 ± 18.0 Ma, respectively, and no grains significantly younger than the respective stratigraphic ages of ~40 and ~65 Ma. In these two samples, individual grains with older ages in the 250-400 Ma range are evident.

Thus AFTA data in all samples from Kupe-1 are dominated by the characteristics of source regions. As explained in more detail elsewhere (Kamp and Green, in press), track length data in the five shallower samples are consistent with this conclusion, while those in the deepest sample suggest that some annealing may have occurred since the recent phase of heating began, although not enough to show clear signs of age reduction.

The lack of discernible annealing in samples presently at temperatures of almost 100°C can be understood in terms of the kinetics of fission track annealing. Because of the rapid Pliocene to Recent burial of the sequence in Kupe-1, all samples have increased in temperature by ~55°C during the last few million years. As fission tracks take up to ~10 Ma to *react* to increases in temperature (Green et al., 1989b), the AFTA parameters in samples from Kupe-1 have not had sufficient time to achieve a degree of annealing appropriate to the present temperatures. Thus until the onset of Pliocene de-position, the deepest sample was at a temperature of below 50°C, where annealing since deposition would have been very minor, and the AFTA parameters in this and shallower samples retain their source characteristics.

The seismic section shown in Fig. 3 suggests that a ~1.9 km-thick pile of late Miocene sediments were deposited and subsequently removed by uplift and erosion from the section in Kupe-1 between 8 Ma and 5 Ma. Because of the resulting rapid time scale of heating, such an amount of uplift and erosion could have occurred without affecting the AFTA parameters in 8694-4 or deeper samples.

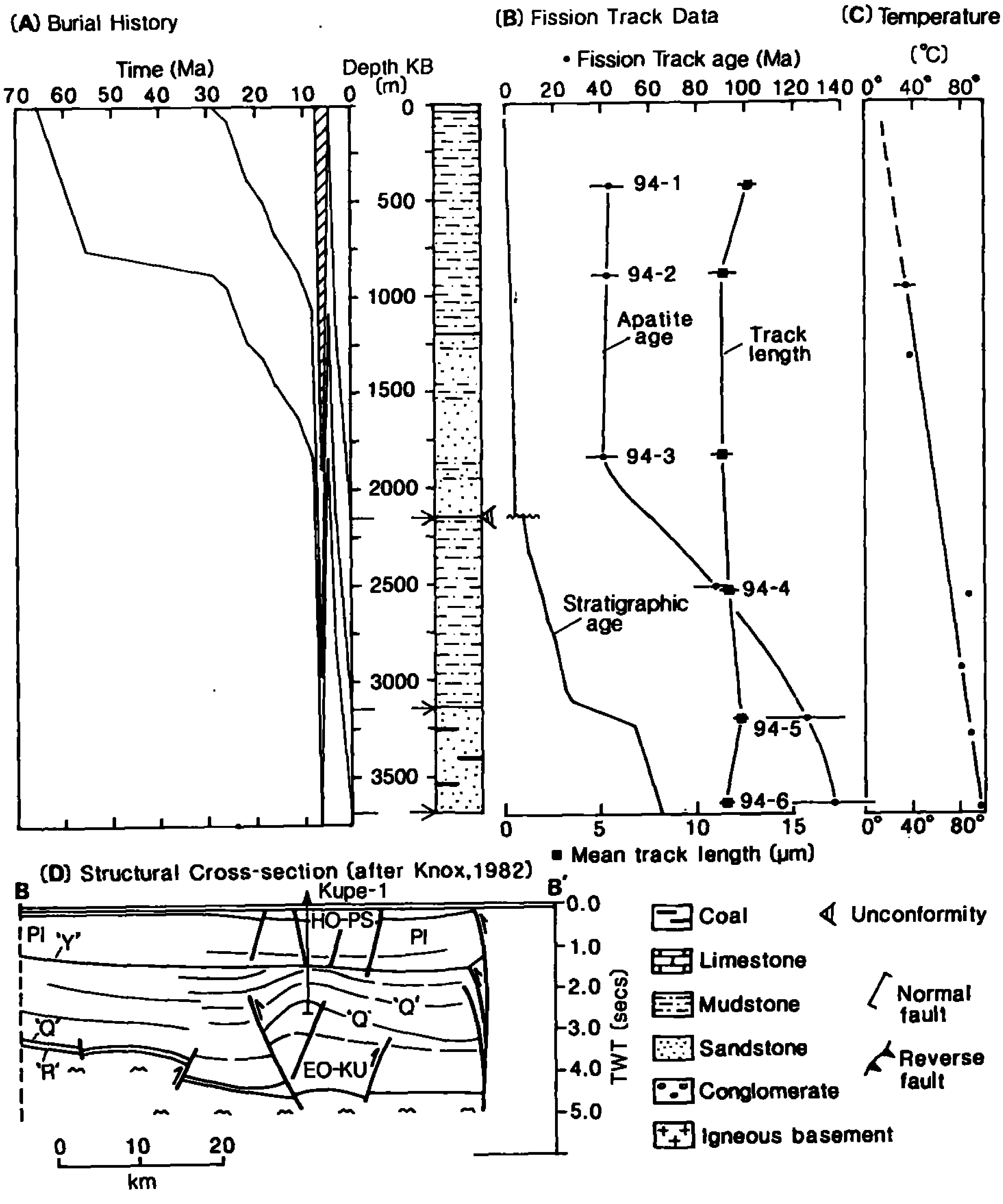

Fig. 3: Composite figure showing compaction-corrected burial history (A), fission track data (mean age and track length) (B), present formation temperatures (C) and structural setting (D) of Kupe-1. Timing and magnitude of late Miocene structural inversion in (A) from Knox (1982). See Fig. 2D for location of seismic section, and Fig. 4 for age of seismic horizons. Error bars are ± one standard deviation of mean values.

In summary, AFTA parameters in Kupe-1 are dominated by inheritance from source areas, with the thermal regime in the well having little effect. This is the opposite situation to that interpreted for Fresne-1, where the thermal regime in the well had a profound effect on the AFTA parameters. The AFTA data for North Tasman-1 and Surville-1 indicate that the successions have experienced higher paleotemperatures in the past, but not as high as those identified for Fresne-1.

North Tasman-1

In North Tasman-1 the apatite fission track ages are similar in the two shallowest samples and then decrease with increasing depth (Fig. 4). This age pattern is more obvious in the peak positions of the smoothed probability curves for successively deeper samples, and is considered to reflect provenance control on the uppermost sample, and annealing control on the lower three samples.

The two deepest samples show the clearest evidence of annealing within the basin. In 8694-21 the mean age of 67.8 ± 5.3 Ma is close to the stratigraphic age of ~70 Ma, and a number of grains give ages that are significantly younger than the stratigraphic age. Sample 8694-22, a basement granitoid, gives a mean age of 60.9 ± 7.2 Ma, and a large number of individual grains give ages which are significantly younger than the stratigraphic age of overlying sediments, some as young as 10 Ma. The occurrence of significant annealing is also shown by the mean track lengths for these samples, which are quite short at 9.83 ± 0.26 and 9.93 ± 0.28 µm in 8694-21 and 22, respectively. Expected mean lengths of tracks produced since burial in these samples if there had been no changes in geothermal gradient and no periods of uplift and erosion are 12.1 and 10.6 µm, respectively.

In summary, the AFTA data from the three deeper samples in this well suggest that they may have been slightly hotter than their present temperatures, though since none of these samples has been totally annealed since deposition of 8694-21, a direct estimate of the timing of any elevated paleotemperatures is not available from the data. However this does set a limit on the amount by which paleotemperatures could have exceeded present values of ~25°C. Broad estimates of maximum paleotemperature in other samples from this well are consistent with this figure.

Knox (1982) suggested a Pliocene episode of structural inversion involving erosion of 1350 m of Late Miocene section from this well. Assuming that the geothermal gradient (31°C/km) has remained constant over the last 10 Ma, the AFTA data are broadly consistent with this figure, but suggest that a maximum of ~1000 m of late Miocene section was removed.

Surville-1

Data from the shallower three samples from Surville-1 are very similar, except that whereas 8694-15 and 16 show a significant spread of single trains ages, data from 8694-17 are consistent with a single age component. Mean ages are all around 80 Ma (Fig. 5), and individual grains are all greater than the respective stratigraphic ages, so the age data do not show any direct signs of annealing since deposition. Mean track lengths are between 10.1 and 11.6 µm, with broad distributions in each sample and a fair proportion of tracks in each sample shorter than 10 µm. Since the fission track ages are much greater than the stratigraphic ages, much of the observed shortening could have been inherited from source regions.

However tracks produced since burial in these samples would, in the absence of any changes in geothermal gradient or periods of uplift and erosion, be expected to be between 14 and 15 µm. Given the age data from these samples, up to 30% of the tracks in each sample might be expected to have formed since deposition. Inspection of the track length distributions in these samples shows that they do not show major contributions at these lengths, but that the majority of tracks in each sample are shorter than expected. This therefore suggests that these samples may have been rather hotter than at present, at some time since deposition.

This is supported by data from the deepest sample, of granitoid basement. This sample (8694-18) shows a significant spread of single grain ages with a mean of 74.5 ± 6.4 Ma. A number of grains give fission track ages which are significantly younger than the depositional age of the sediments overlying this basement sample, some giving ages as young as 10 Ma. While not being sufficient to produce a distinct young peak in the smoothed probability function of single grain age data, these grains do produce a noticeable shoulder towards younger ages. Since the present temperature of this sample is only ~66°C, annealing of this degree would not be expected at such a temperature, showing that this sample must have been exposed to higher paleotemperatures at some time since emplacement. Track length data support this conclusion.

In the absence of samples in this well that have been severely annealed, it is again difficult to obtain direct estimates of the timing of cooling from the elevated paleotemperatures, or to make precise estimates of maximum paleotemperature in each sample. Most likely timing for cooling, based on the preserved section in the well and the seismic section shown in Fig. 5, would be that represented by the late Miocene-Pliocene unconformity in this well. On this assumption, attempts to model the degree of annealing seen in each sample suggest that maximum paleotemperatures were ~40°C greater than present values, which would imply ~2.0 km of uplift and erosion for the current geothermal gradient of ~21°C/km.

DISCUSSION OF THERMAL AND TECTONIC HISTORY

The AFTA results presented above establish four different and unique elements of the thermo-tectonic history of the hydrocarbon sequences considered here.

(1) Quantitative modelling of the AFTA data establish directly the maximum paleotemperatures experienced during burial by three of the four well sequences. For Fresne-1, North Tasman-1 and Surville-1, these temperatures were higher in the past by 80°, 25° and 40°C, respectively. We have not modelled the Kupe-1 data to derive maximum paleotemperatures, as analysis of the AFTA data shows that all samples are presently at their maximum temperatures since deposition.

(2)AFTA has established the timing of cooling from maximum paleotemperatures. In Fresne-1 the start of cooling occurred about 12 million years ago, a datum calculated by length correcting the stratigraphically highest of the totally

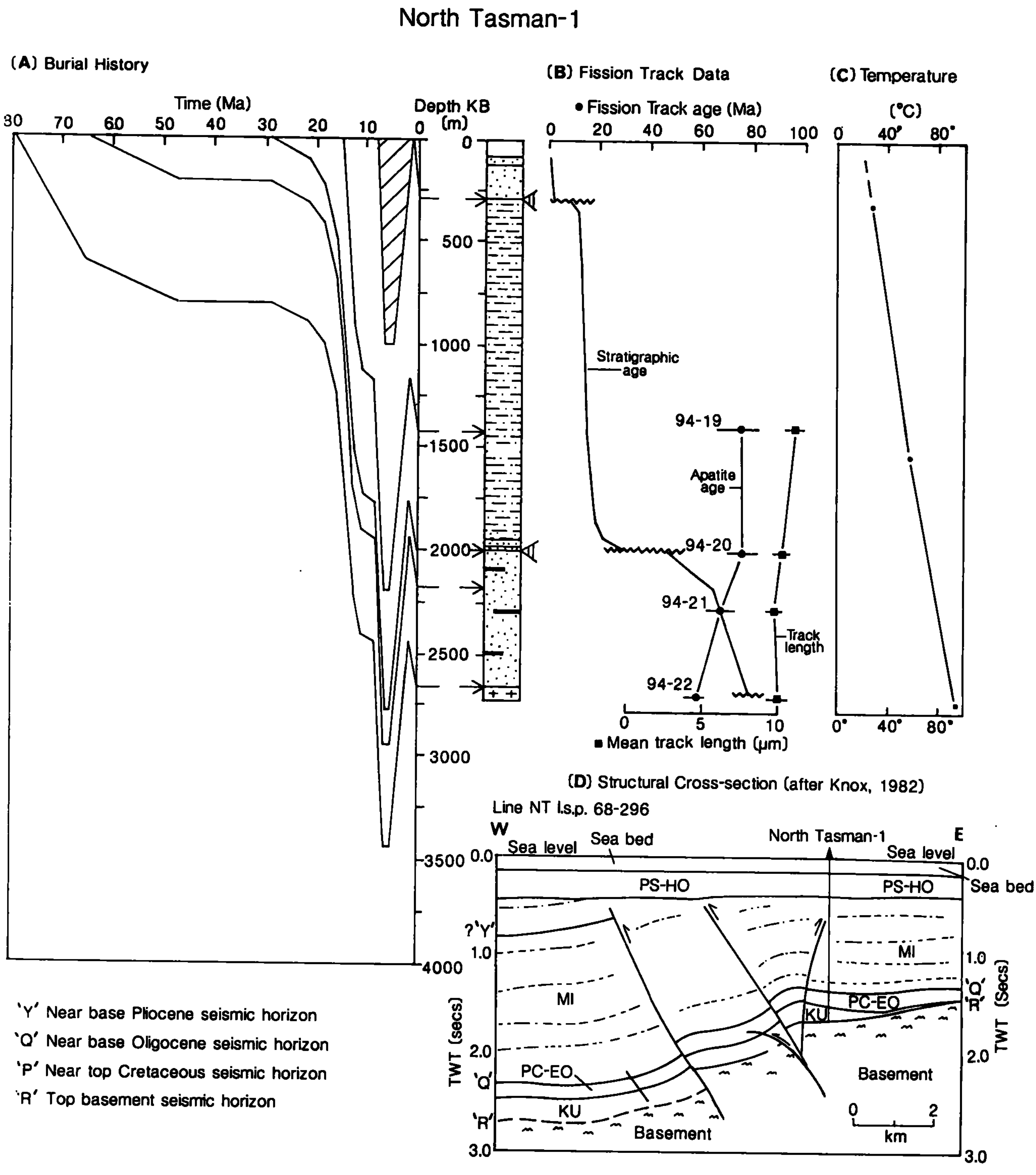

Fig. 4 Composite figure showing compaction-corrected burial history (A), fission track data (mean age and track length) (B), present formation temperatures (C) and structural setting (D) of North Tasman-1. Timing of structural inversion in (A) from Knox (1982); the magnitude is from fission track results, which agrees with the estimate from seismic profile. Error bars are ± one standard deviation of mean values.

reset ages (8694-11) in the well. This datum lies within the time interval of the upper unconformity in the Fresne-1 succession. This datum cannot be established from stratigraphic ages because of the missing section. It is established by AFTA, however, because the age of the start of uplift is recorded several kilometres deeper in the section (where the chances of preservation are higher), as a result of the upward passage of a horizon, lying initially at a temperature at which no tracks are stable, into a slightly cooler zone where (partial) track accumulation can begin. An estimate of the duration of the uplift (cooling) phase is given by corrected ages of samples lower in the well; this indicates uplift

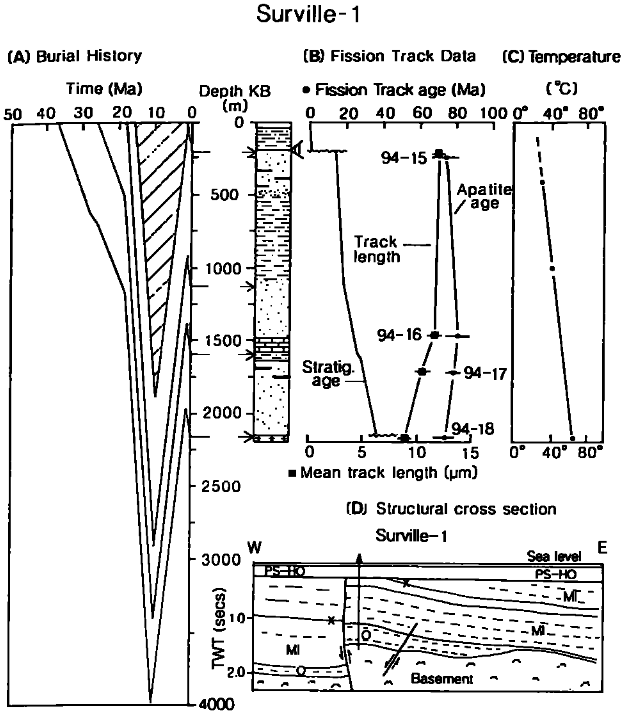

Fig. 5 Composite figure showing compaction-corrected burial history (A), fission track data (mean age and track length) (B), present formation temperatures (C) and structural setting (D) of Surville-1. Timing of structural inversion in (A) from Knox (1982); magnitude from fission track results which agrees with the estimate from seismic profile. Location of cross-section shown in Fig. 2D. Error bars are ± one standard deviation of mean values.

continued until 8 Ma, at least. Assuming all of the 3.0 km uplift occurred during the interval 12-8 Ma, the rate of uplift was 0.75 m/ky or 0.75 mm/y.

(3) The results of modelling Fresne-1, North Tasman-1 and Surville-1 data suggest that geothermal gradient values in the past were very similar to those at present. This is indicated by the consistent difference between the current formation temperatures and maximum paleotemperatures for each sample in depth sequence. This conclusion strictly applies to the interval (mid-Miocene) preceding the start of structural inversion, when maximum paleotemperatures (and burial) were experienced by the succession sampled.

(4) For Fresne-1, North Tasman-1 and Surville-1, the degree of inversion, estimated from the AFTA parameters, can more tightly constrain a critical part of the burial history: the interval of rapid subsidence leading up to the start of uplift when maximum paleotemperatures, and hence maturation, were experienced. A common method of estimating the thickness of section eroded involves extrapolating into unconformities within structural inversions the thickness of correlative strata in adjacent regions. Where the inverted strata accumulated in half-grabens against syn-sedimentary faults, this method may underestimate the thickness of strata eroded during the inversion and hence the amount of sediment deposited before uplift and erosion commenced. This factor may account, for example, for the greater AFTA estimate of (3.0 km) uplift and erosion in Fresne-1, compared with the estimate (2.0 km) from interpretation of seismic profiles (Knox, 1982).

From interpretation of seismic profiles, Knox (1982) showed clearly that the late Miocene-Pliocene uplift was associated with localised inversions along discrete axes involving syn-sedimentary normal faults that changed their sense of displacement to become reverse faults. The structural inversions are an intrabasin culmination of a change to compression heralded earlier by changes in sedimentation patterns. These included the ~17 Ma peak of marine transgression in the Taranaki basin, and the ~16 Ma increase in sediment supply from the south and east with associated development of large submarine fans within the southern and eastern parts of the basin (King and Robinson, 1988). This north and west directed progression into the Taranaki basin of compressive deformation overprinted in its southern part the earlier (mid-Tertiary) twofold subdivision of Western Platform and Taranaki Graben (Fig. 1), and was part of a more extensive change in New Zealand from extension and subsidence to compression and differential vertical crustal movement, caused by evolution of the modern Australia-Pacific plate boundary through New Zealand (Kamp, 1986a, b).

IMPLICATIONS FOR HYDROCARBON PROSPECTIVITY

The thermal history of a sedimentary basin is a critical factor governing the hydrocarbon prospectivity of its successions, although many different opinions have been expressed as to the definition of suitable conditions for generation of hydrocarbons. Quigley and Mackenzie (1988) recently suggested that for heating rates around 1-10°C/My, temperatures in the range 100-150°C and 150-220°C are required for generation of oil and gas, respectively.

Our AFTA study has established several important elements of the thermal history of four southern Taranaki well successions. These show that the proposed source rock horizons (Pakawau Group) in Fresne-1 passed into the oil generation window (100-150°C), and the lower part of the sequence passed into the region of gas generation (150°-220°C), before the onset of late Miocene structural inversion that would have produced potential trapping structures. Therefore Fresne-1 was dry probably because hydrocarbons were generated during the late Miocene, and have subsequently migrated elsewhere. The Pakawau Group source rocks encountered in North Tasman-1 entered the lower part of the oil generation window during the late Miocene, and we presume any hydrocarbons generated at that time have also migrated elsewhere. In Surville-1 the Oligocene coal measure source rocks probably did not reach sufficiently high temperatures for significant generation during the late Miocene peak in burial. Therefore, hydrocarbons have probably not yet been generated from this succession, which overlies basement.

In contrast to the other wells, AFTA results show that source rocks in Kupe-1 are currently at their maximum temperatures since deposition, and that any heating associated with the late Miocene unconformity was not significant. Therefore, Tertiary source rocks encountered in Kupe-1 have not reached temperatures where significant oil generation would be expected (100-150°C, following Quigley and Mackenzie, 1988). However, as another 2-3 km of Upper Cretaceous section occurs below TD of Kupe-1, much prospectivity is potentially preserved within the vicinity of this well, and hydrocarbons generated during rapid Pliocene to Recent burial could have accumulated in structures formed during Late Miocene uplift. This has already been proven by the drilling of Kupe-South higher up on the same anticlinal structure as Kupe-1, which encountered commercial quantities of oil and condensate.

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