

Integrated (U-Th)/He apatite and fission track thermochronology as combined thermal history tools for hydrocarbon exploration: an example from the Taranaki Basin

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Abstract

Earlier AFTA (apatite fission track analysis) results from four wells in southern parts of Taranaki Basin revealed major cooling as a result of Late Miocene inversion. Combined AFTA and vitrinite reflectance data from the Fresne-1 well suggest around 2.5 to 3 km of section was eroded from the Fresne-1 structure, which is highly consistent with estimates from reconstructions based on seismic sections. The well-constrained tectonic and thermal history framework for this well established by this earlier study provides an ideal test-bed for the novel thermochronological technique of (U-Th)/He dating of apatite, as part of a project to assess the utility of this new technique in sedimentary basins. Helium ages have been determined in apatites from the original AFTA study. New AFTA analyses have also been undertaken, using improved methods, and integrated with vitrinite reflectance data in order to provide a thermal history framework for understanding the He dating results. He ages decrease progressively from around 6 Ma at a depth of ~400 m to ~1 Ma at 2465 m. The oldest He ages (in the shallowest samples) are slightly younger than the youngest fission track ages (in the deepest samples), and are qualitatively consistent with Late Miocene cooling as suggested by the AFTA results. Results of quantitative modelling of (U-Th)/He ages, using the best-fit thermal histories from AFTA, are generally consistent with measured values, while in detail suggesting that cooling was protracted, involving accelerated cooling during the Pliocene. These results illustrate how integration of AFTA and (U-Th)/He dating can provide improved constraints on thermal histories in sedimentary basins, particularly on rates of cooling and/or resolution of multiple events. By defining the timing of peak maturation in relation to the formation of potential trapping structures, such information can provide invaluable information for assessing hydrocarbon prospectivity and can significantly reduce exploration risk.

Introduction

The novel technique of (U-Th)/He dating of apatite is emerging as an important low-temperature thermochronometer that can be applied to many geologically settings. Here, we investigate the potential application of the technique as a tool for petroleum exploration in sedimentary basins, by detailing a case example from a well section in the Taranaki Basin in New Zealand. A well-constrained tectonic and thermal history framework for this well established by earlier apatite fission track analysis (AFTA) (Kamp and Green 1990) provides an ideal test-bed for the method, as part of a project to assess the utility of this new technique in sedimentary basins.

Helium is produced within apatite grains as a result of alpha decay from uranium and thorium isotopes, present as impurities at ppm levels. As reviewed by Lippolt et al. (1994), this process formed the basis of the first attempts at geochronology. However, it soon became clear that at least a fraction of radiogenic Helium was lost from the host crystal lattice, and with the advent of apparently more reliable methods of geochronology (e.g. K-Ar, Rb-Sr, U-Pb), interest in the Helium systematics of minerals waned.

More recently, however, the realisation that the partial loss of radiogenic products could provide quantitative information on the thermal history of mineral grains led to a resurgence of interest in this topic (e.g. Zeitler, 1987; Lippolt et al., 1994). In particular, efforts at Caltech through the

1990s led to the development of (U-Th)/He dating of apatite as a rigorous, quantitative technique (Wolf et al., 1996). Studies of the diffusion systematics of Helium in apatite (Wolf et al., 1998; Farley, 2000) also revealed the unique temperature sensitivity of the technique, with all Helium being lost over geological timescales at temperatures as low as 90°C or less, and a “closure temperature” as low as 75°C. A number of subsequent applications of the method (e.g. House et al., 1997; Warnock et al., 1997; Wolf et al., 1997) have illustrated the potential of the technique to provide useful thermochronometric information at temperatures in the 40-80°C range.

In principle, therefore, this technique can be used to determine thermal histories in samples from depths of up to 2 km or more in sedimentary basins, which should provide a useful complement to the information provided by apatite fission track analysis, which typically provides information on paleotemperatures up to 110°C or more. (e.g. Green et al., 1998a, b, 1995, 1996). Here, we assess this possibility in detail, by comparing (U-Th)/He ages in apatites from a hydrocarbon exploration well (Fresne-1 in the Taranaki Basin of New Zealand), with the thermal history defined by AFTA and vitrinite reflectance (VR) data. Quantitative modelling of the (U-Th)/He ages, using the thermal history framework provided by AFTA and VR data, is used to assess the consistency of the different techniques. Recent investigations of (U-Th)/He ages in samples from hydrocarbon exploration boreholes in the Otway Basin of S.E. Australia (House et al., 1999; in press) suggest that helium diffusion systematics derived from laboratory measurements can be extrapolated to geological conditions with confidence. The well-constrained thermal history framework provided by the AFTA and VR data in the Fresne-1 well therefore provides an ideal test-bed for the new technique.

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Regional geology

Taranaki Basin lies along the western margin of North Island, New Zealand, mainly offshore beneath the modern continental shelf and slope (Figure 1). The basin has a composite morphology reflecting its mid-Cretaceous to Recent evolution in a variety of tectonic regimes (King and Thrasher 1996).

Most of the structure at the margins and within Taranaki Basin has formed during the Neogene. The Southern Inversion Zone encompasses several discrete anticlines forming positive inversion structures. These have formed by Late Miocene reverse displacement on previous normal faults, resulting in the inversion of late Cretaceous-Eocene half grabens (Figures 1&2). Many of these inversion structures have been drilled for hydrocarbon exploration, and the Maui, Kapuni and Kupe structures contain the largest petroleum accumulations in the basin. The inversion was

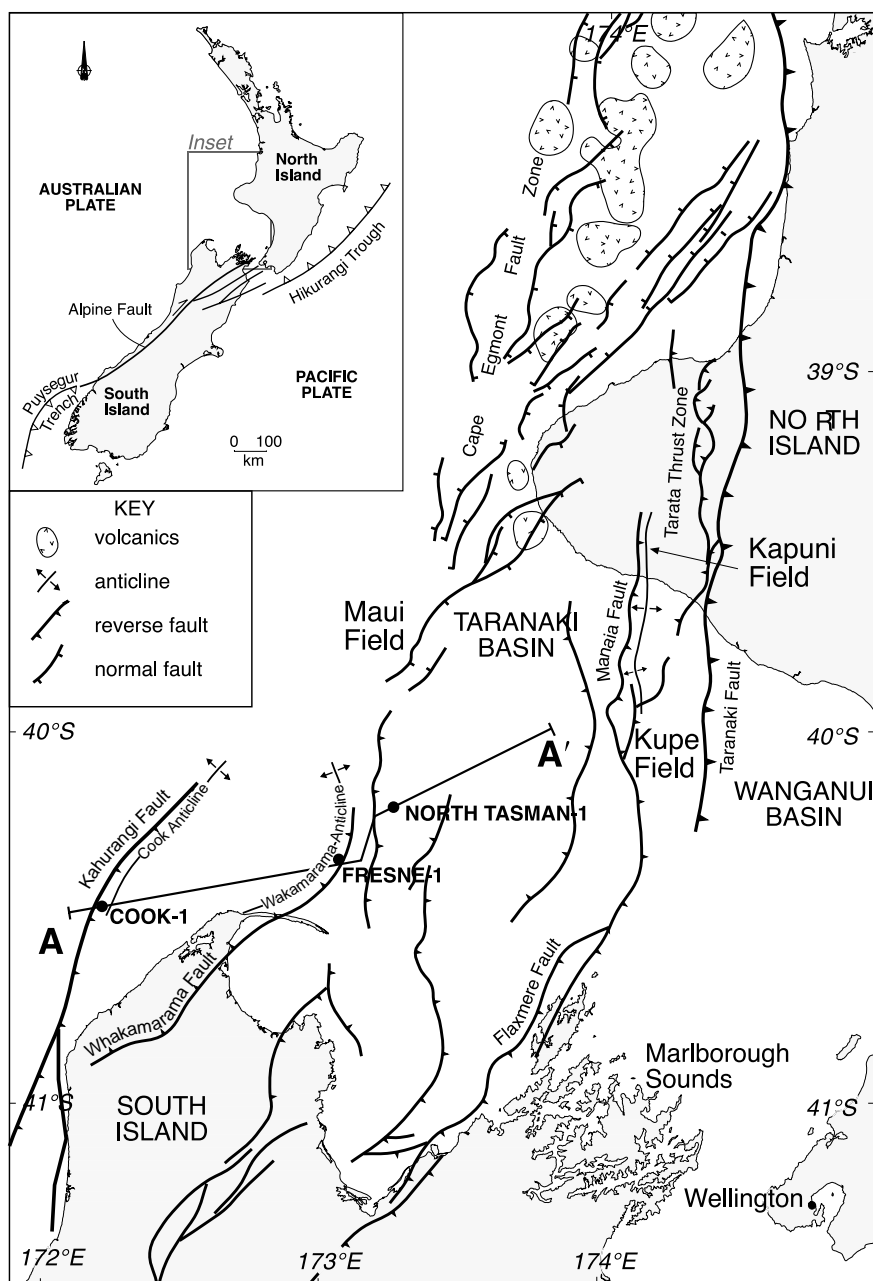


Figure 1: Map of central-western New Zealand showing the location of Taranaki Basin west of Taranaki Fault and north of South Island and some of the main oil and gas fields. Also shown are the location of Fresne-1 and the line of the cross-section illustrated in Fig 2.

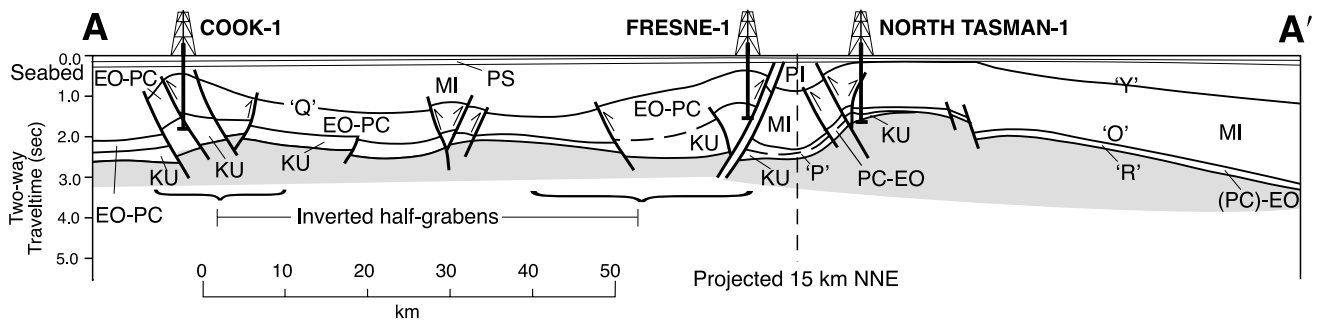


Figure 2: Cross-section (see line on Fig.1) through the Southern Inversion Zone of Taranaki Basin showing the inversion structures drilled with Fresne-1, Cook-1 and North Tasman-1.

accompanied by erosion and an angular unconformity truncates all of the structures and is a general feature in the Southern Inversion Zone (King and Thrasher 1996). The unconformity is flat lying in the east-west direction and rises to the south. It is overlapped in a southward direction by poorly dated late Pliocene then Pleistocene sediments, commonly 100-200 m thick, reflecting recent submergence of southern parts of Taranaki Basin.

The Cook and Wakamarama anticlines are typical and prominent structures drilled by the Cook-1, Fresne-1 and Farewell-1 wells (Figures 1&2), and have been described and interpreted by Knox, (1992), Kamp and Green (1990), King et al (1991), Green et al (1995), and Bishop and Buchanan (1995).

The Fresne-1 well was drilled near the crest of the Wakamarama Anticline. It encountered thick Late Cretaceous Pakawau Group (923 m bdf– 2504 m T.D.), which accumulated as terrestrial deposits in a half graben bounded immediately to the east by the Wakamarama Fault (Figure 2). This is overlain by Kapuni Group (408-923 m bdf), which also accumulated in terrestrial environments, with continuing displacement on the Wakamarama Fault, but with a more even thickness distribution in the basin (Figure 2). An Eocene-Early Oligocene unconformity separates Kapuni Group from a thin Late Oligocene to early-Middle Miocene calcareous to muddy succession (203-408 m bdf). This is in turn overlain unconformably by a 120 m thick section between seabed (83 m) and 203 m bdf. This section is poorly dated in the hole, but regionally is of Late Pliocene and Pleistocene age.

The inversion of the Wakamarama and Cook anticlines post-dates the Middle Miocene, based on the presence of early-Middle Miocene beds preserved on the flanks of these structures (Figure 2). The inversion of Wakamarama and Cook anticlines probably occurred at the same time. The bounding faults are antithetic such that the two half grabens and intervening strata form a “pop-up” structure (Figure 2). In both anticlines the crest is formed above the thickest syn-rift sequence. In the Wakamarama Anticline the top Eocene horizon is displaced about 2.5 km on the fault, but at basement level the sense of throw remains normal, reflecting the greater overall degree of Late Cretaceous extension compared with Late Neogene compression.

Various estimates have been made of the amount of section eroded at the level of the Middle Miocene-Late Pliocene unconformity in Fresne-1. Based on seismic reflection data Knox (1982) estimated >2.0 km of erosion, Ellyard and Beattie (1990) 3.5 km, King et al (1991) 2.8+ km, and Bishop and Buchanan (1995) c.3.0 km. Based on AFTA Kamp and Green (1990) estimated 3.0±0.3 km of erosion, and from offset in porosity v depth trends Funnel et al. (1996) estimated 3.0 km of erosion. The only numerical ages on the timing of erosion have been established from AFTA (Kamp and Green, 1990) at 12-8 Ma. The poorly dated Late Pliocene-Pleistocene deposits overlying the Wakamarama Anticline currently provide the only constraints on the timing of the end of erosion.

Thermal history reconstruction using apatite fission track analysis and vitrinite reflectance

New AFTA data from Fresne-1

Samples from the Fresne-1 well originally analysed by Kamp and Green (1990) have been reanalysed using latest methods, in which chlorine contents are measured in every apatite grain analysed. Figure 3 shows fission track ages plotted against depth (wrt kb) in the Fresne-1 well. Values for each sample are generally very similar to those reported by Kamp and Green (1990), showing a progressive reduction from around 80 Ma in the shallowest part of the Late Cretaceous to Early Tertiary coal measures section, to values consistently around 5 to 10 Ma at depths greater than 1500 m. As discussed by Kamp and Green (1990), this pattern of variation is characteristic of sections that have been hotter in the past, with the point marking the transition from rapidly decreasing ages to consistent values corresponding to the paleotemperature at which all samples are totally annealed prior to the onset of cooling (taken to be 130°C by Kamp and Green (1990), reflecting the rapid timescale of heating and cooling).

Figure 3 also shows the variation of mean confined track length with depth, as well as the distribution of confined track lengths in each sample. The trends with depth reflect progressive length reduction of the population of tracks formed prior to the onset of cooling, which are totally annealed in the four deepest samples, leaving only the longer tracks formed after the onset of cooling.

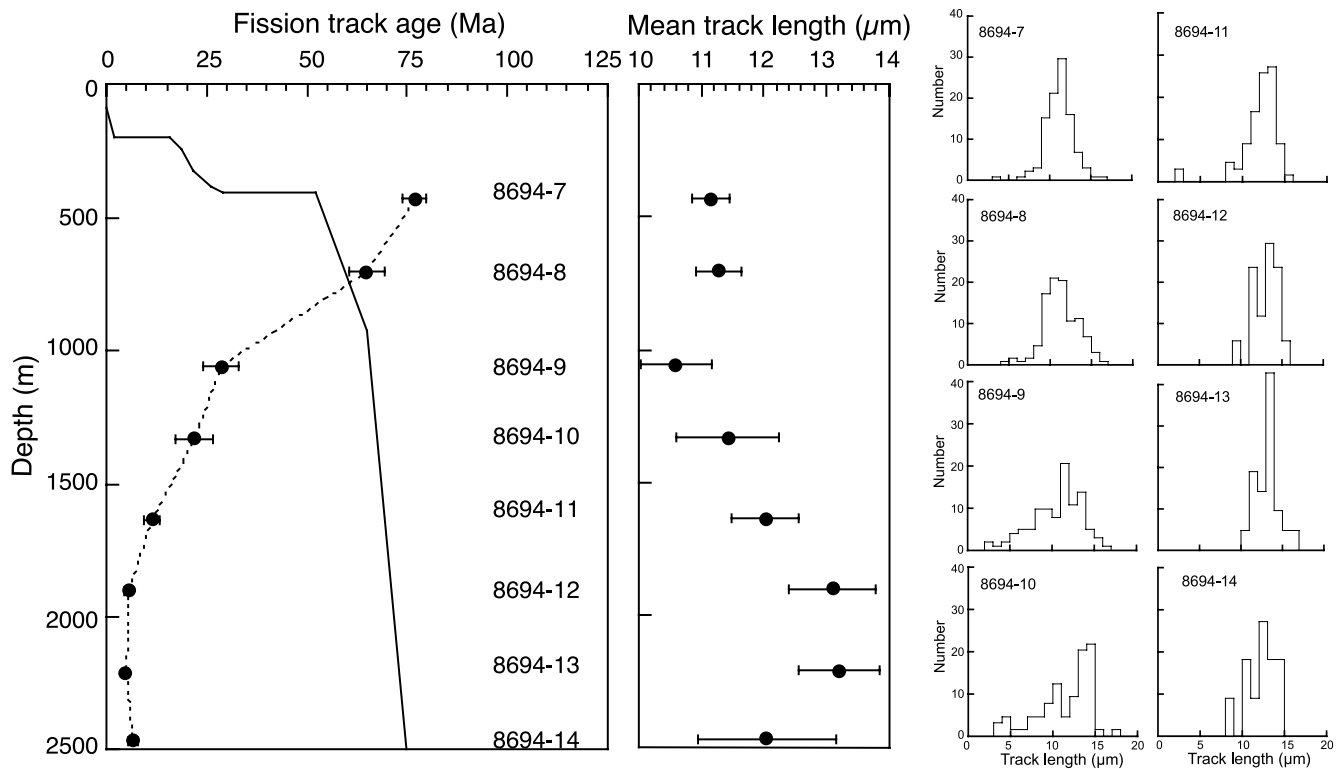


Figure 3: Pooled or central fission track ages and mean confined track lengths in samples from Fresne-1, plotted against depth (rkb). Distributions of confined track lengths are also shown for each sample. These new results are very similar to values originally reported by Kamp and Green (1990).

Figure 4 shows the variation of fission track ages of individual apatite grains within each sample with chlorine content. In samples 8694-7 and -8, in which the “central” or “pooled” fission track ages, characterising data from the entire collection of grains from each sample, are higher than the stratigraphic age of the samples, the individual grain ages show little or no variation with Cl content. But in sample 8694-9, in which the central fission track age is reduced to less than 50% of the stratigraphic age (Figure 3), the individual grain ages show a clear and consistent trend, with those grains with less than 0.1 wt% Cl having very young ages, and with ages increasing with Cl content such that in grains with greater than 0.3 wt% Cl, ages are indistinguishable from the stratigraphic age. Results from deeper samples show similar effects, but with the transition from very young ages to much older ages occurring at progressively higher Cl contents with increasing depth. In the deepest sample, 8694-14, all grains except for that with the highest Cl content between 0.6 and 0.7 wt% Cl give very young ages.

These trends represent the progressive overprinting of tracks formed prior to the paleo-thermal maximum. In the deeper samples, the lower Cl-content grains were totally annealed prior to the onset of cooling (the fission track ages of these grains provides the best constraint on the time of cooling), with the range of Cl contents which were totally annealed prior to the onset of cooling increasing with depth, corresponding to progressively higher maximum paleotemperatures.

Results from a small number of grains, circled in Figure 4, do not fit within this general pattern. These results highlight

the fact that secondary controls on annealing rates exist, in addition to the first-order control exerted by Cl content. Data from these grains have been removed prior to detailed thermal history interpretation.

To further highlight the importance of compositional effects in these data, Figure 5 shows the fission track age of individual Cl content groups (up to 0.6 wt% Cl) within each sample, plotted against depth. While the behaviour of the data in this plot are more erratic than those in Figure 3, due mainly to the small numbers of grains involved, the trend is clear with apatites with higher Cl contents achieving a particular degree of age reduction at progressively deeper levels, corresponding to higher maximum paleotemperatures. As a guide to visualising these effects, also shown in Figure 5 are the trends of fission track age with depth for separate compositional groups corresponding to the best-fit thermal history solution presented in later discussion. Predicted patterns of age vs Cl content within each sample corresponding to these solutions are also shown in Figure 4. Similar trends are also evident within the track length data in these samples, but these are not illustrated here.

Thermal history interpretation of AFTA and VR data from the Fresne-1 well

Thermal history solutions have been derived from the AFTA data in each of the eight samples analysed from the Fresne-1 well. The range of allowed values (corresponding to $\pm 95\%$ confidence intervals) are defined by comparing measured parameters with values predicted from a range of likely thermal history scenarios, systematically varying the timing of the onset of cooling and the peak paleotemperature and

using rigorous statistical procedures to define the range of conditions which are compatible with the data.

The estimated times for the onset of cooling in each sample are highly consistent between the various samples. By combining estimates from all eight samples, the best available estimate of the time at which cooling commenced is the interval 9 to 8 Ma. This is consistent with the somewhat

broader estimate of 12 to 8 Ma provided by Kamp and Green (1990), with the improved precision highlighting the advantages of the improved techniques employed in this study. The refined timing estimate also falls within the period represented by the Late Miocene to Pliocene unconformity in the Fresne-1 well, consistent with an interpretation of the observed paleo-thermal effects in terms of heating due to deeper burial and cooling related to subsequent Late

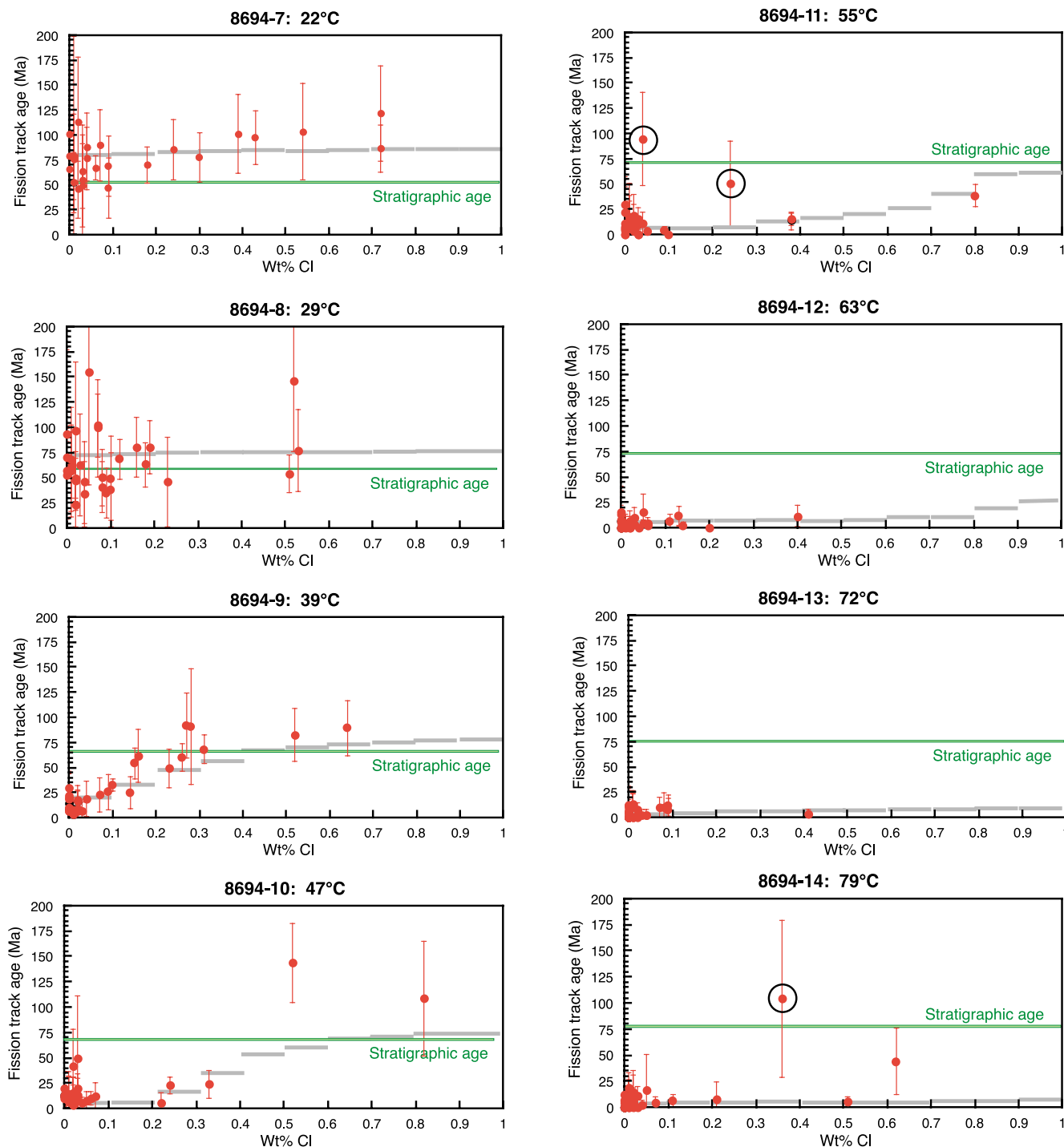


Figure 4: Fission track ages of individual apatite grains in samples from the Fresne-1 well, plotted against Cl content of each grain (Cl contents were measured using an electron microprobe). With increasing present-day depth in the well, corresponding to increasing maximum paleotemperatures prior to the onset of cooling, the fission track ages of the samples are progressively reduced. But in addition, age reduction is more rapid in apatites with little or no Chlorine compared to those with higher Cl contents. This variation in annealing response produces a pronounced spread in fission track ages of grains within individual samples, as shown e.g. for samples 8694-9, -10 and -11. A small number of grains (circled in these plots) do not fall within this overall pattern, highlighting possible secondary controls on annealing rates which are, as yet, undefined.

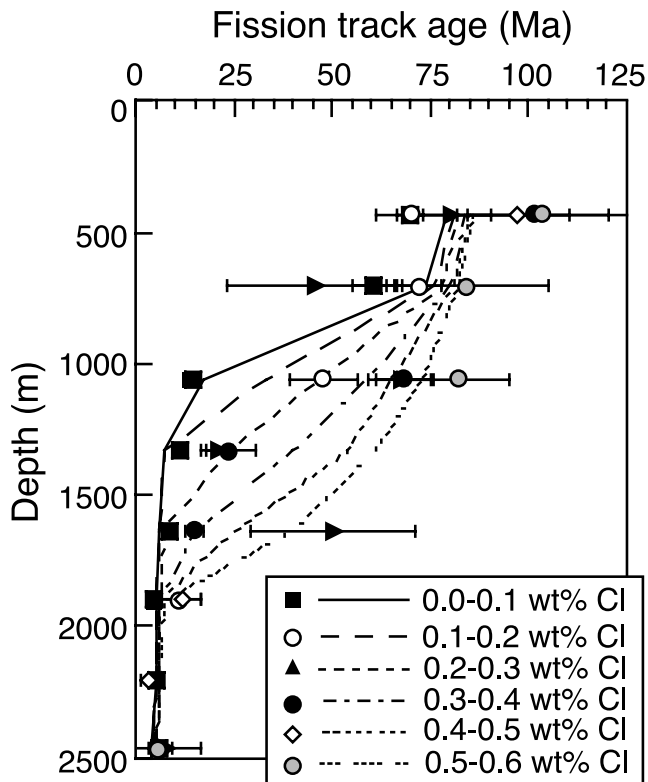


Figure 5: Pooled or central fission track ages for discrete compositional groups within samples from Fresne-1, plotted against depth (rkb). Trends corresponding to the final reconstructed thermal histories of individual samples are also shown.

Miocene Basin inversion. Amounts of additional burial and exhumation required to account for the observed paleotemperatures are discussed in the next sub-section.

Paleotemperature profiles, palaeogeothermal gradients and removed section

Analysis of a series of samples using AFTA and VR over a range of depths reveals the variation of maximum paleotemperature with depth characterising a particular paleo-thermal episode. This "paleotemperature profile" provides key information on likely mechanisms of heating and cooling (eg. Bray et al., 1992; Duddy et al., 1994; Green et al., 1995; Green et al., in press).

Paleotemperature estimates from AFTA and VR in the Fresne-1 well are plotted against depth in Figure 6. This plot illustrates the high degree of consistency between the maximum paleotemperatures indicated by the two techniques. The combined paleotemperature constraints define a linear profile, with a slope, which is similar to that of the present-day temperature profile, suggesting a most likely explanation of heating due solely to deeper burial.

This can be assessed quantitatively by fitting a line to the paleotemperature profile to obtain an estimate of the paleogeothermal gradient at the paleo-thermal maximum. Extrapolating the fitted linear profile to an assumed paleo-surface temperature then provides an estimate of the amount of section removed by erosion. These two parameters are highly correlated, such that higher paleogeothermal gradients require correspondingly lower values of removed section, and vice versa. Statistical techniques allow definition

of the range of each parameter allowed by the paleotemperature constraints within 95% confidence limits (Bray et al., 1992).

Application of these methods to the paleotemperature constraints from AFTA and VR in the Fresne-1 well provides the results shown in Figure 7, which also highlights the correlation between allowed values of paleogeothermal gradients and removed section. The maximum likelihood paleogeothermal gradient is 24.5°C with upper and lower 95% confidence limits of 30 and 19°C/km, respectively. The present-day thermal gradient of 28°C/km (Kamp and Green, 1990) falls well within this trend, and given the relatively late timing for the main cooling phase, it seems most likely that the paleo-thermal gradient at the time at which cooling began was close to this value. From Figure 7, a paleogeothermal gradient of 28°C/km corresponds to between 2550 and 2800 m of removed section. Thus, we adopt the mid-point value of 2675 m as the best estimate of the amount of section removed on the Late Miocene-Pliocene unconformity in the Fresne-1 well.

Thermal history synthesis

Taking values of 28°C/km for the paleogeothermal gradient and 2675 metres of section removed, reconstructed thermal histories for units intersected in the Fresne-1 well are shown in Figure 8a.

It should be appreciated that while we have assumed here that heating was solely due to deeper burial, alternative scenarios are possible and a variety of combinations of paleo-thermal gradient and removed section are capable of satisfying the paleotemperature constraints from AFTA in these wells, as shown by the contoured regions in Figure 7. However, all such combinations of paleogeothermal gradient and removed section in each well result in reconstructed thermal histories for the preserved units which are very similar to those shown in Figure 8, being tightly constrained by the AFTA and VR data throughout the well.

The heating and cooling rates of 10°C/Ma assumed in interpreting the data appear to be realistic, based on the final solutions shown in Figure 8a. The youngest unit below the unconformity being dated at 15.5 Ma (Kamp and Green, 1990), the total amount of heating involved of ~75°C, and cooling beginning at around 8.5 Ma, combine to suggest a heating rate very close to 10°C/Ma. Similarly, with a depositional age of around 2 Ma for the youngest sediment above the unconformity, cooling by 75°C in 6 Ma again suggests an overall cooling rate close to 10°C/Ma. Thus, based on data discussed so far, the thermal history reconstruction illustrated in Figure 8a for units intersected in the Fresne-1 well can be regarded as reliable.

(U-Th)/He dating: analytical procedures

Instrumentation

The CSIRO He extraction and analysis facility comprises an all-metal He extraction and gas-handling line connected to

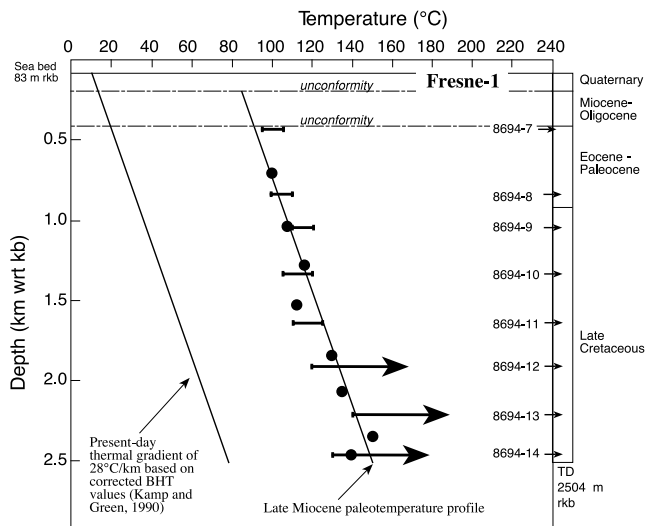


Figure 6: Late Miocene paleotemperatures from AFTA and VR data in the Fresne-1 well, plotted against depth (rkb). These constraints can be used to constrain possible values of paleogeothermal gradient and removed section, as illustrated in Figure 7.

a dedicated on-line Balzers Prisma™ 200 quadrupole mass spectrometer. Gas extraction is performed by using either of the 2 identical single vacuum resistance furnaces, where samples are heated to ~900°C for ~15 minutes. The line and furnace are evacuated to ~10-8 mbar via ion, turbo and backing pumps. Active gases, particularly hydrogen are removed using SAES getters. The analysis procedure is operated by LabVIEW™ automation software supplied by Ken Farley at Caltech.

Sample selection

Apatite grains are carefully handpicked in order to avoid U- and Th-rich mineral inclusions that may produce excess He (eg. zircon). Images of selected grains are captured by a CCD video camera mounted on the microscope and measured using image analysis techniques for the purposes of alpha ejection correction calculation. This correction is mathematically calculated using the estimated dimensions of each grain and is applied directly to the final age (discussed in more detail below). Aliquots of ~5-30 grains are sealed into stainless steel capsules and then up to 6 capsules are loaded into the furnace sample holders.

Helium measurement

⁴He abundances are determined by isotope dilution using a pure ³He spike, which is calibrated on a regular basis against an independent ⁴He standard tank. ⁴He hot blanks (or re-extracts) are performed routinely before and after each sample. If the ⁴He standard and blank levels are acceptable (<0.05ncc ⁴He), a sample capsule is dropped into a ceramic crucible within the furnace. After the heating and purification procedures, the extracted gas is handled and measured via the fully automated computer controlled system.

Uranium and thorium concentration

The U and Th content of degassed apatite samples are determined on a Perkin Elmer Sciex 5000a ICP-MS using the Isotope Ratio application. 100µl of each ²³⁵U and ²³⁰Th spike solution (about 5ng and 6ng, U and Th respectively)

and 200µl of concentrated nitric acid are added to a vial containing the capsule and degassed apatite. 100µl of 0.25ppm U and Th standard solutions (Johnson Matthey) are similarly spiked and acidified. We have determined the ²³⁵U/²³⁸U ratio of the Johnson Matthey U-standard solution to be 135, close to the natural value of 138.

Blanks are prepared by adding an equivalent amount of nitric acid to washed, empty capsules. The blanks, standards and samples are all diluted to 5% nitric solution with Alpha Q water prior to analysis. Based on replicate analysis of spiked standard solutions, precision for ²³⁵U/²³⁸U and ²³⁰Th/²³²Th determination is 0.77% and 0.41%, respectively.

Grain size effects

The ranges of alpha particles produced by decay of uranium and thorium isotopes are typically between 12 and 34 mm (Farley et al., 1996). Since these "stopping distances" are a significant fraction of the radius of typical accessory or detrital apatite grains (between 30 and 100 mm), a significant proportion of alpha particles produced within an apatite grain may be emitted from the grain, resulting in loss of radiogenic helium. Farley et al. (1996) showed how this effect can be corrected for, by calculation of a correction factor (known as FT) for a particular grain size.

In addition, helium diffusion rates in apatite are related to grain radius (Farley, 2000). As a result, the closure temperature varies with grain size, and grain size becomes an important parameter in modelling the expected patterns of He age, for a specified thermal history. While the overall variation in closure temperature for samples with grain radii of 50-150 microns is only 5°C, this difference may be significant in the interpretation of apatites from drill holes which have resided within the partial retention zone for prolonged periods of time (House et al, in press). In general, aliquots comprised of larger grains are expected to yield an older age than aliquots of the same sample that consist of smaller grains, especially in the case of slow cooling (House et al, in press; Farley, 2000).

Several studies suggest that the composition of the apatite does not appear to affect the sensitivity of the He closure temperature (Wolf et al., 1996; House et al., in press), which is in contrast to the effect of Cl contents on AFTA annealing kinetics.

U-Th)/He results

Where possible at least two aliquots of a sample were analysed to check reproducibility and to confirm the level of precision that can be obtained. On average each aliquot contained ~18 grains consisting of clear, euhedral grains in which inclusions that could be optically identified were absent or minimal. The absence of significant contribution to the analyses from inclusions is supported by the fact that there were very few re-extracts during He outgassing. Considering the low ages in this suite of samples, the precision appears to be very good, with only sample # 8694-9 showing a spread in ages from the three aliquots analysed. This could, in principle, be due either to grain size variation between

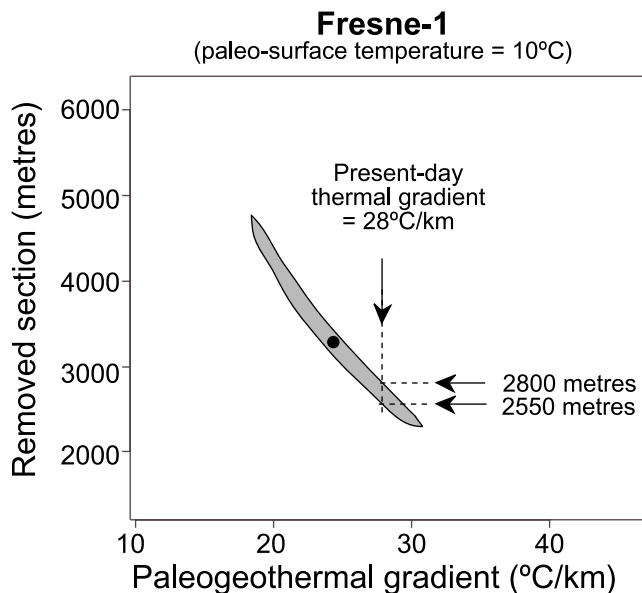


Figure 7: The shaded region shows the allowed ranges (within 95% confidence limits) of palaeogeothermal gradient and removed section which are consistent with the Late Tertiary palaeotemperature constraints from AFTA and VR in the Fresne-1 well (summarised in Figure 6). The correlation in the allowed values of the two parameters results because the removed section estimates are obtained by extrapolation of fitted linear palaeotemperature profiles (Bray et al., 1992), with higher gradients requiring lower amounts of removed section and vice versa. Maximum likelihood estimates are represented by the black dot. Assuming that the thermal gradient has been constant over the last 10 Ma, a

aliquots or a minor amount of down hole contamination producing a mixed age) But as there is little variation in the average grain sizes for the three aliquots of sample 8694-9, this is not the cause for the variation in the apparent age yielded from each aliquot. Therefore this is more likely due to contamination of the sample or possibly to the presence of inclusions that totally outgassed, but did not dissolve in nitric acid thus yielding an older apparent age.

The He ages are plotted against depth in Figure 9, where they are contrasted with the fission track ages for each sample, and also with the variation of stratigraphic age through the section. All of the He ages are younger than the corresponding AFTA ages, which is expected because of the lower closure temperature of helium in apatites. This plot highlights the trend of decreasing age with depth as expected. He ages around 6 Ma in the shallowest samples are similar to the fission track ages in the deepest samples, consistent with Miocene cooling as discussed earlier. In considering the results shown in Figure 9, it is important to appreciate that the raw He ages do not accurately represent the timing of any specific particular event in their own right, because only a proportion of the He formed since the onset of cooling has been quantitatively retained in these apatites. To more completely understand these ages requires modelling of the results through a variety of scenarios, in

order to determine the range of thermal history solutions consistent with the measured data.

Thermal history interpretation of (U-Th)/He age results

Introduction

Experimental investigations in recent years at Caltech have led to a detailed understanding of the diffusion systematics of Helium in apatite (Farley, 2000). Results of this work, focussed on the much-studied Durango apatite, suggests that diffusion systematics are controlled by the physical grain size. This key observation implies that for any specified thermal history, modelled (U-Th)/He ages can be produced for a particular sample using the measured mean grain size together with single values of the key diffusion parameters E_a and $\log(D_0)$, using best estimates of $E_a = 33 \pm 0.5$ kcal/mol and $\log(D_0) = 1.5 \pm 0.6$ cm²/s. These values have been used in modelling (U-Th)/He ages for this study.

Because of the greater diffusive loss expected from smaller grains compared to larger grains, effects related to grain size may be significant in the interpretation of apatites from sediments which have been heated to paleotemperatures within the He PRZ, as grains of different radii should give different ages for a particular thermal history. While this has yet to be demonstrated consistently in natural samples, this effect holds considerable promise for obtaining more precise thermal history control from He data in sedimentary basins.

Modelling of Fresne-1 He data

As a starting point to more fully understanding the Helium age results shown in Figure 9, we have modelled the values expected in each sample on the basis of the thermal history framework obtained from the AFTA and VR data, as shown in Figure 8a.

Figure 10a shows ages predicted by the thermal histories shown in Figure 8a, plotted against depth and compared with the measured ages. Predicted values are shown for four-grain radii. The mean radii in the samples analysed from Fresne-1 are generally around 50 μ m, and this trend in Figure 8 is the most appropriate for direct comparison with the measured ages. In general, the predicted and measured ages in Figure 10a show a fair degree of agreement, particularly at the shallowest and deepest extremes of the depth range, while predicted values from the middle of the sampled interval are higher than measured values.

Given that the predictions are based purely on diffusion systematics derived from extrapolation of results from laboratory conditions, it is not, at present, clear whether the slight mis-match between measured and predicted ages arises because the real thermal histories are somewhat different from those in Figure 10a, or because of slight errors in the diffusion systematics. Similar comparisons of measured (U-Th)/He ages with predicted values in samples from wells located in the Otway Basin of south-east Australia by House et al. (1999) suggested that the diffusion systematics could be extrapolated to geological conditions with confidence, and on this basis, we proceed to consider how the thermal

histories in Figure 8a could be refined to give a better fit to the measured ages.

Figure 8b shows an alternative thermal history style, characterised by rapid cooling from the maximum at 8.5 Ma, with all cooling achieved within 1 Ma. Figure 10b shows a comparison of (U-Th)/He ages predicted from these histories with the measured values. In this case, rapid cooling predicts much older ages than in Figure 10a, and a much worse fit to the measured ages, and this scenario can be eliminated. As a further alternative, Figure 8c illustrates a scenario involving protracted cooling, where 50°C of the total 75°C cooling occurs between 4 and 2 Ma. The predicted age trends in Figure 10c now show an improved match to the measured ages, especially at depths greater than ~1000 m, although the predicted ages in the two shallowest samples are younger than the measured values. This suggests that these samples perhaps cooled earlier than the deeper samples, suggesting a thermal history scenario similar to that illustrated in Figure 8d, involving two discrete cooling episodes, with an initial phase at 8.5 Ma and a later cooling phase beginning at 4 Ma (again with 50°C of cooling since 4 Ma). Figure 10d shows the age trends predicted from this scenario, and in this case

the agreement between measured and predicted ages is extremely good across the whole depth range.

While it remains, to some extent, uncertain whether this treatment represents over-reliance on the extrapolation of laboratory diffusion systematics, and more tests are required in controlled geological conditions, this procedure certainly illustrates the potential of the (U-Th)/He technique to complement AFTA and VR data in sedimentary basins to provide further definition of thermal history styles, particularly in terms of refining the most recent, low temperature, phase of the history.

Discussion

The structural and stratigraphic development of the southern parts of Taranaki Basin, and in particular the Wakamarama Anticline, show no direct evidence to support the notion of two separate cooling events in the Late Neogene, if the thermal events were indeed driven by cycles of burial and subsequent exhumation. A history involving protracted cooling (Figures 8c and 10c), which gives an acceptable fit to both the integrated thermochronological data and the

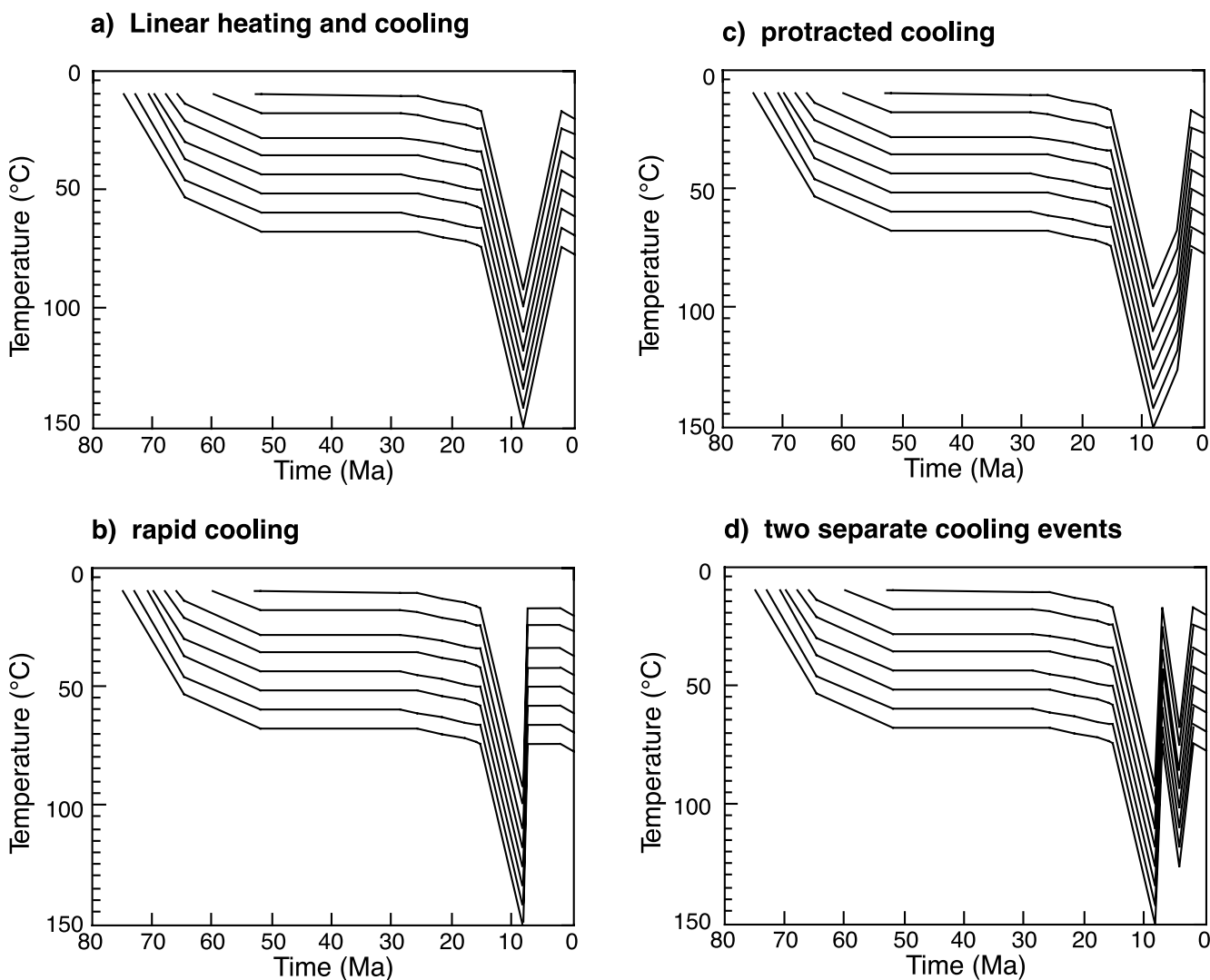


Figure 8: Possible thermal history reconstruction scenarios for the Fresne-1 well, embodying different styles of cooling from the paleothermal maximum at ~8.5 Ma. Corresponding patterns of apatite (U-Th)/He age with depth are shown in Figure 10.

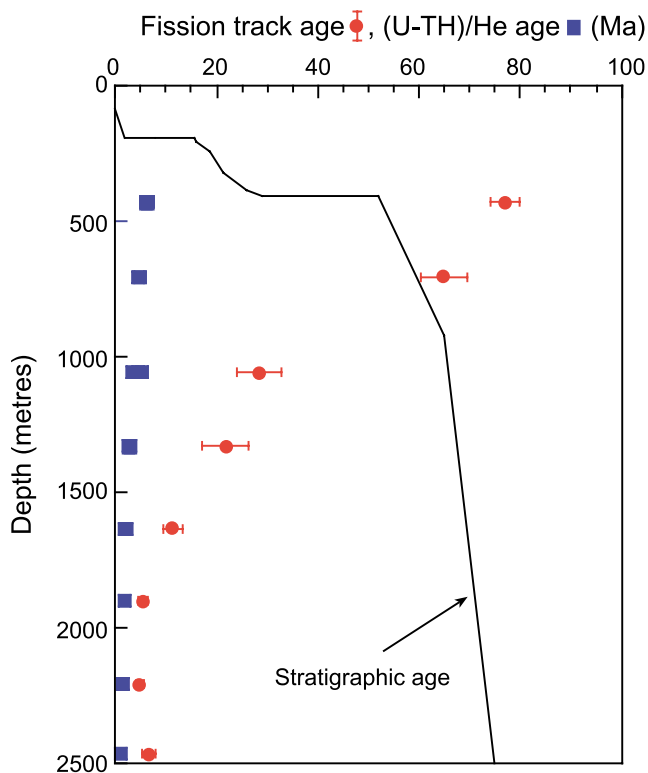


Figure 9: (U-Th)/He ages in apatites from the Fresne-1 well plotted against depth (rkb). Fission track ages in these apatites are also plotted, for comparison, together with the variation of stratigraphic age with depth through the section.

basin stratigraphy and structure therefore seems more likely on this basis. The interval of inversion and erosion at Fresne-1 between 8.5 and 2 Ma coincides with the timing of widespread compression in northwestern South Island (White and Green, 1986; Kamp et al., 1992; Kamp et al., 1996, 1999), which started at about 12 Ma and is ongoing. The geodynamic cause of this shortening is the development of an obliquely convergent continent-continent collision zone in South Island. The inversion structures in Taranaki Basin represent the distal northern expression of the crustal shortening more strongly developed on land to the south. The late and sudden transition in Fresne-1 from cooling (erosion) to heating (burial) at c.2 Ma coincides with the passage of the leading edge of the subducted slab of Pacific plate beneath the vicinity of the well site (Kamp and Xu, this volume). In the Neogene geological development of North Island, there is a close relationship between the position of the leading edge of the slab and crustal subsidence – basin formation (Kamp, 1999). At the same time, the loci of the continent-continent collision zone in South Island have been moving southwestward as a function of displacement on the Alpine Fault. Currently the northern coastal areas of South Island are subsiding, which is particularly evident in the drowned topography of Marlborough Sounds.

Aside from high-level stratigraphic traps in the Kaimiro oil field in Taranaki Peninsula, all the known condensate and oil fields in Taranaki Basin occur in structural traps. Positive inversion structures in the Southern Inversion Zone provide traps for the three largest oil and gas fields in Taranaki Basin (Maui “B”, Kapuni and Kupe South), as well as several other fields (Toru, Maui-4, Moki) (King and Thrasher, 1996). A

critical element in assessing the hydrocarbon prospectivity of particular prospects is the timing of maximum temperatures, and the consequent expulsion of oil and gas, in relation to the timing of structure (trap) formation. Comprehensive modelling of the thermal and hydrocarbon generation history of the succession encountered in Fresne-1 and other well sections in the basin have been undertaken by Armstrong et al. (1996). Because of the rapid deposition of thick (>4000 m) Late Cretaceous deposits (Rakopi Formation, Pakawau Group), oil generation and expulsion at the level of the top of basement in Fresne-1 began about 70 Ma. The Wakamarama Anticline was clearly not a potential trap for this phase of hydrocarbon generation and expulsion. Subsequently, maximum temperatures at all horizons declined by about 20°C during the late rift-drift phase of basin evolution (Armstrong et al., 1996). During the Middle to Late Miocene, maximum temperatures increased by about 70°C and the Pakawau Group re-entered the oil generation and expulsion window. This phase of generation and expulsion also predated the age of formation of the potential trap (Wakamarama Anticline), which occurred during the Late Miocene-Pliocene, as described above. Consequently, the hydrocarbons would have been lost to the surface or will have migrated elsewhere.

Although hydrocarbons sourced from beds low in the Wakamarama Anticline succession dispersed before the structure formed, hydrocarbons could possibly have migrated into it from elsewhere in the basin after the late Pliocene. The accumulations in the Maui field, for example, are considered to have migrated there following Late Miocene inversion (Thrasher, 1989). What becomes critical to assessing this possibility is the timing of maturation in more northern parts of the basin in relation to the timing of structure formation further south, and migration between them. Most potential source rocks (Pakawau and Kapuni Groups) probably reached maturity for hydrocarbon expulsion during or following deep burial in the past 10 m.y. (Armstrong et al., 1996; King and Thrasher, 1996). These lie mainly in the Central and Northern Grabens, which suggests considerable distances of migration to reach places like the Maui field. The timing of burial is accessible from the burial history. This study shows that better constraints can be established on the timing and duration of structure (trap) formation by integrated application and modelling of low temperature geothermochronometers (AFTA and U-Th/He). The application of these techniques to more structures in Taranaki Basin (and similar approaches in other prospective basins) will provide access to a level of detail not previously available. In turn this will enable important questions about the direction and timing of migration in relation to the timing of maturation and trap formation to be addressed, each occurring in different parts of the basin.

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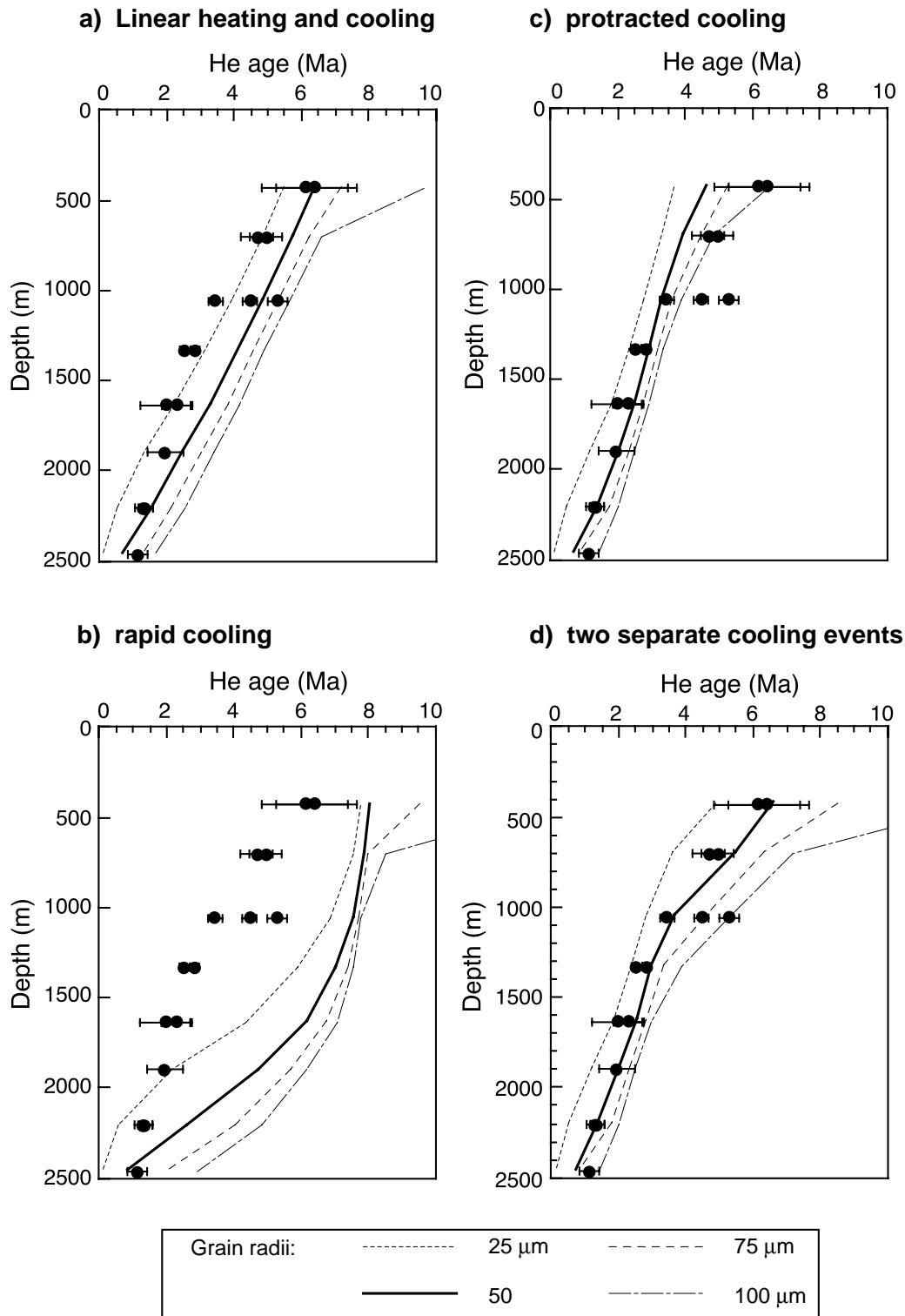


Figure 10: These four plots show the patterns of apatite (U-Th)/He age with depth predicted by the four thermal history styles illustrated in Figure 9, based on He diffusion systematics reported by Farley (2000). As discussed in the text, two discrete cooling episodes (d) provides the best fit to the measured ages, although geological evidence favours the protracted cooling scenario (c).

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