Regional palaeo-thermal episodes in northern Australia

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Abstract

Numerous AFTA-focused thermal history studies, carried out in basins of northern Australia, have identified a series of major regional palaeo-thermal episodes, which appear to share common timing and underlying mechanisms.

Kilometre-scale uplift and erosion in the Late Triassic–Early Jurassic is a major feature of the eastern onshore Canning Basin (e.g. White Hills-1), corresponding to structuring associated with the Fitzroy Movement. A distinctly older mid-Permian to mid-Triassic episode, identified in the near-offshore Canning Basin, was a response to localised transient hot-fluid flow associated with shallow igneous intrusions into wet sediment, and does not appear to have regional significance.

Elevated basal heat flow, perhaps combined with deeper burial, is prominent in the Early to Middle Jurassic, with pervasive effects identified in the Browse and southern Bonaparte basins and possibly in the Vulcan Sub-basin. This episode is most likely associated with the dominant period of rifting on Australia's northern margin.

A number of regional thermal episodes are observed since the Jurassic, the more prominent related to Early Cretaceous uplift and erosion in the onshore Canning and McArthur basins, and early to mid-Tertiary uplift and erosion in the Canning, Browse and southern Bonaparte basins, the Vulcan Sub-basin and the Londonderry High. The most recent episode identified is interpreted to be due to transient, but regionally pervasive, hot fluid flow during the Pliocene, with major effects observed in most basins of northern Australia.

Each of these episodes can have an important influence on the generation and distribution of hydrocarbons in particular parts of the basins of northern Australia, as illustrated by constrained thermal history reconstructions in key wells.

Introduction

AFTA® Apatite Fission Track Analysis provides a measurement of the magnitude of maximum temperature (up to 150°C for normal geological heating rates), to which apatite grains in a sediment were subjected, and the time at which cooling from those palaeo-temperatures began, together with a measure of the style of cooling. When combined with maximum temperature, derived from VR data in a vertical sequence of samples, AFTA can also provide constraints on the timing and magnitude of palaeo-geothermal gradients and the magnitude of any associated uplift and erosion, thus providing a constrained thermal and burial history framework, in which the hydrocarbon generation and migration history can be quantitatively evaluated (e.g. Duddy *et al*., 1991).

Numerous studies over the last 20 years or so of Australia's northern sedimentary basins have applied basin models to assist in understanding the hydrocarbon generation and preservation histories (e.g. Kennard *et al*., 1999; 2002). Thermal history forms a fundamental part of these models, yet in most instances, the main aspects of the thermal history (i.e. timing and magnitude of palaeo-heat flow, thermal conductivities of sediments) have been assumed, albeit with these assumptions tested against some palaeo-temperature indicator, normally vitrinite reflectance or some closely associated surrogate, such as FAMM (Fluorescence Alteration of Multiple Macerals) or Rock-Eval T_{max}. Assumptions concerning the timing of peaks in basal heat flow in each basin are universally based on interpretations of the regional tectonic history, strongly influenced by interpretation of the local structural history and identification of extensional faulting with periods of rifting. Elevated basal heat flow is then attributed to these periods of rifting thus revealed, on the basis of the theoretical understandings promulgated by McKenzie (1978). This "conventional" approach, with only minor variations, underlies all published basin modelling studies in northern Australia.

In essence, these conventional models are at best only partly calibrated, with vitrinite reflectance (VR) used to assess the magnitude of palaeo-heat flow, while the timing of heat flow maxima is simply assumed. Similarly, the timing and magnitude of uplift and erosion on unconformities is also assumed, or extrapolated from regional stratigraphic data.

In contrast, our approach involves the direct measurement of the timing and magnitude of maximum palaeo-temperatures using AFTA apatite fission track analysis, and the estimation of the magnitude of palaeo-geothermal gradients (essentially palaeo-heat flow), and associated uplift and erosion, at key points in the basin's history. Incorporation of AFTA provides an improved understanding of the thermal and burial histories, by not only allowing quality control on the organic maturity data most commonly used in constraining these previous basin models, but by also providing a quantitative estimate of the timing at which maximum maturity developed.·

This approach to direct thermal history calibration incorporating AFTA and VR data, including quantitative determination of palaeo-geothermal gradients, is described in detail in publications by Green *et al*. (1989), Bray *et al*. (1992), Duddy *et al*. (1994) and Green *et al*. (1995; 1996), and summarised more recently in Duddy and Erout (2001) and Duddy *et al*. (2003), and is not repeated here. The maximum palaeo-temperature required to produce each of the VR values

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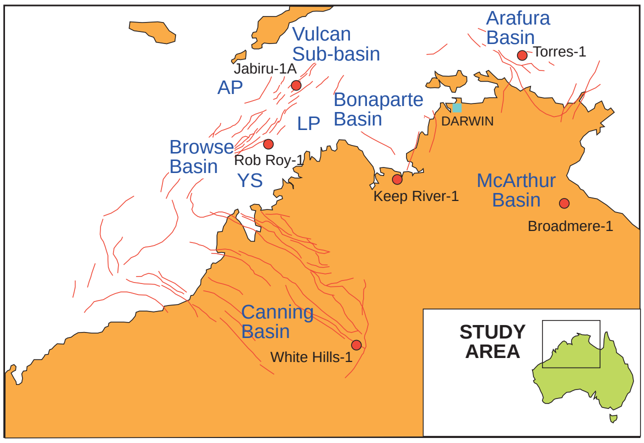


Figure 1. Location map, with key thermal history reconstruction wells discussed in this paper. YS = Yampi Shelf; AP = Ashmore Platform; LP = Londonderry Platform.

has been determined from the distributed activation energy model describing the evolution of VR, with temperature and time developed by Burnham and Sweeney (1989). Notional heating rates of 1 to 5°C/Ma and a cooling rate of 10°C/km have been used, in estimation of the maximum palaeo-temperatures in each well from the AFTA and VR data. *In situ* present temperatures in each well were estimated from raw BHT measurements, corrected using a simplified correction procedure, which was adapted from that of Andrews-Speed *et al*. (1984) and defined in Duddy and Erout (2001).

In this paper, thermal history reconstructions are summarised in a number of key wells, from a range of sedimentary basins across northern Australia, drawn from unpublished studies carried out by Geotrack since the early 1980s. The following wells are discussed: White Hills-1 in the onshore eastern Canning Basin, Jabiru-1A in the Vulcan Sub-basin, Keep River-1 in the southern Bonaparte Basin, Broadmere-1 in the McArthur Basin and Torres-1 in the Arafura Basin (Fig. 1). These reconstructed thermal histories are used to provide constraints on the burial and source rock maturation histories of the specific well sequences, as well as insights into the timing and magnitude of the major thermal episodes affecting the Palaeozoic, Mesozoic and Tertiary sedimentary basins of northern Australian, and their tectonic significance.

Regional thermal episodes revealed by AFTA

Results from 38 AFTA samples in six key wells, representing the six northern Australian basins noted in the previous section, are provided in the Appendix. Maximum and peak palaeo-temperature estimates and timing constraints, derived directly from kinetic modelling of the AFTA data, are attributed to four major thermal episodes, interpreted from the overlapping time constraints obtained from the individual samples (Fig. 2). In general, AFTA in a single sample is capable of revealing two thermal episodes (with timing and temperature constraints quoted at ± 95% confidence limits), or occasionally three, depending on how these episodes are separated in time and temperature. However, by considering the overlap in AFTA timing constraints obtained from individual samples in vertical depth sequence, and by integration of vitrinite reflectance data, a comprehensive assessment of the thermal history at each well site can be compiled. Compilation of the timing constraints in this way assumes that the events revealed in the individual samples are regionally synchronous and as AFTA only "sees" cooling events of >10°C, this assumption is generally considered to be reasonable. In any case, revelation of events of similar timing in samples across a broad region often provides *a priori* evidence that such events are regionally significant.

These major events are notionally referred to in the Appendix as Event 1: Palaeozoic; Event 2: Early Mesozoic; Event 3: Late Mesozoic; Event 4: Tertiary–Recent. Note, however, that each of these major events

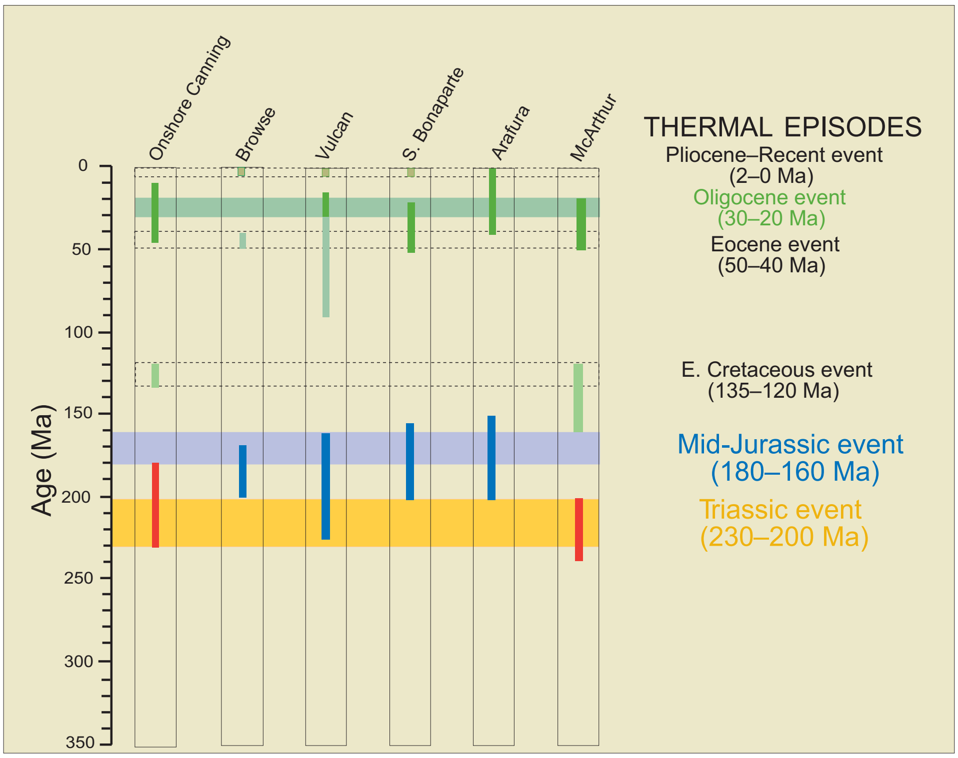


Figure 2. Summary of thermal episodes in northwest Australia revealed by AFTA-based thermal history reconstruction.

might actually consist of one or more episodes that vary in time in different regions. This is more clearly indicated by summary results illustrated in Figure 2, which plots the same AFTA timing constraints as listed for the individual wells in the Appendix. This plot suggests that six distinct post-Permian thermal episodes have affected these northern Australia basins to various degrees. Not all episodes observed in all basins, although this observation should be treated with caution, given the restrictions on the number and magnitude of events that AFTA can reveal, as noted in the previous paragraph. Despite this caveat, several major events are clearly observed across a broad region, especially during the "Oligocene" (30–20 Ma, so actually late Oligocene–early Miocene), Middle Jurassic (180–160 Ma), and to a lesser extent, the Triassic (230–200 Ma).

Other events are not observed so widely, but it is not clear whether this is due to their absence, or whether they were of lower magnitude, so that other events dominate the measured AFTA parameters. Thus, an Eocene (50–40 Ma) event is interpreted for the Vulcan and Browse basins, while an Early Cretaceous event (135–120 Ma) is only seen in the onshore Canning and McArthur basins. On the other hand, a Middle Jurassic episode in not observed in the onshore Canning Basin, where a distinctly earlier Triassic event is present, as it is in the McArthur Basin. A Middle Jurassic episode is also interpreted for the Vulcan Sub-basin, even though the timing constraint overlaps the Triassic episode. This is because the palaeo-geothermal gradient for the well-defined Triassic episode in the onshore Canning and McArthur basins is "normal' (i.e. similar to the present-day geothermal gradient), whereas those determined for the Vulcan, southern Bonaparte and Browse basins, are significantly elevated compared to the present-day geothermal gradient. Constraints obtained on palaeo-geothermal gradients for each episode are discussed in the following section.

To some extent, the lack of resolution of earlier thermal episodes reflects the lack of sampling of early Palaeozoic and older rocks in the present study, which would allow the assessment of such earlier episodes. However, it also reflects the high magnitude of palaeo-temperatures involved in the Triassic event, which may have overprinted evidence for such earlier episodes in older sequences sampled in the onshore Canning and McArthur basins (Fig. 2).

Mechanism of heating associated with regional thermal episodes

The mechanism(s) of heating involved in the regional thermal episodes shown in Figure 2 can be determined by assessment of the palaeo-geothermal gradient associated with each event, by using plots of palaeo-temperature derived from AFTA and VR results from exploration wells against sample depth (e.g. Bray *et al*., 1992; Duddy *et al*., 1994). This has been carried out for each of the exploration wells listed in the Appendix for each of the thermal episodes revealed by AFTA in these wells, using the AFTA palaeo-temperatures listed in this Appendix and incorporating palaeo-temperatures derived from open-file VR data, available from the appropriate well completion reports (a summary of this data is available from the authors). Quantitative estimates (maximum likelihood values and ± 95% confidence limits) of palaeo-geothermal gradients

Table 1. Quantitative estimates of palaeo-geothermal gradient and removed section derived from the thermal history results for AFTA-constrained thermal episodes in key wells from northern Australian basins. [1] Derived from corrected BHT data using method described in text. [2] 95% confidence range from AFTA. [3] Maximum likelihood value and 95% confidence limits in brackets. [4] Section removed since time indicated by AFTA. [5] Estimated assuming an elevated palaeo-geothermal gradient of 50°C/km. [6] Estimated assuming a palaeo-geothermal gradient equal to the present-day value.

Well	Present-day geothermal gradient[1] (°C/km)	AFTA timing constraint[2] (Ma)	Palaeo-geothermal gradient[3] (°C/km)	Removed section[3, 4] (m)
Rob Roy-1	36.3	240–170	77.0 (48.0–114.5)	900 (450–1,750)
		55–30	24.5 (31.5–38.0)	1,300 (950–1,850)
White Hills-1	31.0	230–180	33.0 (31.0–35.0)	2,550 (2,300–2,900)
		135–120	35.0 (22.5–48.5)	1,100 (450–2,450)
		45–10	18.0 (6.5–33.5)	2,050 (350–8,300)
Jabiru-1A	27.4	225–160	84.0 (60.5–114.0)	100 (0–600)
		30–15	25.0 (15.0–36.5)	1,500 (450–3,700)
Keep River-1	29.8	200–155	53.0 (48.0–59.5)	1,000 (750–1,250)
		50–20	19.5 (0–67.0)	2,350 (>450)
Torres-1	35.0	220–150	No effective constraint	1,500[5]
		40–0	No effective constraint	950[6]
Broadmere-1	29.5	240–200	No effective constraint	2,000[6]
		160–120	No effective constraint	1,850[6]
		50–20	No effective constraint	1,700[6]

and any associated removed section derived from this formal analysis are listed in Table 1.

Inspection of the results in Table 1 shows that some thermal events in several wells were associated with a period of highly elevated palaeo-geothermal gradients, as compared to present-day levels, while palaeo-geothermal gradients for other events are consistent with present-day levels. Thus, in Rob Roy-1, Jabiru-1A and Keep River-1, palaeo-geothermal gradients for the mid-Jurassic episode are significantly higher than the present-day gradients (at ± 95% confidence limits), while in White Hills-1, the palaeo-geothermal gradient for the Triassic episode is remarkably similar to the present-day gradient. No effective constraints were available on the palaeo-geothermal gradients for any of the events revealed in Torres-1 and Broadmere-1. This largely reflects the lack of reliable VR data, in the case of Torres-1 due to VR suppression and in the case of Broadmere-1 due to the Proterozoic section lacking true vitrinite.

Recognition of consistent patterns of palaeo-geothermal gradients, associated with each major AFTA-derived thermal episode across the region, allows correlation with regional tectonic episodes, as revealed by conventional geological and geophysical studies and summarised in regional studies (e.g., AGSO, 1994; Baillie *et al*, 1994; Barber, 1982; Etheridge and O'Brien, 1994; Bradshaw *et al*., 1998); Struckmeyer *et al*., 1998). These correlations are summarised in Table 2.

Thermal and burial history reconstruction in White Hills-1 (Canning Basin), Rob Roy-1 (Browse Basin), Jabiru-1A (Vulcan Sub-basin), Keep River-1 (Bonaparte Basin), Torres-1 (Arafura Basin) and Broadmere-1 (McArthur Basin)

AFTA- and VR-derived thermal histories of key wells in the Vulcan Sub-basin, Bonaparte Basin, Arafura Basin and McArthur Basin, and the implications of these histories for the burial and hydrocarbon source rock maturation histories, are discussed in this section.

Eastern Canning Basin: White Hills-1

The thermal, burial and source rock maturation histories reconstructed for White Hills-1 are illustrated in Figures 3–5, 6–9 and 10–13. Two key conclusions can be drawn from these results: 1, the Permian to Devonian section cooled from maximum temperatures in Late Triassic to Early Jurassic times (beginning at some time between 230 and 180 Ma); and 2, the heat flow at this time was similar to that of the present-day (Appendix). It is also clear from the AFTA results that active source rock maturation in the vicinity of White Hills-1 ceased due to cooling resulting from kilometre-scale uplift and erosion (Table 1) at this time. This episode in the onshore Canning Basin is quite distinct from an earlier mid-Permian to mid-Triassic episode identified in the near-offshore Canning Basin, which resulted from localised heating related to transient hot-fluid flow, associated with shallow igneous intrusions into wet sediments (Duddy *et al*., 1994).

Episode	Timing (Ma)	Regional tectonic correlation	Mechanism of heating and cooling [1]
Arafura Basin offshore			
Episode 1:	200–150	Callovian break-up unconformity	Elevated HF + U&E
Episode 2:	40–0	?Oligocene "hiatus"	?Normal HF + U&E
Browse Basin			
Episode 1:	200–170	Callovian break-up unconformity	Elevated HF + U&E
Episode 2:	50–40	E. Tertiary unconformity	Normal HF + U&E
Episode 3:	5–0	Timor collision	Local shallow hot FF
Canning Basin onshore			
Episode 1:	230–180	Fitzroy Movement	Normal HF + U&E
Episode 2:	135–120	?Valanginian unconformity	?Normal HF + U&E
Episode 3:	45–10	Oligocene "hiatus"	Normal HF + U&E
McArthur Basin onshore			
Episode 1:	240–200	Fitzroy Movement	?Normal HF+ U&E
Episode 2:	160–85	Jurassic–Cretaceous	?Elevated HF + U&E
Episode 3:	50–20	Oligocene "hiatus"	Normal HF + U&E
Southern Bonaparte Basin			
Episode 1:	200–155	Callovian break-up unconformity	Elevated HF + U&E
Episode 2A:	90–30	?E. Tertiary unconformity	Normal HF + U&E
Episode 2B:	50–20	Oligocene "hiatus"	Normal HF + U&E
Episode 3:	5–0?	Timor collision	Local shallow hot FF
Vulcan Sub-basin offshore			
Episode 1:	225–160	Callovian break-up unconformity	Elevated HF + U&E
Episode 2:	30–15	Oligocene "hiatus"	U&E?
Episode 3:	2–0	Timor collision	Local shallow hot FF

Table 2. Summary of regional palaeo-thermal episodes in northern Australia identified using AFTA®-based thermal history reconstruction on well and outcrop samples. [1] Significant palaeo-surface temperature changes may be involved in cooling associated with the Oligocene "hiatus". HF = heat flow; FF = fluid flow; U&E = uplift and erosion.

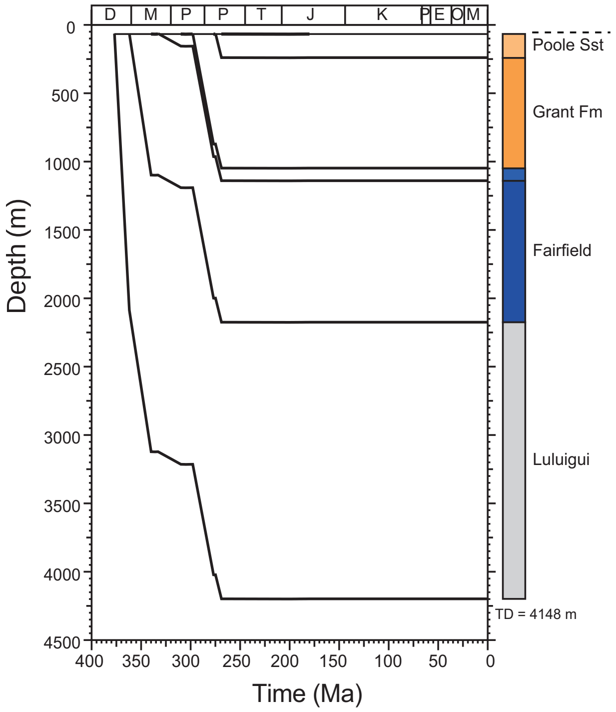


Figure 3 (left). Default Burial History for White Hills-1, eastern Canning Basin, derived from the preserved stratigraphy. This history, together with the present-day geothermal gradient of 31°C/km and a palaeo-surface temperature of 20°C, has been used to calculate the Default Thermal Histories for each sample, from which default parameters are calculated. Default parameters are compared with observed AFTA parameters (Figure 4) and measured VR data (Figure 5), to evaluate the degree of heating attributable to the present thermal regime and hence, to determine whether samples have been hotter in the past.

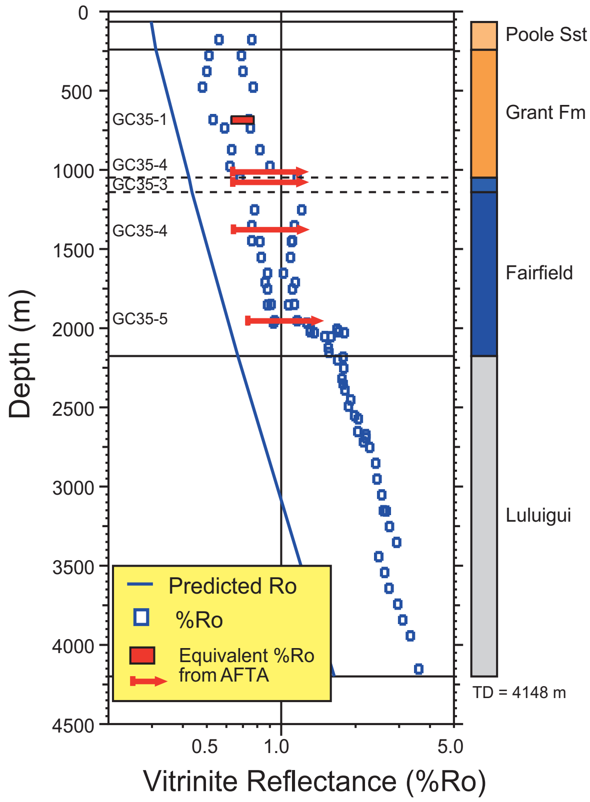


Figure 4 (right). Measured and predicted vitrinite reflectance with respect to depth for White Hills-1. The square symbols denote open-file VR data ("low" and "high" reflecting populations) and the red boxes and range bars designate equivalent VR ("VRE") values inferred from AFTA data. The solid line shows the VR profile calculated on the basis of the Default Thermal History. While there is some uncertainty as to which VR population provides an accurate measure of the thermal history, it is clear that all VR values and AFTA-derived VRE values plot above the predicted profile throughout the sampled section, suggesting that this section was exposed to maximum palaeo-temperatures higher than present-day temperatures at some time after deposition. Furthermore, the gradient of the measured data trend is similar to the predicted profile, providing qualitative evidence that heat flow at the time of maximum palaeo-temperatures was similar to the present-day heat flow.

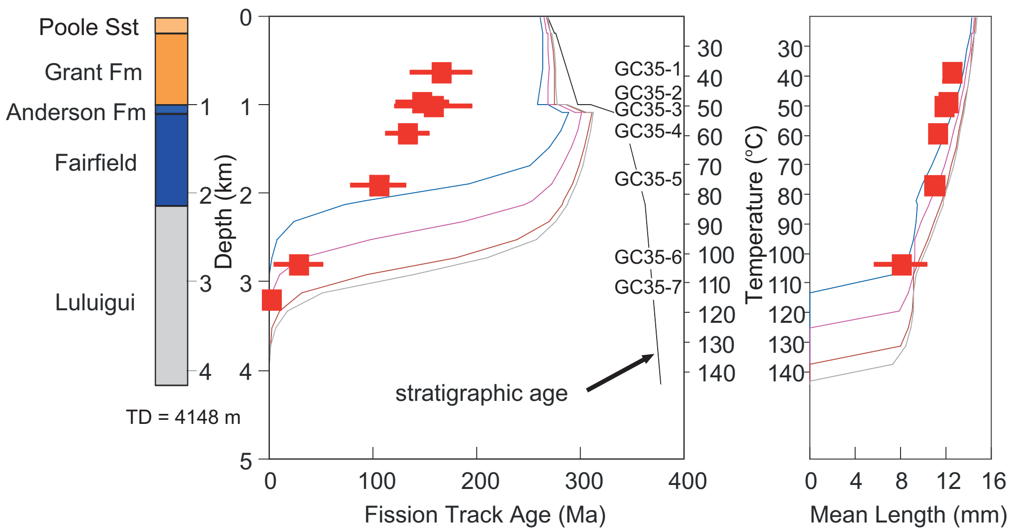


Figure 5. AFTA parameters plotted against sample depth and present-day temperature for White Hills-1. The variation of stratigraphic age with depth, together with the variation in fission track age, as predicted from the Default Thermal History for a range of apatite compositions, are also shown in the central panel. Predictions are shown for 0–0.1 (blue), 0.4–0.5 (magenta), 0.9–1.0 (red), and 1.5–1.6 (grey) wt % Cl groups. Measured ages from the five shallower samples are much younger than predicted, and mean track lengths are generally shorter than predicted, from the Default Thermal History, providing prima facie evidence that these samples have been subjected to maximum palaeo-temperatures higher than present-day temperatures at some time after deposition of the sampled sequences. Measured ages and length in the deeper samples are more consistent with the predictions from the Default Thermal History, as these data are dominated by the high present-day temperatures and preserve little information on the palaeo-thermal history.

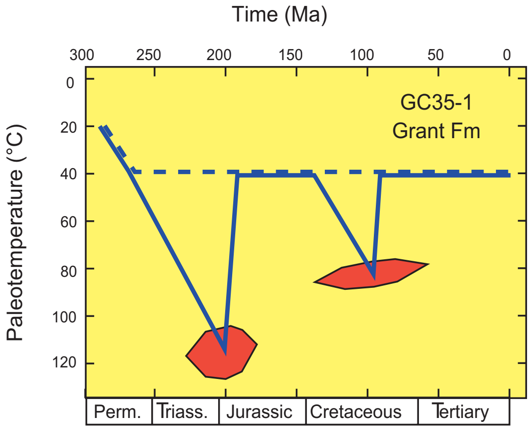


Figure 6. AFTA thermal history solution (solid path) for Grant Formation sample GC35-1, White Hills-1. Red fields show the AFTA-derived time-temperature constraints, showing cooling from maximum palaeo-temperatures of 105–125°C, beginning at some time in the Late Triassic–Early Jurassic (230–180 Ma) and cooling from a lower peak in palaeo-temperatures of 75–95°C, beginning at some time in the Early Cretaceous–Early Tertiary (130–60 Ma). The dashed path shows the DTH for this sample.

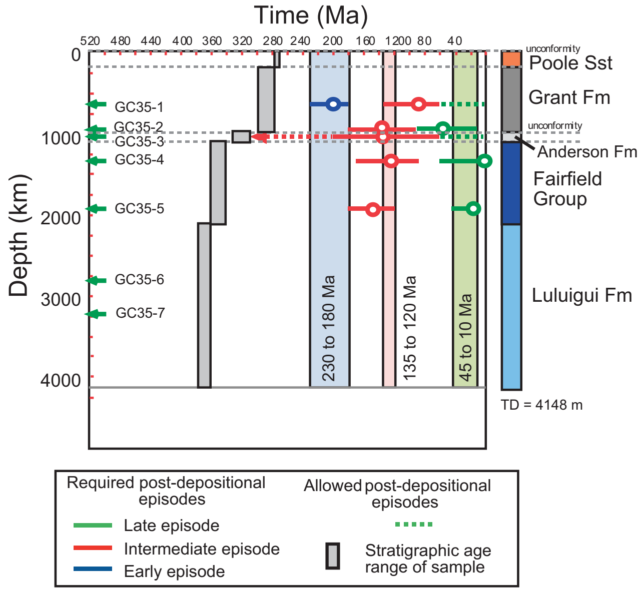


Figure 7. Summary of timing constraints on thermal episodes from AFTA for White Hills-1. Overlap of constraints from individual samples is interpreted in terms of three major thermal episodes: 230–180 Ma (Late Triassic–Early Jurassic); 135–120 Ma (Early Cretaceous); 45–10 Ma (Eocene–late Miocene). The mechanism of heating in each of these episodes is attributed to deeper burial, with cooling due to uplift and erosion as discussed in the text.

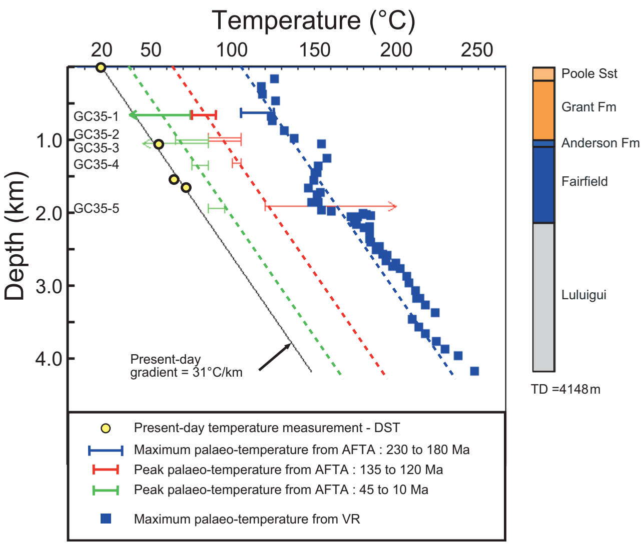


Figure 8 (left). Plot of palaeo-temperatures derived from AFTA and VR data against depth and the estimated present-day temperature profile. Overlap of AFTA timing constraints from individual samples for White Hills-1 (Fig. 7) indicates cooling from the maximum palaeo-temperatures required by the VR results began at some time between 230 and 180 Ma (Late Triassic–Early Jurassic). AFTA also indicates cooling in two subsequent episodes, beginning between 135 and 120 Ma (Early Cretaceous) and between 45 and 10 Ma (Eocene–late Miocene). Qualitative inspection of the palaeo-temperature constraints is consistent with the palaeo-geothermal gradient in each episode being similar to the present-day geothermal gradient, allowing little variation in basal heat flow since the Triassic.

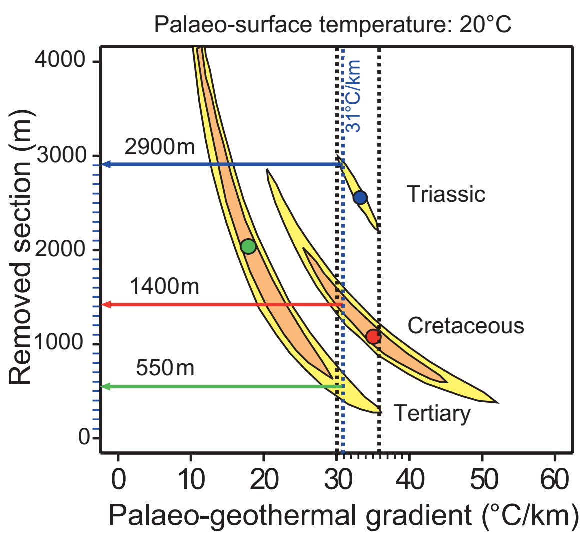


Figure 9 (left). Cross-plot of total section removed from the top-Poole Sandstone unconformity in White Hills-1 against palaeo-geothermal gradient as required by the AFTA and VR results for the three palaeo-thermal episodes revealed by AFTA. The plot shows the range of values (paired within the contoured regions) compatible with the maximum palaeo-temperatures derived from the AFTA and VR data, at the 95% confidence level. Inspection of the plot shows that a palaeo-geothermal gradient of 30–36°C/km, encompassing the present-day value of 31°C/km, is compatible with the results in each thermal episode, and this corresponds to the removed section estimates shown. For example, for a palaeo-geothermal gradient of 31°C/km for the Triassic episode, ~2,900 m (± 100 m) of removed section is required on the top-Poole Sandstone unconformity, in order to honour the palaeo-temperature constraints. Similarly, for the same geothermal gradient 1,400 m (± 200 m) and 550 m (± 200 m) of section has been eroded since the Early Cretaceous and Eocene–Miocene, respectively. Other values of removed section are allowed during each episode, as shown, but these can only be used in the burial history reconstruction when combined with the corresponding values of palaeo-geothermal gradient.

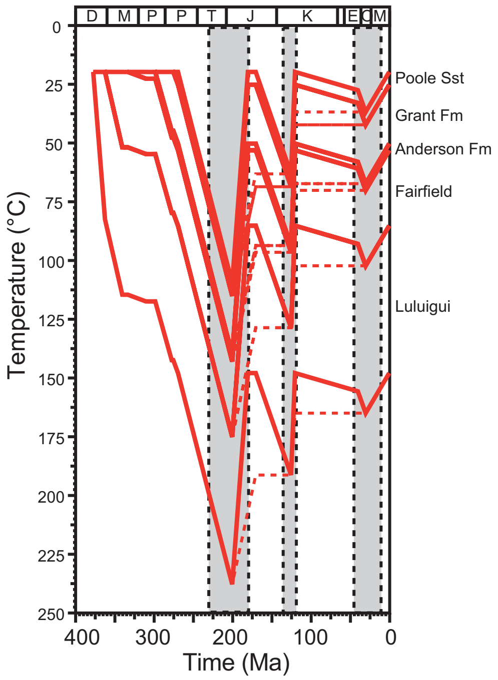


Figure 10. Reconstructed thermal history for White Hills-1, using a constant palaeo-geothermal gradient of 31°C/km and palaeo-surface temperature of 20°C for the entire history, as derived from the AFTA and VR results. While the history illustrated (solid lines) shows a heating period following each of two most recent thermal episodes, this is not constrained by AFTA, and a range of alternative histories with less heating are also possible, limited by the dashed paths.

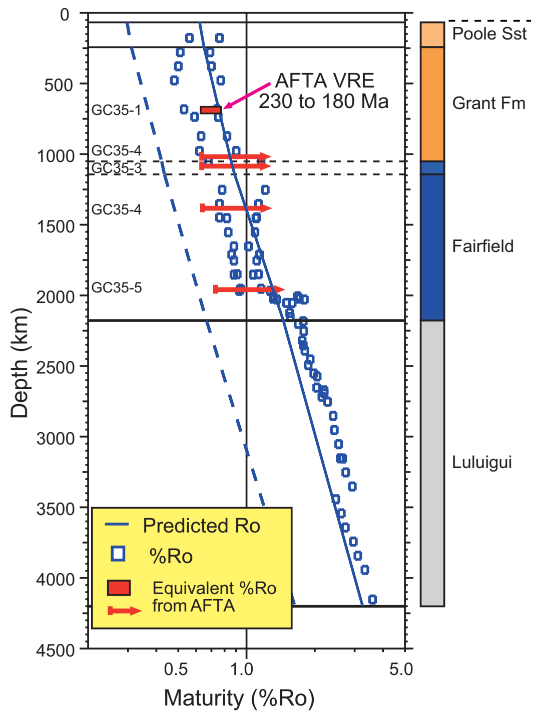


Figure 12. Measured VR data, equivalent VR levels from AFTA and the predicted VR profile, derived from the reconstructed thermal history illustrated in Figure 10 for White Hills-1, incorporating a constant palaeo-geothermal gradient of 31°C/km. The predicted profile shows an acceptable fit to the majority of the high reflecting VR population and the equivalent VR levels estimated from the AFTA data (Appendix), especially given the anomalous VR trend in much of the Luluigi Formation.

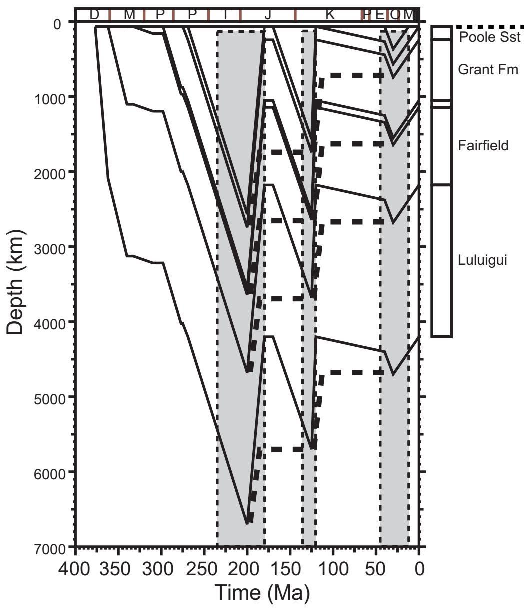


Figure 11. Burial History, reconstructed on the basis of the preferred thermal history reconstruction shown in Figure 10 for White Hills-1. The grey columns show the timing of the three major thermal episodes obtained from integration of the AFTA and VR results (Fig. 7). The history incorporates 2,500 m of total uplift and erosion, beginning at some time between 230 and 180 Ma, 1,500 m of net uplift and erosion, beginning between 135 and 120 Ma, and 500 m of net uplift and erosion, beginning between 45 Ma and 10 Ma, as required to honour the palaeo-temperatures constraints provided by the AFTA and VR data. Alternative burial histories are also possible within the limits of the data, one of which, without reburial between the episodes, is illustrated by the dashed paths. However, in any scenario, the additional 2,500 m of post-Poole Sandstone section required must be of Permian to Early Jurassic age.

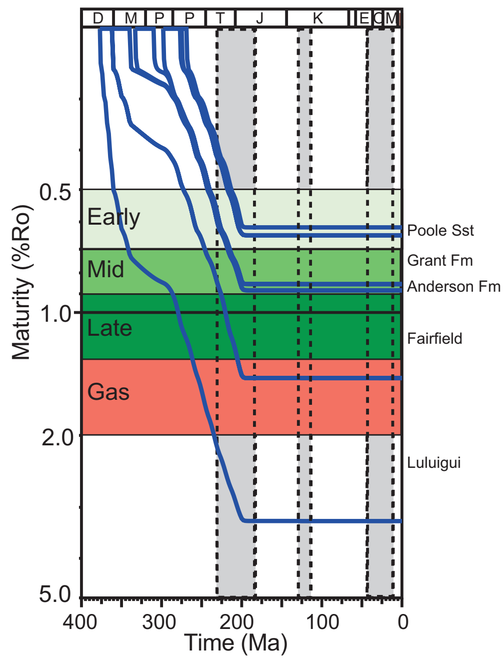


Figure 13. Variation of maturity with time for White Hills-1 derived from the reconstructed thermal history illustrated in Figure 10, with the grey columns representing the three thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation in the entire drilled section at 200 Ma (230–180 Ma allowed by AFTA), due to cooling as a response to kilometer-scale uplift and erosion attributed to the Fitzroy Movement. Note that the Early Cretaceous and Tertiary thermal episodes have no effect on the source rock maturation history, as palaeo-temperatures during these episodes were less than those during the Late Triassic–Early Jurassic.

Cooling associated with the Eocene to late Miocene (45–10 Ma) event in White Hills-1 also involved kilometre-scale uplift and erosion in a normal heat flow regime, while available results for the Early Cretaceous (135–120 Ma) event could be associated with either normal or slightly elevated heat flow (Tables 1 and 2). It is notable that this Eocene to late Miocene thermal episode appears to correlate with the regionally significant Oligocene "hiatus" (Table 2), clearly associated with major cooling in a normal heat-flow regime, which is most simply interpreted as due to major uplift and erosion.

Browse Basin-Londonderry High: Rob Roy-1

AFTA solutions for Rob Roy-1 are summarised in Appendix, with the resultant thermal, burial and source rock maturation histories summarised in Figures 14–16 and 17–20. The AFTA and VR results from Rob Roy-1 clearly demonstrate a period of elevated heat flow associated with maximum palaeo-temperatures in the Middle Triassic to Middle Jurassic (240–170 Ma). They indicate that active source rock maturation in the pre-Middle Jurassic section ceased at this time, due to a combination of a decline in heat flow and relatively minor uplift and erosion (Table 1).

The results also show that a second major thermal episode affected the entire drilled section at some time between the Paleocene and Oligocene (55–30 Ma), and heat

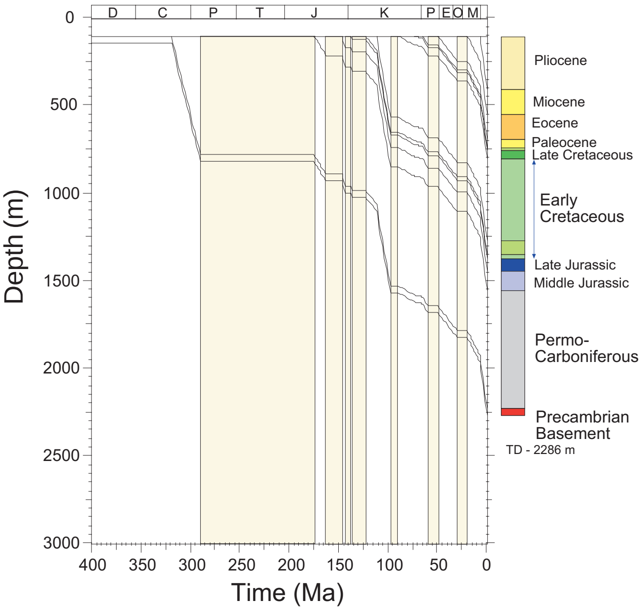


Figure 14. Burial history derived from the preserved section in Browse Basin well Rob Roy-1, used in predicting the "Default History" VR profile shown in Figure 15, by combining with the present-day gradient of 36.3°C/km and a palaeo-surface temperature of 20°C Shaded columns indicate the time represented by unconformities in the well section. Note that the history illustrated begins in the Carboniferous and there is a large unconformity to the underlying Precambrian basement.

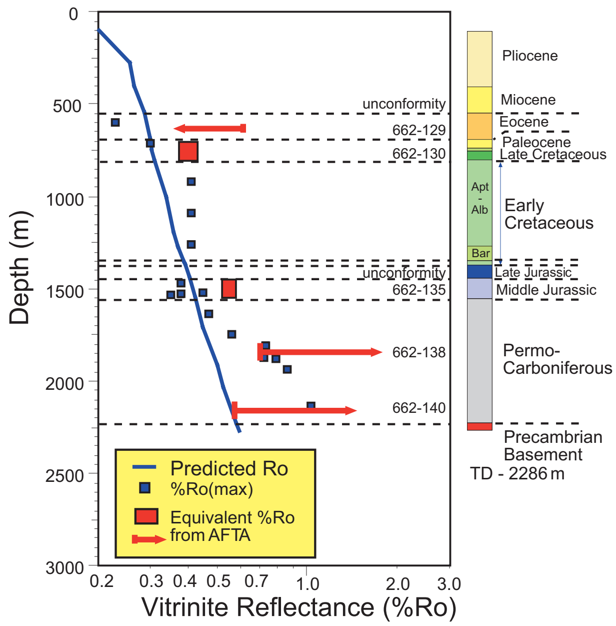


Figure 15. Vitrinite reflectance data and equivalent VR levels derived from AFTA plotted against depth (TVD RKB) for Rob Roy-1. The solid line shows the VR profile predicted by the "Default Thermal History", i.e. the profile expected if all units throughout the well are currently at their maximum temperature since deposition. The majority of the measured VR data and AFTA-derived VRE data plot well above the profile, indicating that the majority of the drilled section, at least the sampled part older than the Paleocene, has been hotter in the past. It is notable that the bulk of the VR data from the Middle Jurassic section is lower than expected, both on the basis of the Default History profile and the VRE level derived from AFTA, and this is attributed to geochemical suppression.

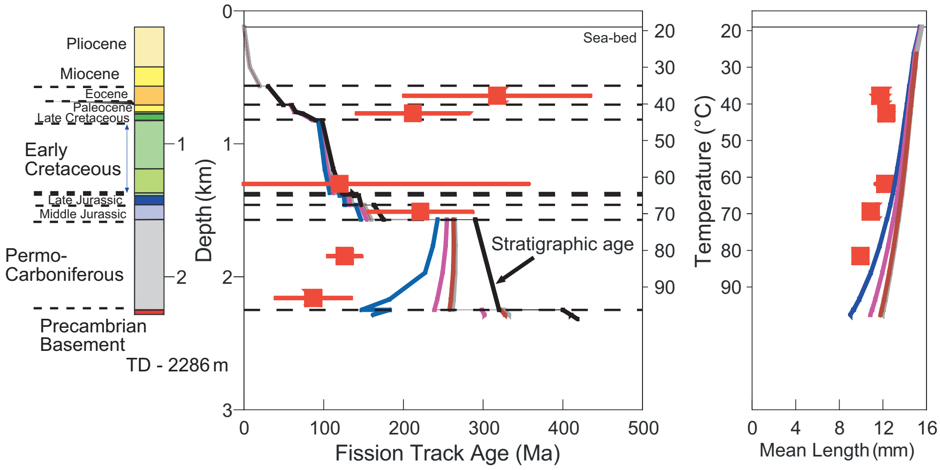


Figure 16. AFTA parameters plotted against sample depth and present-day temperature for samples from Rob Roy-1. Dashed lines represent known unconformities. Measured ages from the two deeper samples are much younger than predicted, and mean track lengths for all samples are shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for explanation of the predicted profiles.

flow at this time was similar to that of the present day. Cooling associated with this episode caused cessation of active source rock maturation throughout the post-Permo–Carboniferous section, and was most likely due to kilometre-scale uplift and erosion. Again the Oligocene "hiatus" in the Browse Basin (Table 2) appears to have been associated with a major uplift and erosion event.

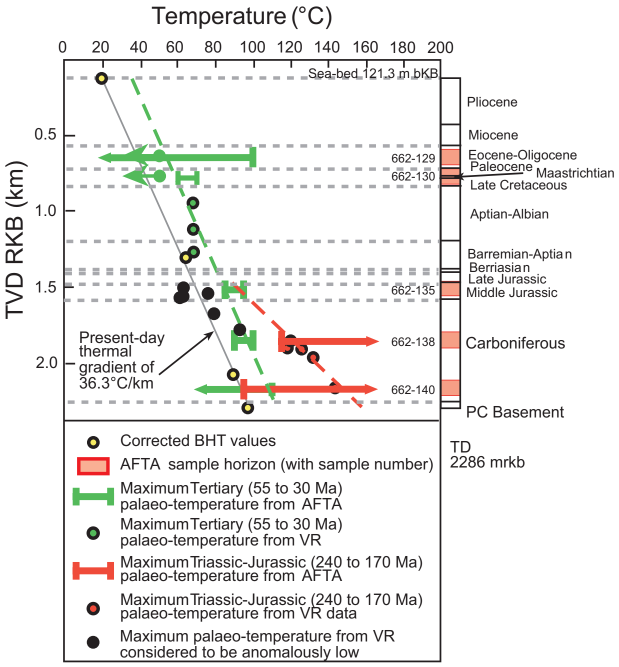


Figure 17. Palaeo-temperature constraints derived from AFTA and VR plotted against True Vertical Depth (RKB) for Rob Roy-1. Two major thermal episodes are recognised: 240–170 Ma (Middle Triassic–Middle Jurassic), associated with an elevated palaeo-geothermal gradient; and 55–30 Ma (Paleocene–Oligocene), associated with a palaeo-geothermal gradient similar to that at the present-day.

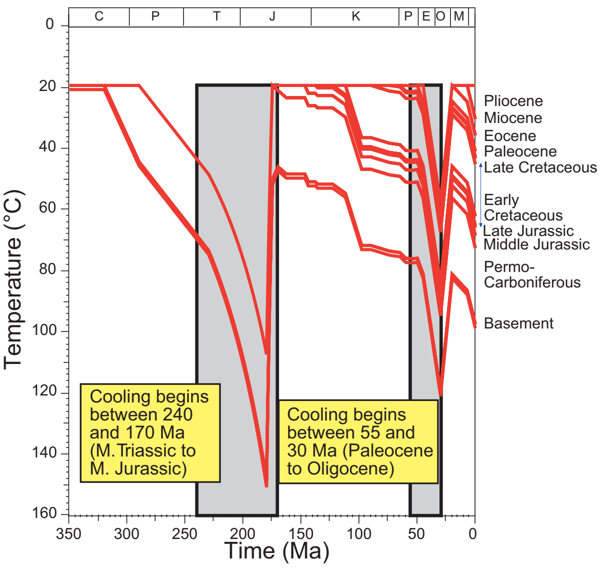


Figure 18. Reconstructed thermal history of units preserved in Rob Roy-1, based on thermal history interpretation of AFTA and VR. Two palaeo-thermal episodes have been recognised, with cooling beginning between 240 and 170 Ma (Middle Triassic–Middle Jurassic) attributed to a decline in basal heat flow combined with uplift and erosion, and with cooling beginning between 55 and 30 Ma (Paleocene–Oligocene) attributed solely to uplift and erosion. Timing limits derived from AFTA samples in this well are shown as the grey shading.

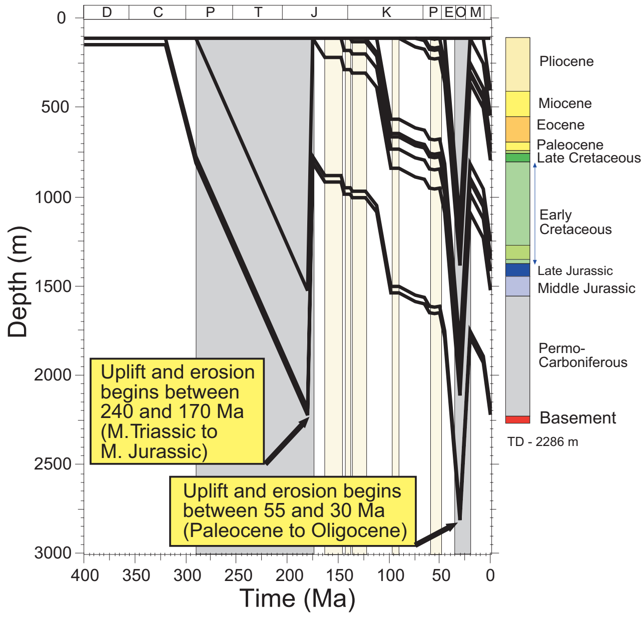


Figure 19. Reconstructed burial history for Rob Roy-1 based on the thermal history interpretation of the AFTA and VR data. Two uplift and erosion episodes have been interpreted from the thermal history results. Timing limits derived from AFTA samples in this well are shown as the grey shading, while the lighter shading represents the timing of additional unconformities in the well.

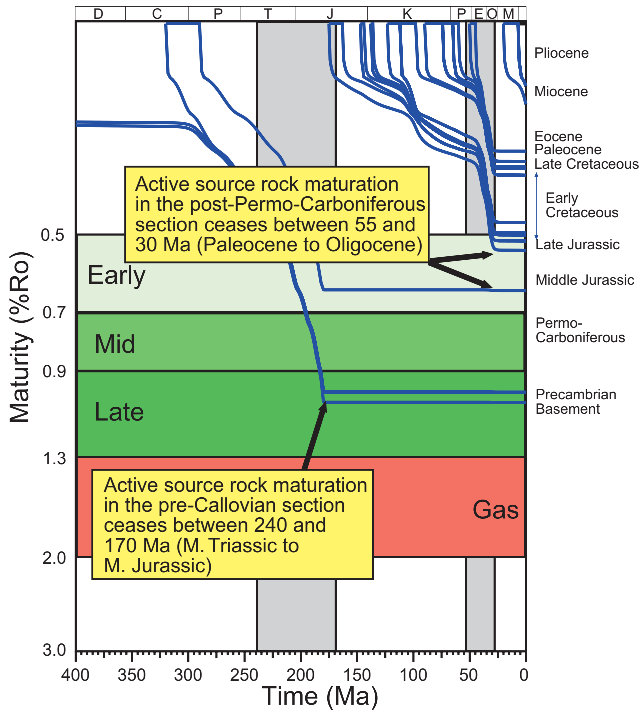


Figure 20. Variation of maturity with time for Rob Roy-1 derived from the reconstructed thermal history illustrated in Figure 18, with the grey columns representing the two major thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation in the deeper section at 180 Ma (240–170 Ma allowed by AFTA), due to cooling as a response to decline in basal heat flow and minor (600 m) uplift and erosion. Note that the Tertiary thermal episodes have no effect on the source rock maturation history in the deeper section, as palaeo-temperatures during this episode were less than those during the Middle Triassic–Middle Jurassic. However, subsequent burial did result in renewed maturation in the shallower section, with cessation of active maturation between 55 and 30 Ma.

Vulcan Sub-basin: Jabiru-1A

AFTA solutions for Jabiru-1A are summarised in the Appendix. Results from Jabiru-1A are very similar to those from Rob Roy-1 in the Browse Basin, as illustrated in Figures 21–23, 24-27 and 28. The data reveal a period of elevated heat flow in the Middle Triassic to Middle Jurassic (225–160 Ma), with active source rock maturation in the pre-Carnian section ceasing at this time due to a combination of decline in heat flow and minor, or no, uplift and erosion. On the other hand peak maturity in the shallower section, between the upper Ladinian and the Eocene, was reached immediately prior to cooling in the Oligocene to middle Miocene (30–15 Ma), due primarily to kilometre-scale uplift and erosion under the influence of a normal heat flow regime (Tables 1 and 2).

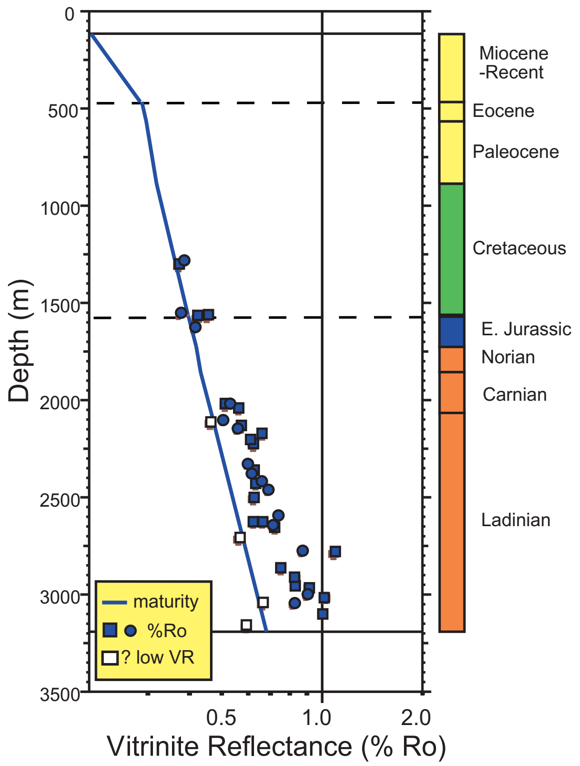


Figure 22. Vitrinite reflectance data and equivalent VR levels derived from AFTA for Jabiru-1A plotted against depth (TVD RKB). The solid line shows the VR profile predicted by the "Default Thermal History", i.e. the profile expected if all units throughout the well are currently at their maximum temperature since deposition. The majority of the measured VR data and AFTA-derived VRE data plot well above the profile, indicating that the majority of the drilled section, at least the sampled part older than the Paleocene, has been hotter in the past.

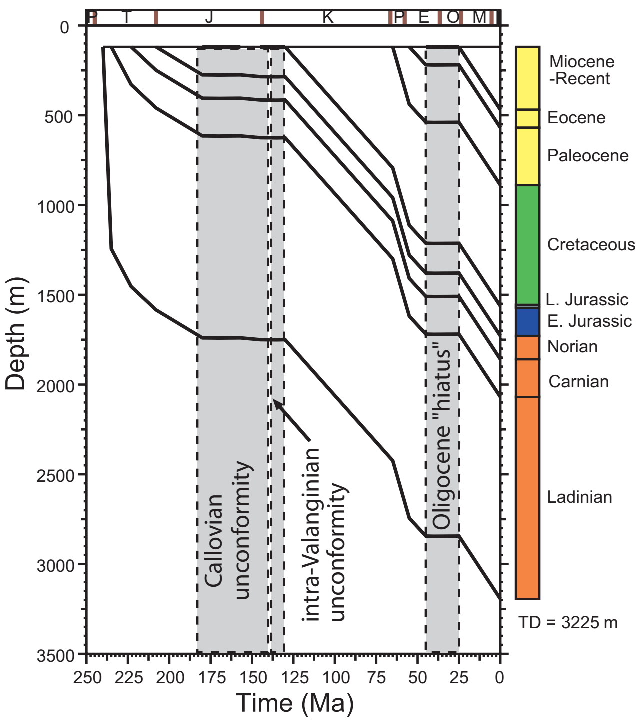


Figure 21 (left). Burial history derived from the preserved section in Vulcan Sub-basin well Jabiru-1A, used in predicting the "Default History" VR profile shown in Figure 22, by combining with the present-day gradient of 274°C/km and a palaeo-surface temperature of 20°C The shaded columns indicate the time represented by unconformities in the well section.

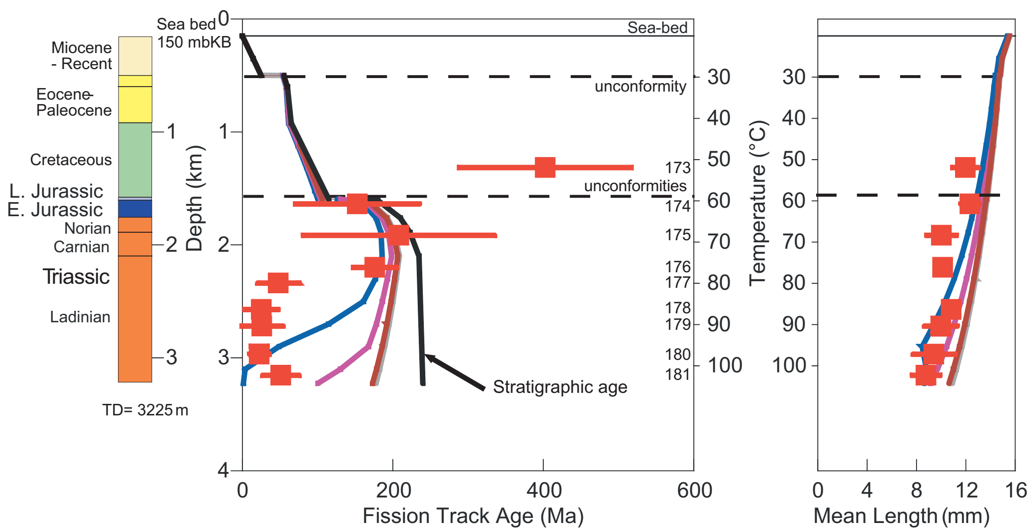


Figure 23. AFTA parameters plotted against sample depth and present temperature for samples from Jabiru-1A. Dashed lines represent known unconformities. Measured ages from the five deeper samples are much younger than predicted, and mean track lengths for all samples are similar to, or shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for explanation of the predicted profiles.

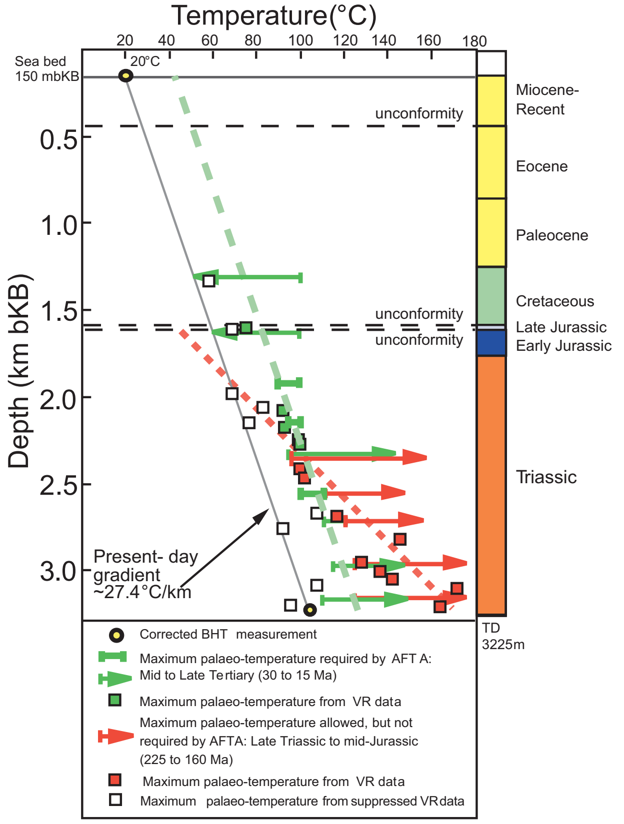
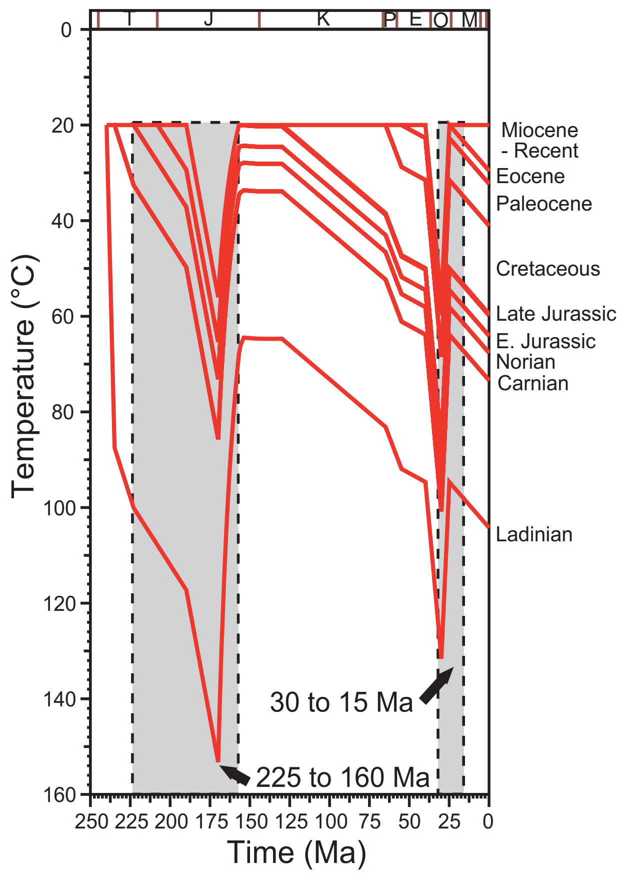


Figure 24. Palaeo-temperature constraints in Jabiru-1A, derived from AFTA and VR, plotted against True Vertical Depth (RKB). Two major thermal episodes are recognised: 225–160 Ma (Middle Triassic–Middle Jurassic), associated with an elevated palaeo-geothermal gradient; and 30–15 Ma (Oligocene–middle Miocene), associated with a palaeo-geothermal gradient similar to that at the present-day.



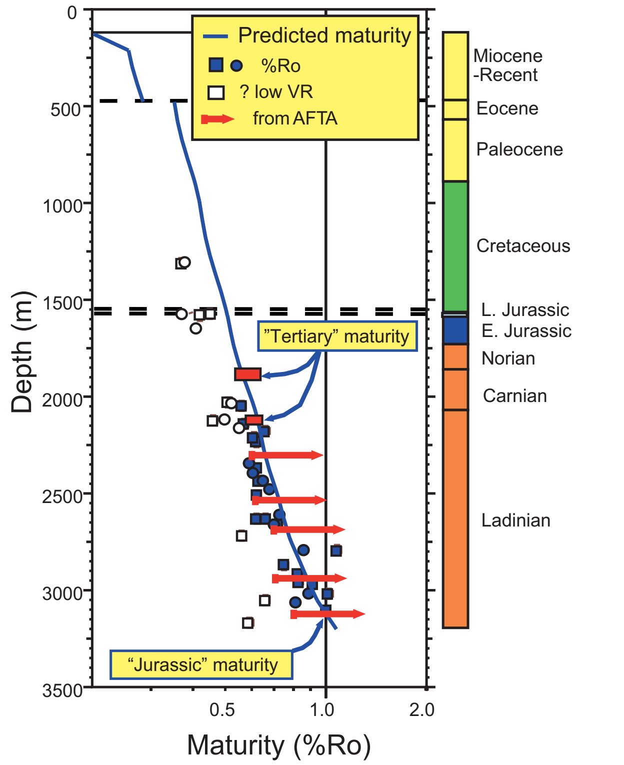


Figure 26. Measured VR data, equivalent VR levels from AFTA and the predicted VR profile derived from the reconstructed thermal history illustrated in Figure 25, for Jabiru-1A. The predicted profile shows a good fit to the majority of the measured VR data and the equivalent VR levels estimated from the AFTA data.

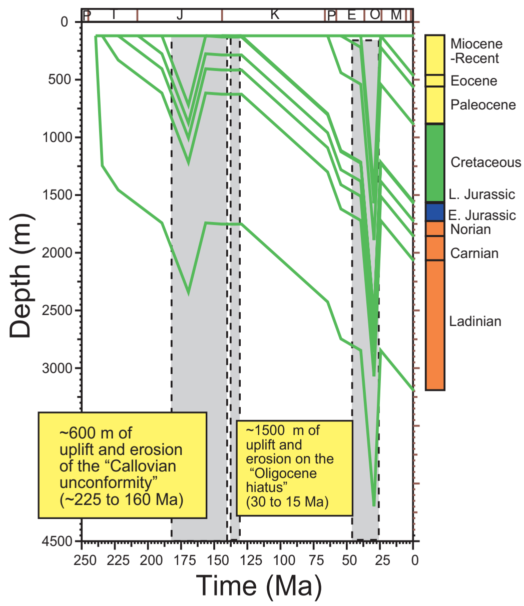


Figure 27. Reconstructed burial history for Jabiru-1A, based on the thermal history interpretation of the AFTA and VR data. Two uplift and erosion episodes have been interpreted from the thermal history results. Timing limits derived from AFTA samples in this well are shown as the grey shading.

Figure 25 (left). Reconstructed thermal history of units preserved in Jabiru-1A, based on thermal history interpretation of AFTA and VR. Two palaeo-thermal episodes have been recognised, with cooling beginning between 225 and 160 Ma (Middle Triassic–Middle Jurassic) attributed to a decline in basal heat flow combined with uplift and erosion, and with cooling beginning between 30 and 15 Ma (Oligocene–middle Miocene) attributed solely to uplift and erosion. Timing limits derived from AFTA samples in this well are shown as the grey shading.

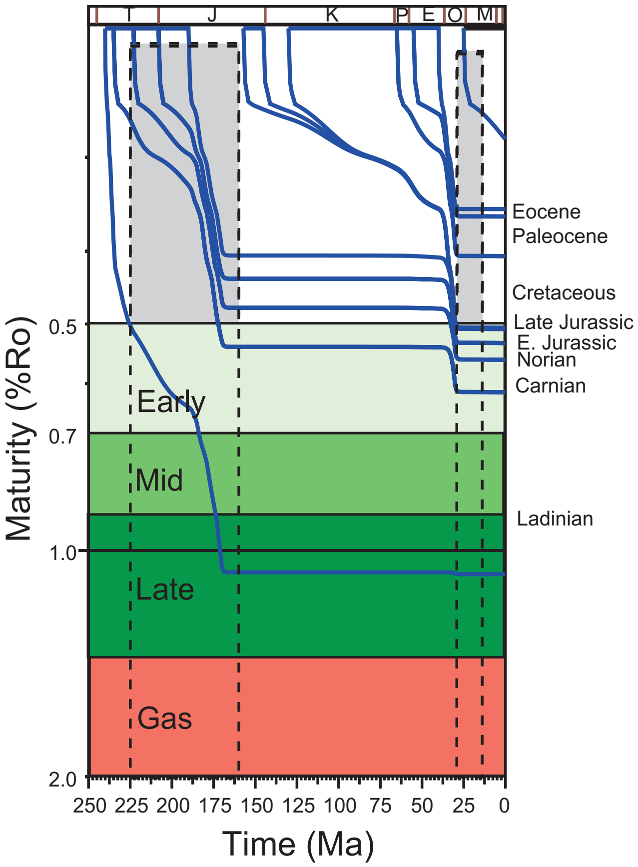


Figure 28 (left). Variation of maturity with time for Jabiru-1A, derived from the reconstructed thermal history illustrated in Figure 25, with the grey columns representing the two major thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation in the deeper section at 175 Ma (225–160 Ma allowed by AFTA), due to cooling as a response to a decline in basal heat flow and minor (600 m) uplift and erosion. Note that the Tertiary thermal episode has no effect on the source rock maturation history in the deeper section, as palaeo-temperatures during this episode were less than those during the Middle Triassic-Middle Jurassic. However, subsequent burial did result in renewed maturation in the shallower section, with cessation of active maturation occurring between 30 and 15 Ma.

Southern Bonaparte Basin: Keep River-1 and shallow bore holes

AFTA solutions for Keep River-1 are summarised in the Appendix, with results illustrated in Figures 29–30, 31–33 and 34–37. A period of elevated heat flow also characterises the Early to Middle Jurassic (200–155 Ma) event recognised in Keep River-1 and nearby shallow bore holes in the southern Bonaparte Basin, with cooling following this event attributed to a combination of decline in heat flow and uplift and erosion (Table 2). A major "Oligocene" cooling event (50–20 Ma) is largely attributed to kilometre-scale uplift and erosion, although decline from somewhat elevated heat flow at this time is also allowed (Table 1).

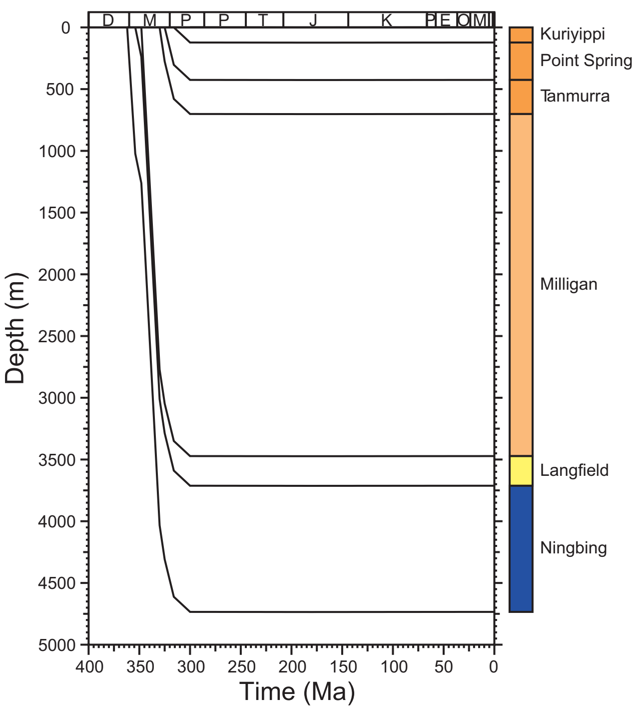


Figure 29. Burial history derived from the preserved section in the southern Bonaparte Basin well, Keep River-1, used in predicting the "Default History" VR profile shown in Figure 30, by combining with the present-day gradient of 29.8°C/km and a palaeo-surface temperature of 20°C. Shaded columns indicate the time represented by unconformities in the well section.

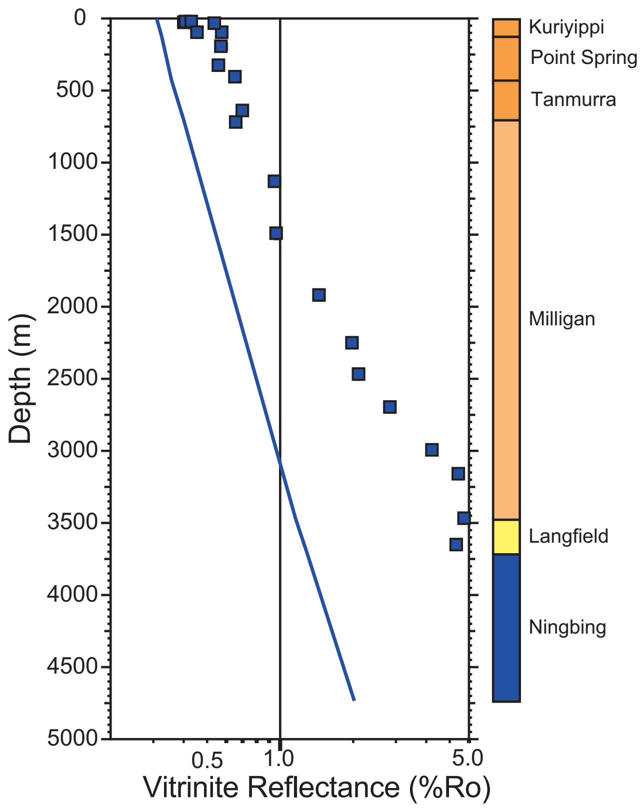


Figure 30. Vitrinite reflectance data for Keep River-1 plotted against depth (TVD RKB). The solid line shows the VR profile predicted by the "Default Thermal History", i.e. the profile expected if all units throughout the well are currently at their maximum temperature since deposition. All of the measured VR data plot well above the profile, indicating that the entire drilled section has been hotter in the past.

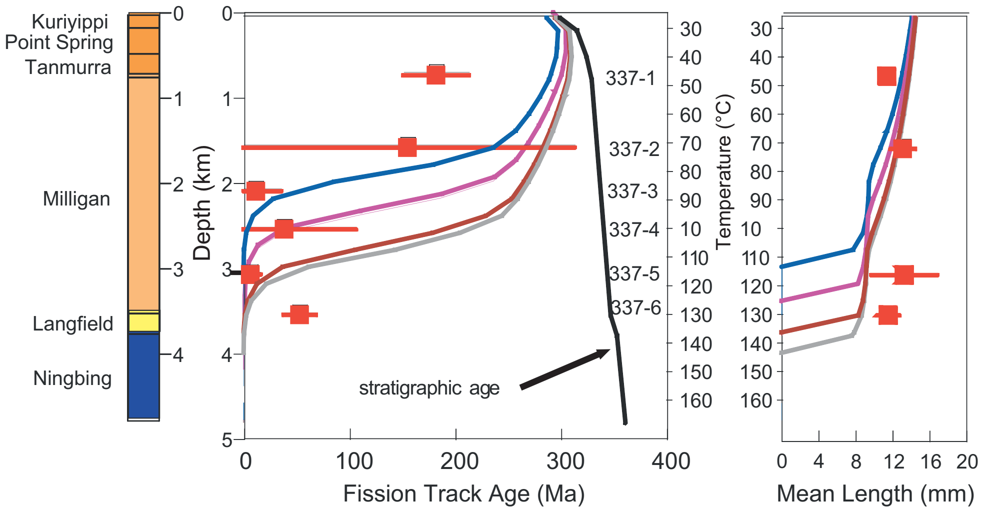


Figure 31. AFTA parameters plotted against sample depth and present temperature for samples from Keep River-1. Dashed lines represent known unconformities. The measured ages from the five deeper samples are much younger than predicted, and mean track lengths for all samples are similar to, or shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for an explanation of the predicted profiles.

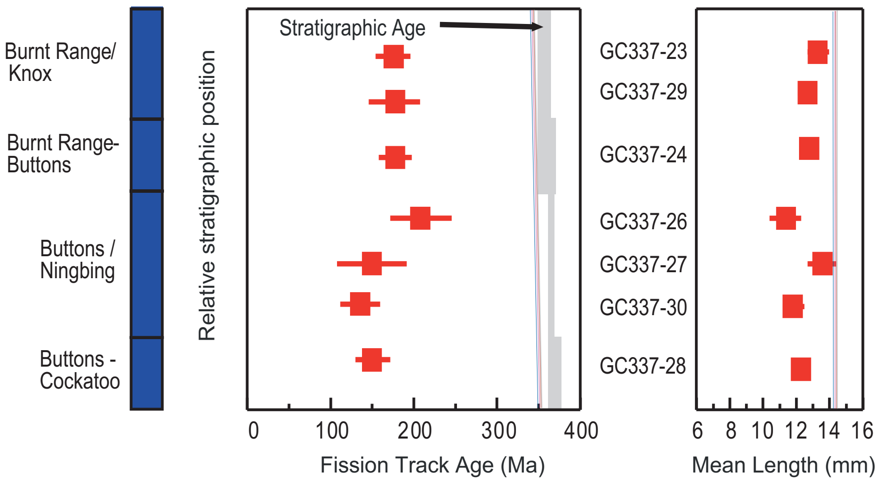


Figure 32. AFTA parameters plotted against sample depth and present temperature for samples from shallow onshore boreholes in the southern Bonaparte Basin. The measured ages from all seven samples are much younger than predicted, and mean track lengths for all samples are similar to, or shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for an explanation of the predicted profiles.

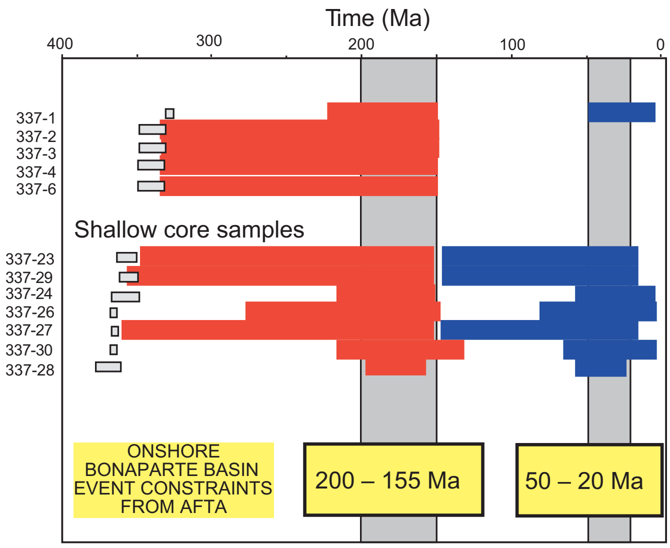


Figure 33. Timing constraints on thermal episodes derived from AFTA data in individual samples from Keep River-1 and shallow onshore boreholes. Two major thermal episodes are recognised: 200–155 Ma (Early–Middle Jurassic); and 50–20 Ma (Paleocene–Miocene).

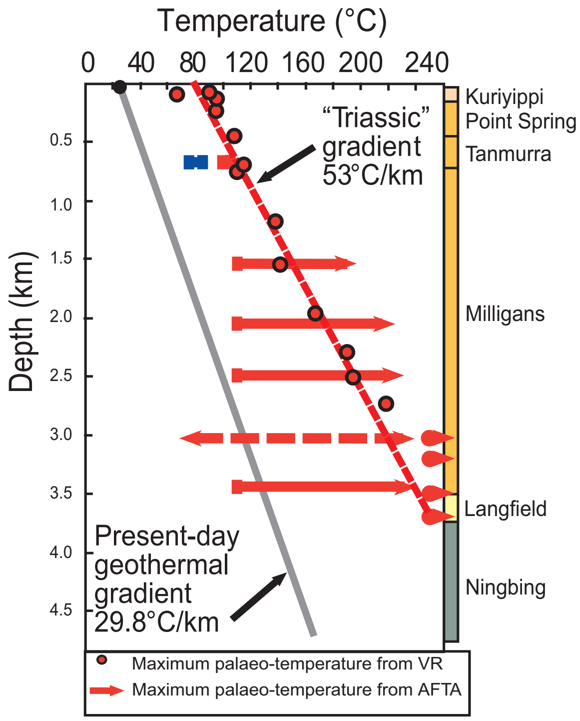


Figure 34. Palaeo-temperature constraints in Keep River-1, derived from AFTA and VR, plotted against True Vertical Depth (RKB). The Early–Middle Jurassic thermal episode is associated with an elevated palaeo-geothermal gradient, whereas there is no effective constraint on the Paleocene–Miocene palaeo-geothermal gradient.

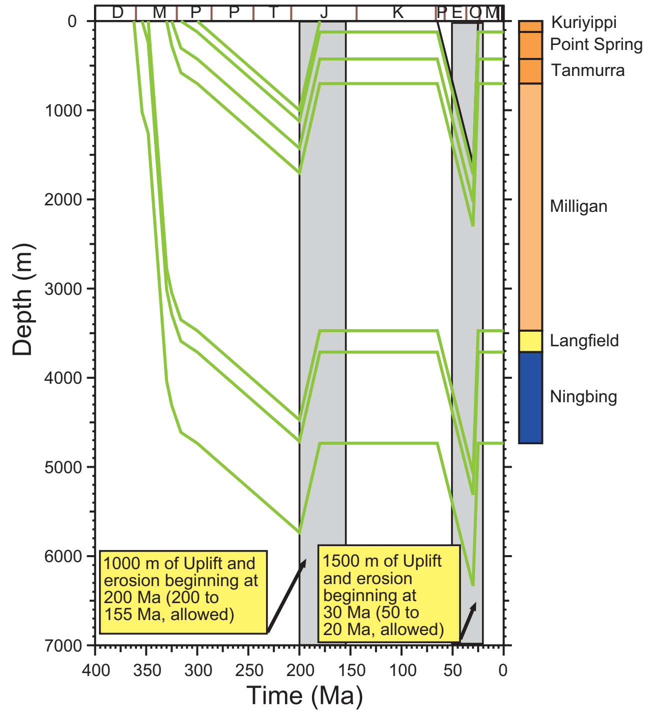


Figure 36. Reconstructed burial history for Keep River-1, based on the thermal history interpretation of the AFTA and VR data. Two uplift and erosion episodes have been interpreted from the thermal history results. Timing limits derived from AFTA samples in this well are shown as the grey shading.

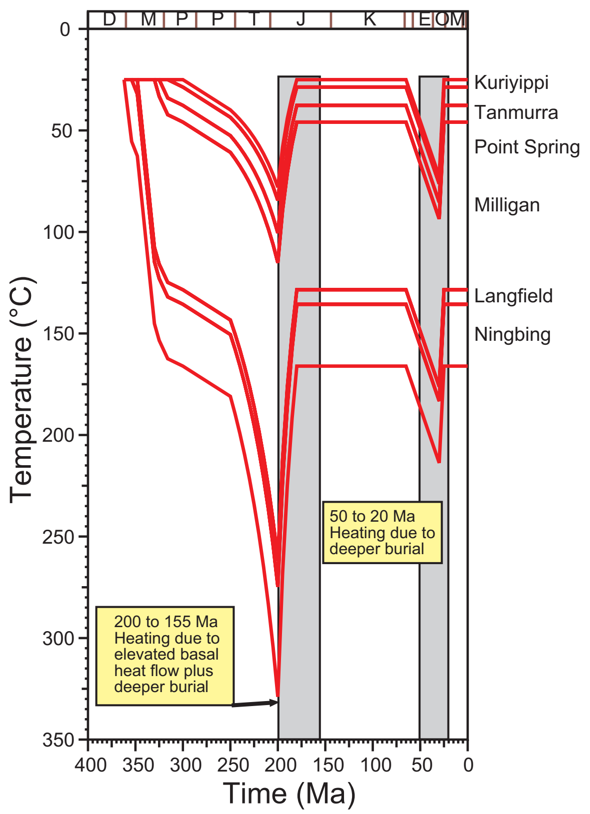


Figure 35. Reconstructed thermal history of units preserved in Keep River-1, based on thermal history interpretation of AFTA and VR. Two palaeo-thermal episodes have been recognised, with cooling beginning between 200 and 155 Ma (Early–Middle Jurassic) attributed to decline in basal heat flow combined with uplift and erosion, and with cooling beginning between 50 and 20 Ma (Eocene–Miocene) attributed solely to uplift and erosion. Timing limits derived from AFTA samples in this well are shown as the grey shading.

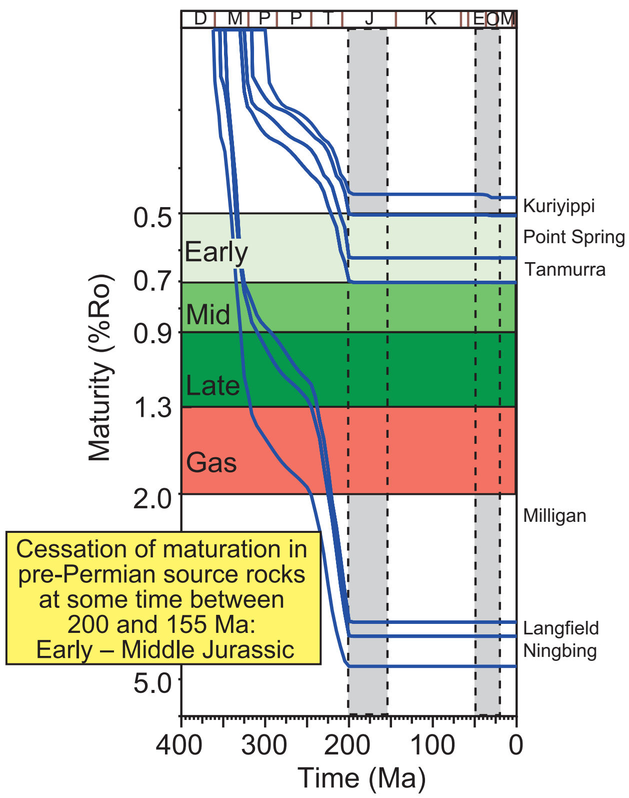


Figure 37. Variation of maturity with time for Keep River-1, derived from the reconstructed thermal history illustrated in Figure 35, with the grey columns representing the two major thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation throughout the drilled section at 200 Ma (200–155 Ma allowed by AFTA), due to cooling as a response to a decline in basal heat flow and minor (1,000 m) uplift and erosion. Note that the Tertiary thermal episode has no effect on the source rock maturation history anywhere in the section.

Arafura Basin: Torres-1

AFTA solutions for Torres-1 are summarised in the Appendix, with results illustrated in Figures 38–40, 41–44 and 45. No effective constraints could be obtained on the palaeo-geothermal gradient for the two thermal episodes identified in the Torres-1 well. Based on the results from the southern Bonaparte, Vulcan and Browse basins, the thermal event identified between 220 and 150 Ma in Torres-1 (i.e. the hydrocarbon generation event for pre-Late Jurassic source rocks) is also attributed to elevated heat flow, with cooling due to a combination of decline in heat flow and kilometre-scale uplift and erosion (Tables 1 and 2). Similar regional timing comparisons suggest the event between 40 and 0 Ma is attributed largely to kilometre-scale uplift and erosion in a normal heat flow regime.

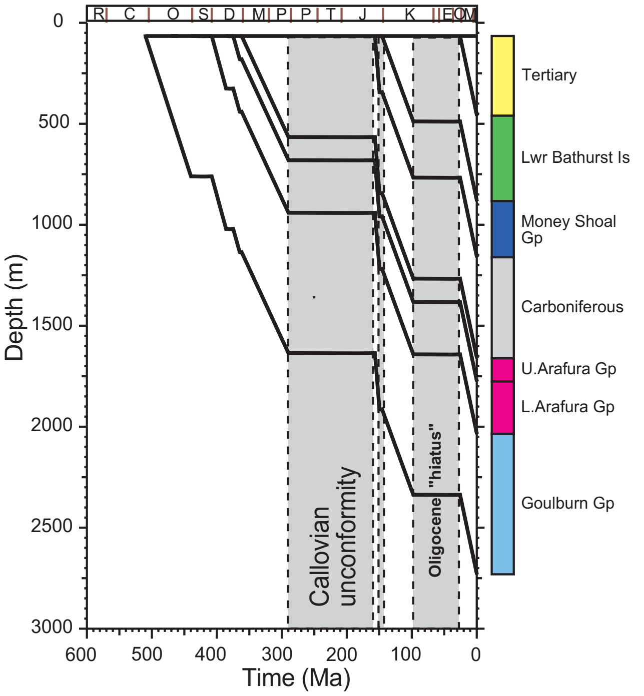


Figure 38. Burial history derived from the preserved section in Arafura Basin well, Torres-1, used in predicting the "Default History" VR profile shown in Figure 39, by combining with the present-day gradient of 35°C/km and a palaeo-surface temperature of 20°C. Shaded columns indicate the time represented by unconformities in the well section.

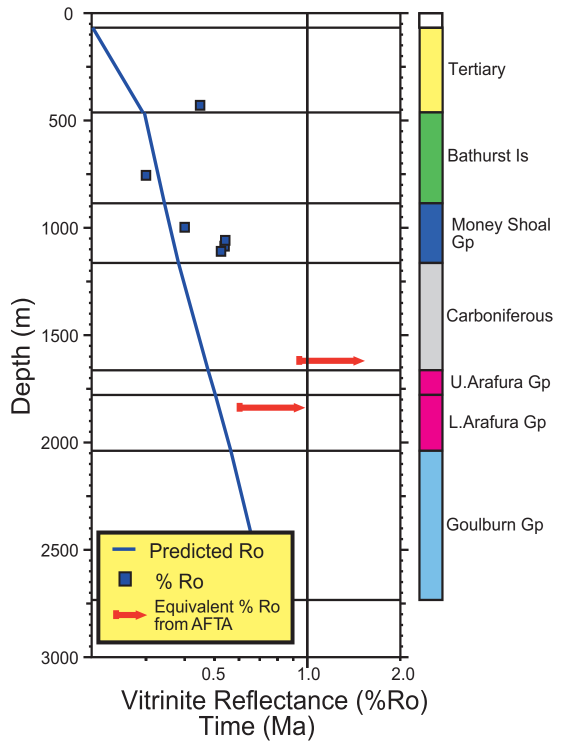


Figure 39. Vitrinite reflectance data and equivalent VR levels derived from AFTA for Torres-1 plotted against depth (TVD RKB). The solid line shows the VR profile predicted by the "Default Thermal History", i.e. the profile expected if all units throughout the well are currently at their maximum temperature since deposition. The limited VR results are somewhat scattered, with some data plotting well above the profile, indicating that the entire drilled section has been hotter in the past, and with other data closer to the profile suggesting that present-day temperatures are close to the maximum temperature since deposition. Equivalent VR levels from AFTA on the other hand, clearly indicate that the deeper section has cooled from maximum temperatures higher than present temperatures at some time since the Carboniferous.

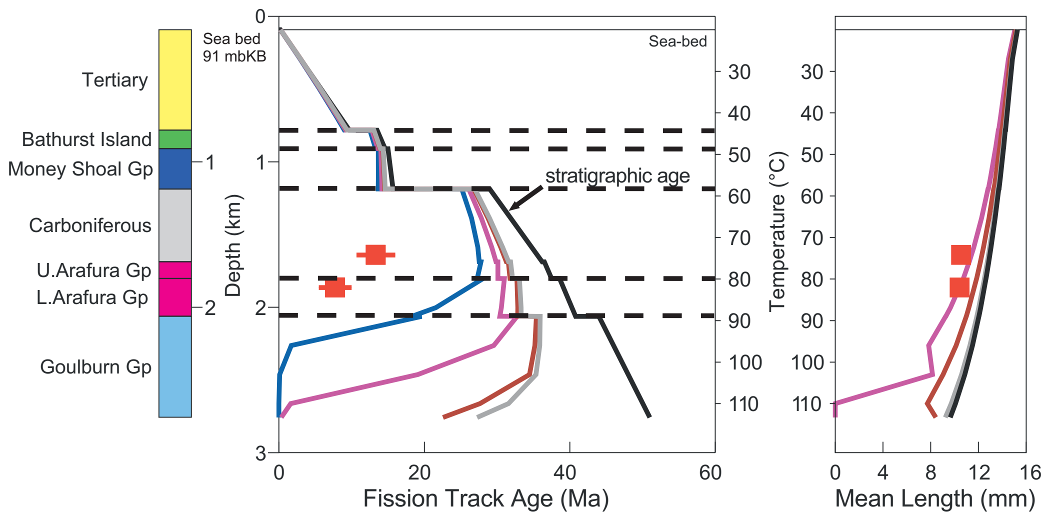


Figure 40. AFTA parameters plotted against sample depth and present temperature for samples from Torres-1. Dashed lines represent known unconformities. The measured ages from both samples are much younger than predicted, and mean track lengths for all samples are similar to, or shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for an explanation of the predicted profiles.

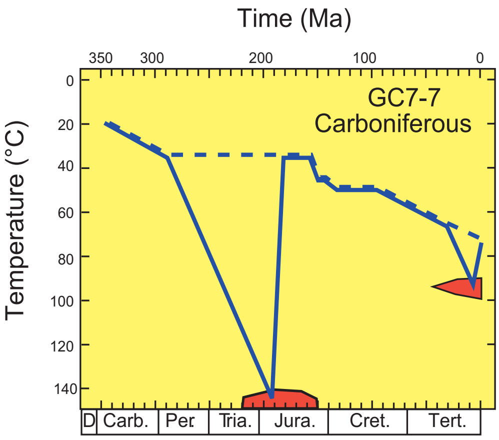


Figure 41. AFTA thermal history solution (solid path) for Carboniferous sample GC7-7, Torres-1. Red fields show the AFTA-derived time-temperature constraints, showing cooling from maximum palaeo-temperatures of >140°C, beginning at some time in the Middle Triassic–Middle Jurassic (220–150 Ma), and with cooling from a lower peak in palaeo-temperatures of 75–95°C beginning at some time since the Eocene (40–0 Ma). The dashed path shows the DTH for this sample.

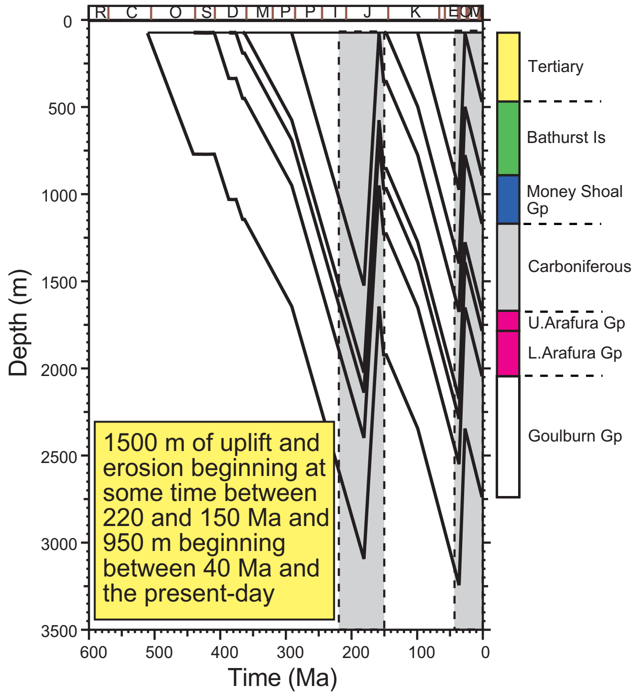


Figure 43. Reconstructed burial history for Torres-1, based on the thermal history interpretation of the AFTA and VR data. Two uplift and erosion episodes have been interpreted from the thermal history results. Timing limits derived from AFTA samples in this well are shown as the grey shading.

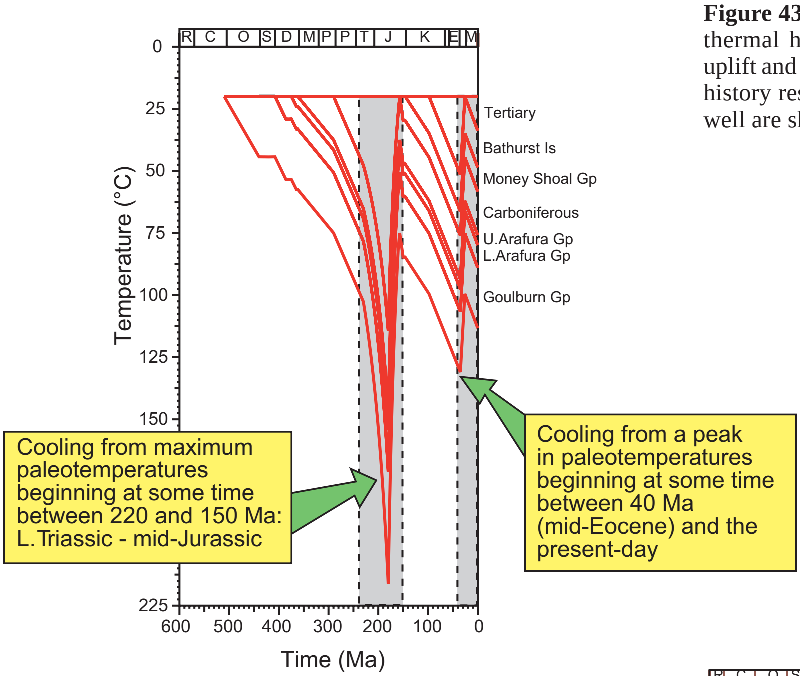
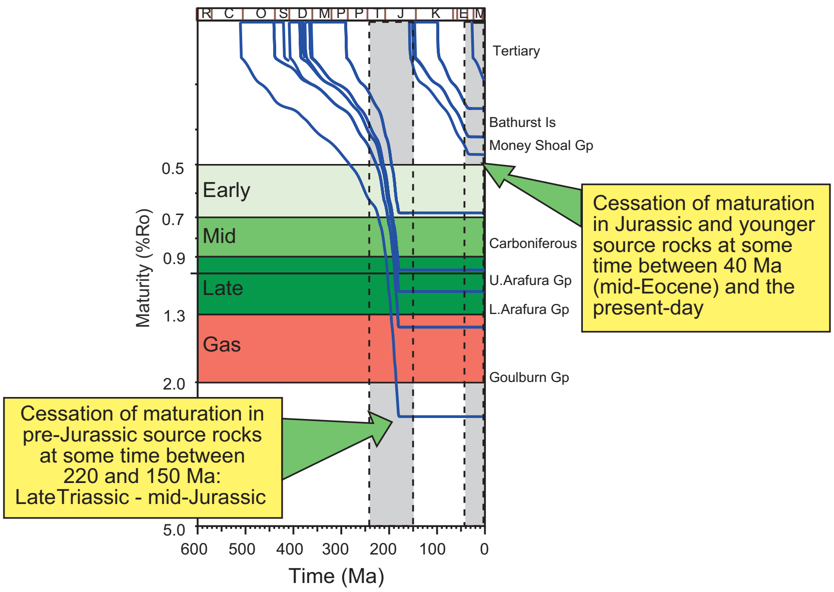


Figure 42 (left). Reconstructed thermal history of units preserved in Torres-1, based on thermal history interpretation of AFTA and VR. Two palaeo-thermal episodes have been recognised, with cooling beginning between 220 and 150 Ma (Middle Triassic to Middle Jurassic) attributed to decline in basal heat flow combined with uplift and erosion, and with cooling beginning between 40 and 0 Ma (Eocene–Present-day) attributed solely to uplift and erosion. Timing limits derived from AFTA samples in this well are shown as the grey shading.

Figure 44 (right). Variation of maturity with time for Torres-1, derived from the reconstructed thermal history illustrated in Figure 42, with the grey columns representing the two major thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation in pre-Jurassic rocks at 200 Ma (220–150 Ma allowed by AFTA), due to cooling as a response to decline in basal heat flow and significant (1,500 m) uplift and erosion. Note that the Tertiary thermal episode has no effect on the source rock maturation history in the deeper section, as palaeo-temperatures during this episode were less than those during the Middle Triassic–Middle Jurassic. However, subsequent burial did result in renewed maturation in the shallower section, with cessation of active maturation in the Jurassic and younger succession occurring between 40 and 0 Ma.



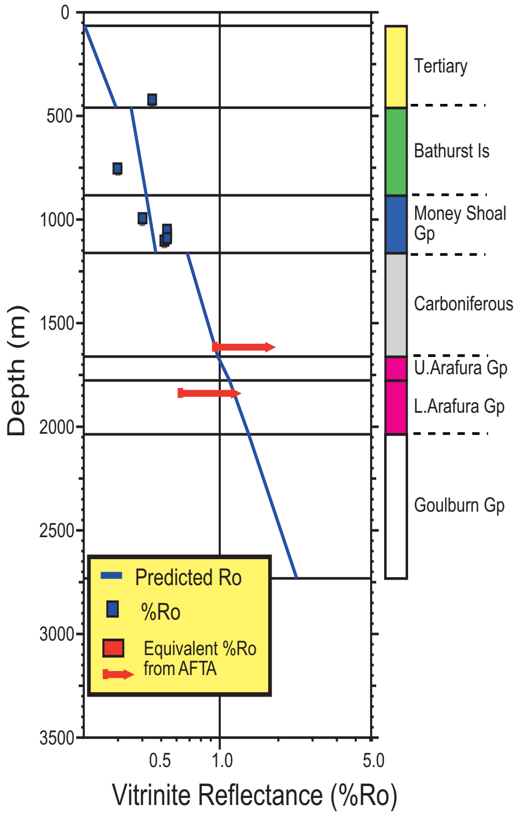


Figure 45. Measured VR data, equivalent VR levels from AFTA and the predicted VR profile derived from the reconstructed thermal history for Torres-1 illustrated in Figure 42. The predicted profile shows a good fit to the majority of the measured VR data and the equivalent VR levels estimated from the AFTA data.

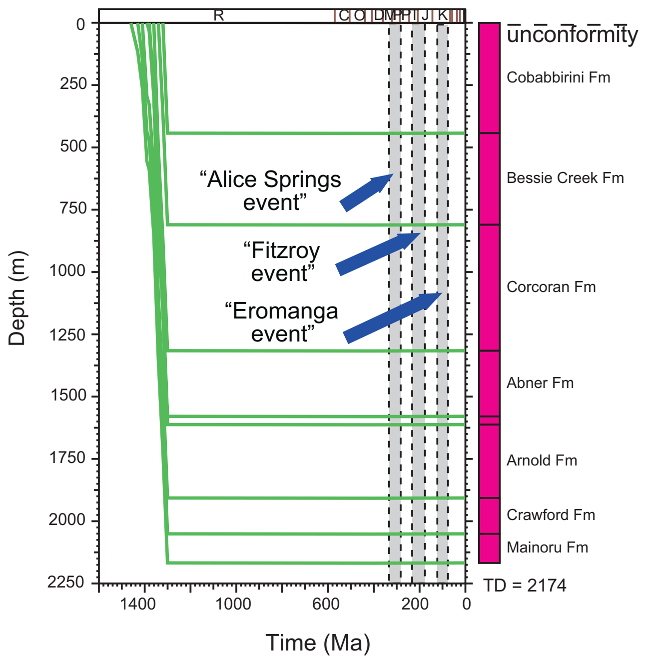


Figure 46. Burial history derived from the preserved section in McArthur Basin well, Broadmere-1, used in predicting the “Default History” VR profile shown in Figure 47, by combining with the present-day gradient of 29.5°C/km and a palaeo-surface temperature of 20°C The shaded columns indicate the time represented by regional unconformities. Note that the history illustrated begins in the Proterozoic and there is a large unconformity from the Proterozoic to the present-day.

McArthur Basin: Broadmere-1

The Broadmere-1 well drilled an entirely Proterozoic succession of the Roper Group and as such no true vitrinite macerals are present in the sequence with which to assess the thermal history, although other organic maturity indicators including Rock-Eval Tmax and aromatic biomarkers have been applied (e.g. Amoco Exploration, 1983; George and Ahmed, 2002). The AFTA results from Broadmere-1 (Appendix) provide direct evidence for three thermal episodes: 240–200 Ma (Triassic–Early Jurassic); 160–120 Ma (Middle Jurassic–Early Cretaceous) and 50–20 Ma (Eocene–early Miocene) (Appendix), but the vertical sequence of results is inadequate to formally define palaeo-geothermal gradient for any of these events (Table 1). Thus the mechanism of heating in each case cannot be independently determined, although correlation of the timing of these events with those identified in other basins suggests that each is best explained in terms of deeper burial in a normal heat flow regime (Table 2). Reconstruction of the thermal, burial and source rock maturation histories is illustrated in Figures 46–47, 48–50 and 51–52.

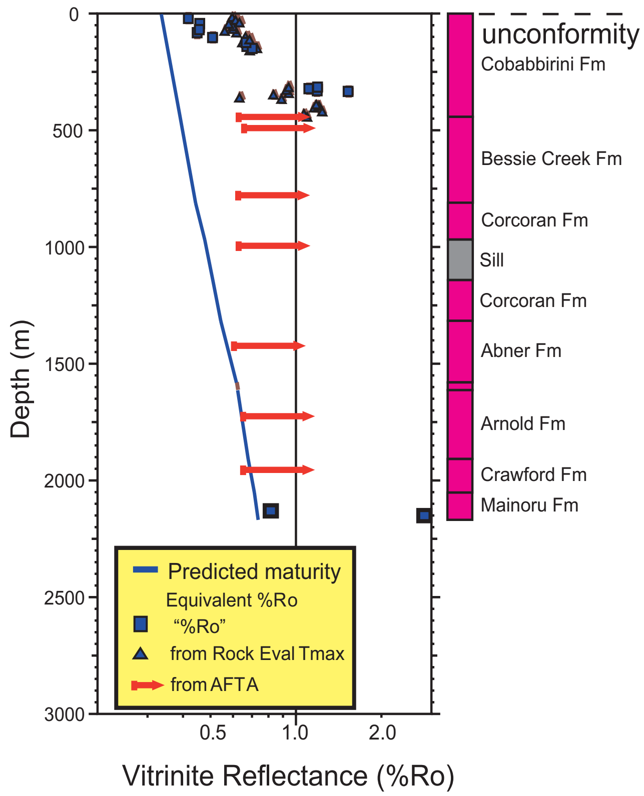


Figure 47. Equivalent VR levels, derived from Rock Eval T_{max}, reflectance of VR-like macerals and AFTA, plotted against depth (TVD RKB), Broadmere-1. The solid line shows the VR profile predicted by the “Default Thermal History”, i.e. the profile expected if all units throughout the well are currently at their maximum temperature since deposition. The majority of the VRE data plot well above the profile, indicating that the majority of the drilled section, at least the sampled part down to ~1,500 m, has been hotter in the past. It is notable that there is broad agreement between the minimum AFTA-derived VR values and the organic VRE values in the shallower section, suggesting AFTA should provide direct information on the time at which these maturity levels were developed.

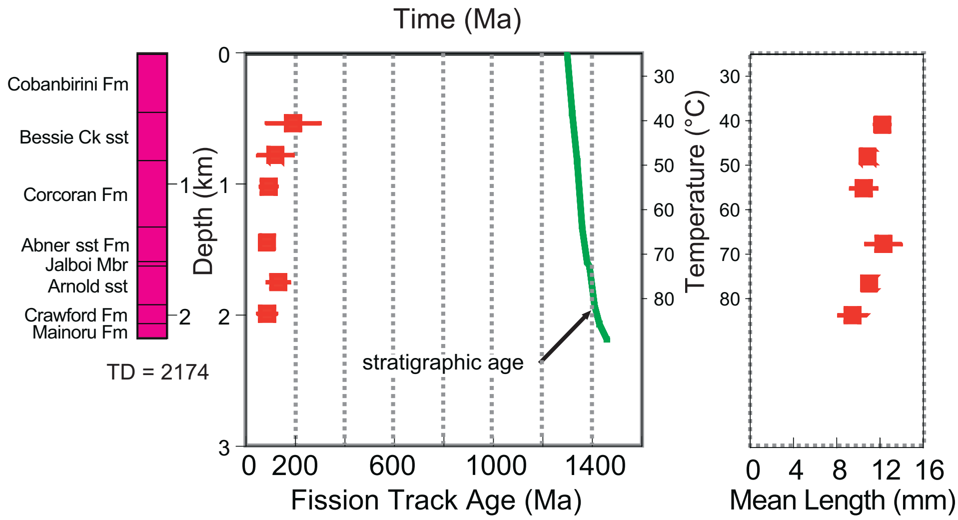


Figure 48. AFTA parameters plotted against sample depth and present temperature for samples from Broadmere-1. The measured ages for all samples are much younger than predicted, and mean track lengths for all samples are shorter than predicted from the Default Thermal History, showing that all samples have been subjected to maximum palaeo-temperatures higher than present temperatures at some time after deposition. See Figure 5 for explanation of the predicted profiles.

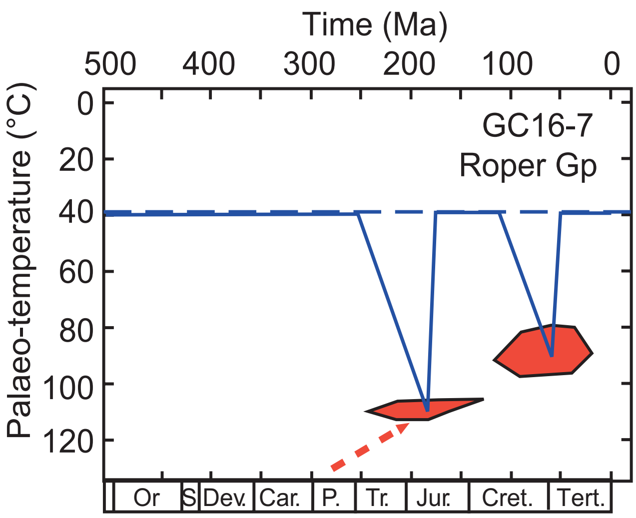


Figure 49. AFTA thermal history solution (solid path) for Roper Group sample GC16-7 Broadmere-1. The red fields show the AFTA-derived time-temperature constraints, showing cooling from palaeo-temperatures of >105°C, beginning at some time in the early Triassic to Early Cretaceous (240–125 Ma), and with cooling from a lower peak in palaeo-temperatures of 80–95°C, beginning at some time in the Early Cretaceous to Miocene (115–20 Ma). The dashed blue path shows the DTH for this sample and the red dashed arrow shows an alternative thermal; history path that is also compatible with the data.

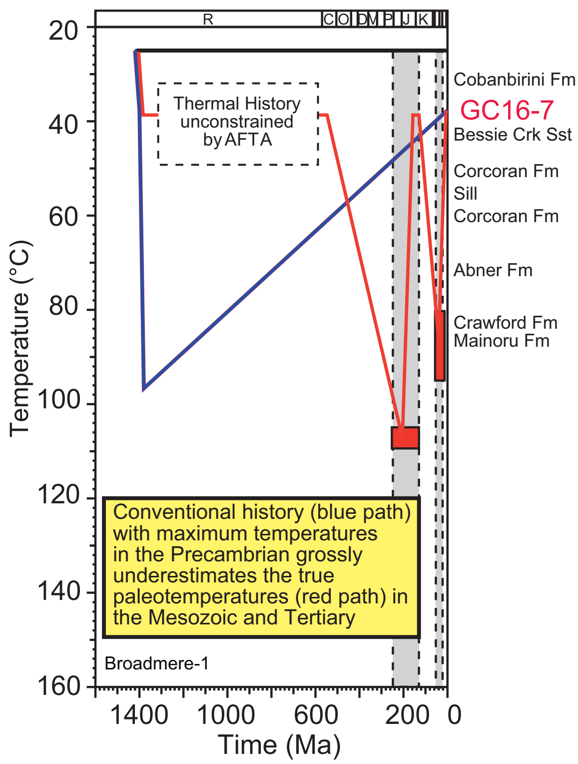


Figure 50. Schematic illustration of the thermal history of Roper Group sample GC16-7, derived from the AFTA results, compared with a thermal history commonly used to explain the organic maturity results in this area of the McArthur Basin. It is clear that AFTA provides a significant improvement in the understanding of the hydrocarbon generation history at Broadmere-1, unavailable from other techniques.

Integration with regional geology and comments on hydrocarbon prospectivity

The thermal history reconstructions for Jabiru-1A, Rob-Roy-1 and Keep River-1 presented here provide the first direct evidence from northern Australia for elevated heat-flow at some time during the interval 180–160 Ma (Middle Jurassic: Bajocian–Callovian). These timing limits defined by AFTA are consistent with a thermal episode prior to, or synchronous with development of the regional mid-Callovian unconformity (e.g. AGSO, 1994), implying that the subsequently deposited mid to Late Jurassic sediments are post-rift successions which were deposited in a declining heat-flow regime. This is at variance with the most recent thermal modelling of Kennard *et al.* (1999) as well as that of Chen *et al.* (2002) in the Vulcan Sub-basin, for example,

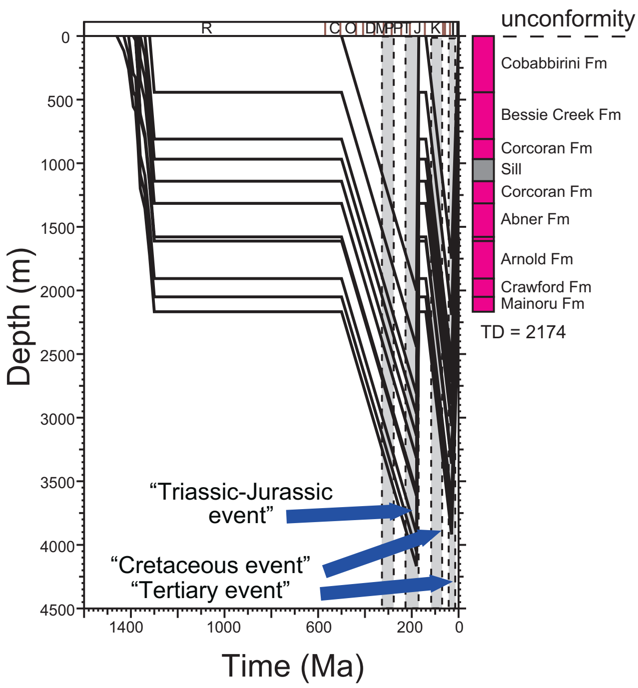


Figure 51. Reconstructed burial history for Broadmere-1, based on the thermal history interpretation of the AFTA data. Two uplift and erosion episodes have been interpreted from the thermal history results. Timing limits derived from AFTA samples in this well are shown as the grey shading, while the lighter shading represents the timing of additional unconformities in the well.

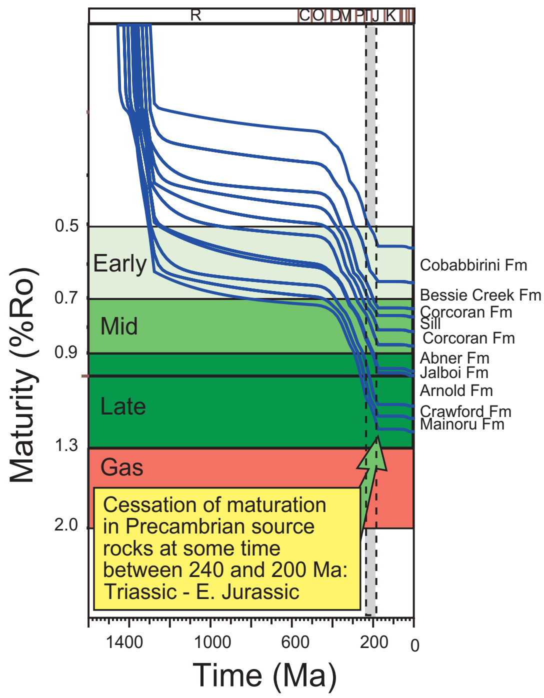


Figure 52. Variation of maturity with time for Broadmere-1, derived from the reconstructed thermal history illustrated in Figure 50, with the grey columns representing the two major thermal episodes revealed by AFTA. The figure shows cessation of active source rock maturation throughout the entire Proterozoic section at 180 Ma (240–200 Ma allowed by AFTA), due to cooling as a response to significant (2,000 m) uplift and erosion associated with the Fitzroy movement. Note that subsequent thermal episodes have no effect on the source rock maturation history anywhere in the section, as palaeo-temperatures were less than those during the Middle Triassic–Middle Jurassic.

which assumes that the main period of rifting was in the Late Jurassic–Early Cretaceous with a heat flow peak at around 140–130 Ma, while the period prior to ~160 Ma is attributed to a pre-rift phase. Constraining the heat flow peak to between 180 and 160 Ma using AFTA not only has a significant effect on the predictions of the timing of peak hydrocarbon generation in the Vulcan Sub-basin, but the regional nature of this event is seen to be a major factor affecting hydrocarbon generation throughout the offshore northern Australian margin. In addition, while an important structural event may be present in the Valanginian, this event does not have a major impact on the thermal history, and there is no evidence that it involved a period of elevated heat flow.

Baxter *et al*. (1997) discussed the uncertainty surrounding the age of break-up as assessed from structural studies, noting that the debate surrounding a Callovian (~160–155 Ma) or Valanginian (~135–130 Ma) timing remains unresolved. The main continental break-up unconformity is usually put near the Callovian–Oxfordian boundary at (e.g. Barber, 1982; Veevers, 1988; Colwell *et al*., 1993). In the Dampier Sub-basin, Barber (1994) attributes Callovian and older sediments to the active rifting phase, the Oxfordian–Tithonian to late syn-rift and the Early Cretaceous to post-rift. A Callovian age is generally favoured on the basis of the age of the oldest oceanic crust (e.g. O'Brien, 1993; Etheridge and O'Brien, 1994; Woods, 1994) while a Valanginan age (i.e. 30 my later) is favoured if extensional structures in the Late Jurassic–Early Cretaceous are attributed to regional stretching due to thermal rifting processes (e.g. Whittam *et al*., 1996).

The thermal histories defined here using AFTA in key wells from the Vulcan, Browse and Bonaparte basins, strongly supports a Callovian age for initial break-up (180–160 Ma) and shows that elevated heat flow associated with rifting (e.g. Rob Roy-1, Figure 17) began to decline rapidly at this time towards normal levels. A normal heat flow regime after the Callovian is also consistent with the arguments of Nelson (1993) and O'Brien (1993; p.110) who recognise that the Late Jurassic succession of the Vulcan Sub-basin are best explained in terms of wrench or transtensional tectonics rather than as pure extensional tectonics associated with rifting.

The Triassic event recognised in the onshore Canning Basin (e.g. White Hills-1) is attributed to the Fitzroy Movement and the recognition that heat flow during this tectonic event was not elevated (Fig. 12) is consistent with this event being associated with a major strike-slip structural event (e.g. Smith, 1984). It is also clear from the AFTA results that active source rock maturation in the vicinity of White Hills-1 ceased due to cooling resulting from kilometre-scale uplift and erosion (Table 1) associated with this period of structuring. The direct quantification of the timing of peak maturation and the mechanism of heating and cooling in this region is significantly different to that assumed in previous basin modelling studies (e.g. Ellyard, 1984; Horstman, 1984; Smith, 1984) and this has significant implications for understanding the hydrocarbon generation, migration and preservation.

The AFTA results summarised here also indicate regional period of cooling between 30 and 20 Ma (late Oligocene–early Miocene), corresponding to a time break that is generally attributed to a depositional hiatus in the Oligocene (e.g. AGSO, 1994). The simplest interpretation of the AFTA results is that this event is not a depositional hiatus, but involves significant uplift and erosion in a normal heat flow regime. The magnitude of erosion required to explain the AFTA results in various wells (Table 1) can be lowered somewhat if the Oligocene palaeo-surface temperature was significantly higher than that at the present day. However, even a 20°C higher Oligocene palaeo-surface temperature, would only result in estimates that are lowered by less than ~600 m. The magnitude of uplift and erosion since the Oligocene might be further overestimated if the mechanism of heating involves a lateral heating by hot fluids. Such a heating mechanism, although transient, has been revealed by AFTA in the Vulcan Sub-basin in the Pliocene to Recent (O'Brien *et al*., 1996), and such a mechanism might also be applicable to the regional Oligocene thermal episode. Regardless of the exact mechanism of heating, it is emphasised that significantly elevated palaeo-temperatures operated for long enough to cause appreciable source rock maturation, and as such this event needs to quantified in order to rigorously predict patterns of hydrocarbon generation in the sedimentary basins of northern Australia.

Concluding remarks

Previous modelling studies of Australia's northern basins have lead to contradictory conclusions regarding timing of hydrocarbon generation from important source rock intervals, partly as a result of having no constraints on the timing of major periods of heating. By providing rigorous constraints on both the time and magnitude of maximum palaeo-temperatures as well as the palaeo-geothermal gradient and heat flow at this time, AFTA permits much more accurate modelling of hydrocarbon generation and migration. Further, by constraining these key aspects of the thermal history, AFTA allows these conflicting interpretations of the structural history of Australia's northern basins to be independently evaluated and the underlying tectonic mechanisms to be ultimately revealed. The examples presented here show how such constraints can be provided to enhance the application of basin modelling as an important tool in quantifying hydrocarbon prospectivity

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Appendix

AFTA Thermal history summary from wells in northern Australia. [1] Present temperature estimates based on geothermal gradients estimated from corrected BHT values as explained in the text. [2] Thermal history constraints shown in italics represent either general limits on the magnitude of allowed palaeo-temperatures at various times, or palaeo-thermal episodes allowed within the analytical uncertainty associated with the data but not definitely required by the data. Thermal history interpretation of AFTA data is based on assumed heating rates of 1°C/Ma and cooling rates of 10°C/Ma. Quoted ranges for palaeo-temperature and onset of cooling correspond to ± 95% confidence limits. [3] If cooling was synchronous throughout the section, a common timing for the onset of cooling can be assigned to all samples, as shown. Attribution to the four palaeo-thermal episodes shown in the headings is made on the basis of synthesis of data from all wells and outcrops in this report.

	Event 1 - Palaeozoic		**Event 2 - E. Mesozoic**		**Event 3 - L. Mesozoic**		**Event 4 - Tertiary–Recent**	
Sample no. Mean depth Strat. age Present temp.[1]	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)
White Hills-1, Canning Basin								
GC35-1 610–660 m 298–276 Ma 39°C (36°C)	-	-	105–125 ?>125	230–180	75–90	135–60	*(<75*	*60–0)*
GC35-2 950–1,000 m 333–276 Ma 49°C (44°C)	-	-	-	-	85–105	180–90	65–85	90–10
GC35-3 1,005–1,030 m 333–310 Ma 50°C (45°C)	-	-	*(>105*	*Dep* to *200)*	85–105	200–60	<85	60–0
GC35-4 1,300–1,350 m 362–340 Ma 59°C (53°C)	-	-	-	-	100–105	170–85	75–85	60–0
GC35-5 1,885–1,925 m 362–340 Ma 77°C (67.5°C)	-	-	-	-	>120	180–120	85–95	45–5
GC35-6 2,780–2,820 m 377–362 Ma 104°C (90°C)	-	-	-	-	AFTA	dominated	by present	temperature
GC35-7 3,170–3,220 m 377–362 Ma 115°C (100°C ~25°C/km)	-	-	-	-	AFTA	dominated	by present	temperature
Common Timing[3]:		-		**230–180**		**135–120**		**45–10**
Rob Roy-1, Browse Basin								
GC662-129 588–689 m 50–30 Ma 38°C	-	-	-	-	-	-	<100	Post-depn
GC662–130 719–823 m 90–60 Ma 38°C	-	-	-	-	-	-	60–70	55–0
GC662-135 1,460–1,561 m 175–163 Ma 69°C	-	-	-	-	-	-	85–95	120–30
GC662-138 1,792–1,897 m 320–290 Ma 82°C	-	-	>115	240–170	-	-	90–100	60–0
GC662-140 2,109–2,210 m 320–290 Ma 93°C	-	-	>95	Prior to 130	-	-	<110	130–0
Common Timing[3]:		-		**240–170**				**55–30**

(continued)

Appendix (continued)

	Event 1 - Palaeozoic		Event 2 - E. Mesozoic		Event 3 - L. Mesozoic		Event 4 - Tertiary–Recent	
Sample no. Mean depth Strat. age Present temp.[1]	Max[m] palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max[m] palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max[m] palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max[m] palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)
Jabiru-1A, Vulcan Sub-basin								
GC577-173 1,315 m 125–65 Ma 52°C	-	-	-	-	-	-	<100	65–0
GC577-174 1,637 m 225–178 Ma 61°C	-	-	*(95–115*	*178–50)*	-	-	<100	50–0
GC577-175 1,915 m 235–225 Ma 68°C	-	-	*(90–110*	*225–130)*	-	-	90–100	130–0
GC577-176 2,149 m 239–225 Ma 76°C	-	-	*(95–130*	*225–120)*	-	-	95–100	40–0
GC577-177 2,338 m 239–225 Ma 80°C	-	-	*(>95*	*225–100)*	-	-	>95	100–0
GC577-178 2,572 m 239–225 Ma 86°C	-	-	*(>100*	*225–50)*	-	-	100–110	50–0
GC577-179 2,719 m 239–225 Ma 90°C	-	-	*(>120*	*225–80)*	-	-	110–120	30–10
GC577-180 2,968 m 239–225 Ma 97°C	-	-	*(>115*	*225–50)*	-	-	>115	50–15
GC577-181 3,154 m 239–225 Ma 102°C	-	-	(*>110* 170 from VR	225–*60*) 225–160	-	-	>110	60–10
Common Timing[3]:		-		**225–160**		-		**30–15**
Keep River-1, southern Bonaparte Basin								
GC337-1 667 m 330–325 Ma 44°C	-	-	100–105	225–145	-	-	75–85	50–0
GC337-2 1,529 m 348–330 Ma 70°C	-	-	>110	348–145	-	-	-	-
GC337-3 2,045 m 348–330 Ma 85°C	-	-	>110	348–145	-	-	-	-
GC337-4 2,492 m 348–330 Ma 98°C	-	-	>110	348–145	-	-	-	-
Shallow onshore boreholes, southern Bonaparte Basin								
337-24 73 m 367–350 Ma 25°C			100–105	220–150	-	-	60–70	60–0
337-26 252 m 367–350 Ma 25°C			95–105	280–145	-	-	65–85	85–0

(continued)

Appendix (continued)

	Event 1 - Palaeozoic		**Event 2 - E. Mesozoic**		**Event 3 - L. Mesozoic**		**Event 4 - Tertiary–Recent**	
Sample no. Mean depth Strat. age Present temp.[1]	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)	Max^{m} palaeo-temp[2] (°C)	Onset of cooling[2] (Ma)
Shallow onshore boreholes, southern Bonaparte Basin (continued)								
337-28 289 m 377–362 Ma 25°C			105–110	200–155	-	-	75–85	60–20
337-30 221 m 362–350 Ma 25°C			>105	220–130	-	-	75–90	70–0
Common Timing[3]:		-		**200–155**				**50–20**
337-28 289 m 377–362 Ma 25°C			105–110	200–155	-	-	75–85	60–20
337-30 221 m 362–350 Ma 25°C			>105	220–130	-	-	75–90	70–0
Common Timing[3]:		-		**200–155**				**50–20**
Torres-1, Arafura Basin								
GC7-7 1,641 m 290–362 Ma 74°C			>140	220–150	-	-	90–100	40–0
GC7-8 1,865 m 386–408 Ma 82°C			>105 >140	Prior to 100 Prior to 120	-	-	95–105	100–0
Common Timing[3]:		-		**220–150**				**40–0**
Broadmere-1, McArthur Basin								
GC16-7 445–449 m ~1300 Ma 38°C	-	-	>105	240–125	80–95	115–20	80–95	115–20
GC16-6 458–533 m ~1300 Ma 40°C	>110	300–210 ?	55–100	210–0	55–100	210–0	(55–85	50–0)
GC16-5 732–777 m ~1300 Ma 47°C	-	-	-	-	>105	200–120	82–92	50–0
GC16-1 1,004–1,006 m ~1300 Ma 54°C	-	-	>105	210–60	>105	210–60	80–100	60–0
GC16-4 1,402–1,448 m ~1300 Ma 67°C	-	-	-	-	>100	160–85	<100	50–0
GC16-3 1,707–1,753 m ~1300 Ma 76°C	-	-	>110	260–70	>110	260–70	<110	70–0
GC16-2 1,951–1,966 m ~1300 Ma 83°C	-	-	-	-	>110	170–100	-	-
Common Timing[3]:		-		**240–200**		**160–120**		**50–20**

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