TIMING CONSTRAINTS ON THE STRUCTURAL HISTORY OF THE WESTERN OTWAY BASIN AND IMPLICATIONS FOR HYDROCARBON PROSPECTIVITY AROUND THE MORUM HIGH, SOUTH AUSTRALIA

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ABSTRACT

Reconstructed thermal and structural histories derived from new AFTA Apatite Fission Track Analysis, vitrinite reflectance and (U-Th)/He apatite dating results from the Morum–1 well, Otway Basin, reveal that the Morum High is a mid-Tertiary inversion structure. Uplift and erosion commencing in the Late Paleocene to mid-Eocene (57–40 Ma) removed around 1,500 m of sedimentary section. The eroded section is attributed to the Paleocene-Eocene Wangerrip Group which is considered to have been deposited in a major depocentre in the vicinity of the present Morum High. This depocentre is interpreted to have been one of a number of transtensional basins developed at the margin of the Morum Sub-basin and adjacent to the Tartwaup Hinge Zone and Mussel Fault during the Early Tertiary. The Portland Trough in Victoria represents a similar depocentre in which over 1,500 m of Wangerrip Group section, mostly represented by deltaic sediments of the Early Eocene Dilwyn Formation, is still preserved.

Quantification of the maximum paleotemperature profile in Morum–1 immediately prior to Late Paleocene to mid-Eocene inversion shows that the paleo-geothemal gradient at the time was between 21 and 31°C/km, similar to the present-day level of 29°C/km, demonstrating that there has been little change in basal heat flow since the Early Tertiary.

Reconstruction of the thermal history at the Trumpet–1 location reveals no evidence for any periods of significant uplift and erosion, demonstrating the relative stability of this part of the Crayfish Platform since the Late Cretaceous.

The thermal and burial histories at Morum–1 and Trumpet–1 have been used to calibrate a Temis2D hydrocarbon generation and migration model along seismic line 85-13, encompassing the Crayfish Platform, Morum High and Morum Sub-basin. The model shows the cessation of active hydrocarbon generation from Eumeralla Formation source rocks around the Morum High due to cooling at 45 Ma (within the range 57–40 Ma) resulting from uplift and erosion of a Wangerrip Group basin. There has been almost no hydrocarbon generation from the Eumeralla Formation beneath the Crayfish Platform.

Migration of hydrocarbons generated from the Eumeralla Formation began in the Late Cretaceous in the Morum Sub-basin and is predicted to continue to the present day, with the potential for accumulations in suitably placed reservoirs within the Late Cretaceous package both within the Morum Sub-basin and at the southern margin of the Crayfish Platform.

KEYWORDS

AFTA, VR, (U-Th/He) dating, 2D basin modelling, South Australia and Victorian Otway Basin, Eocene inversion, Tertiary tectonics, Morum.

INTRODUCTION

This study forms part of a larger on-going project aimed at constraining the thermal and structural evolution of the sedimentary basins of southeastern Australia being undertaken by Geotrack International. Some of this has been published previously (e.g. Duddy, 1994; Duddy, 1997) together with a companion Temis 2D study aimed at reconstructing the structural history of the Mussel Platform and Shipwreck Trough provided by Duddy and Erout (2001).

The work described here on the Morum–1 well (Fig. 1) arose from a Default Thermal History Analysis of all Otway Basin offshore wells, where it was recognised that the open-file vitrinite reflectance data provided an *a priori* case for post-Sherbrook Group kilometre-scale erosion at this location. To further investigate, new vitrinite reflectance determinations at strategic levels in the well were undertaken by Alan Cook of Keiraville Konsultants, Wollongong, to provide quality control on the open-file data sets. In addition, two samples were collected for AFTA apatite fission track analysis and one of these was also subjected to (U-Th)/He apatite dating in order to provide direct information of the time of cooling

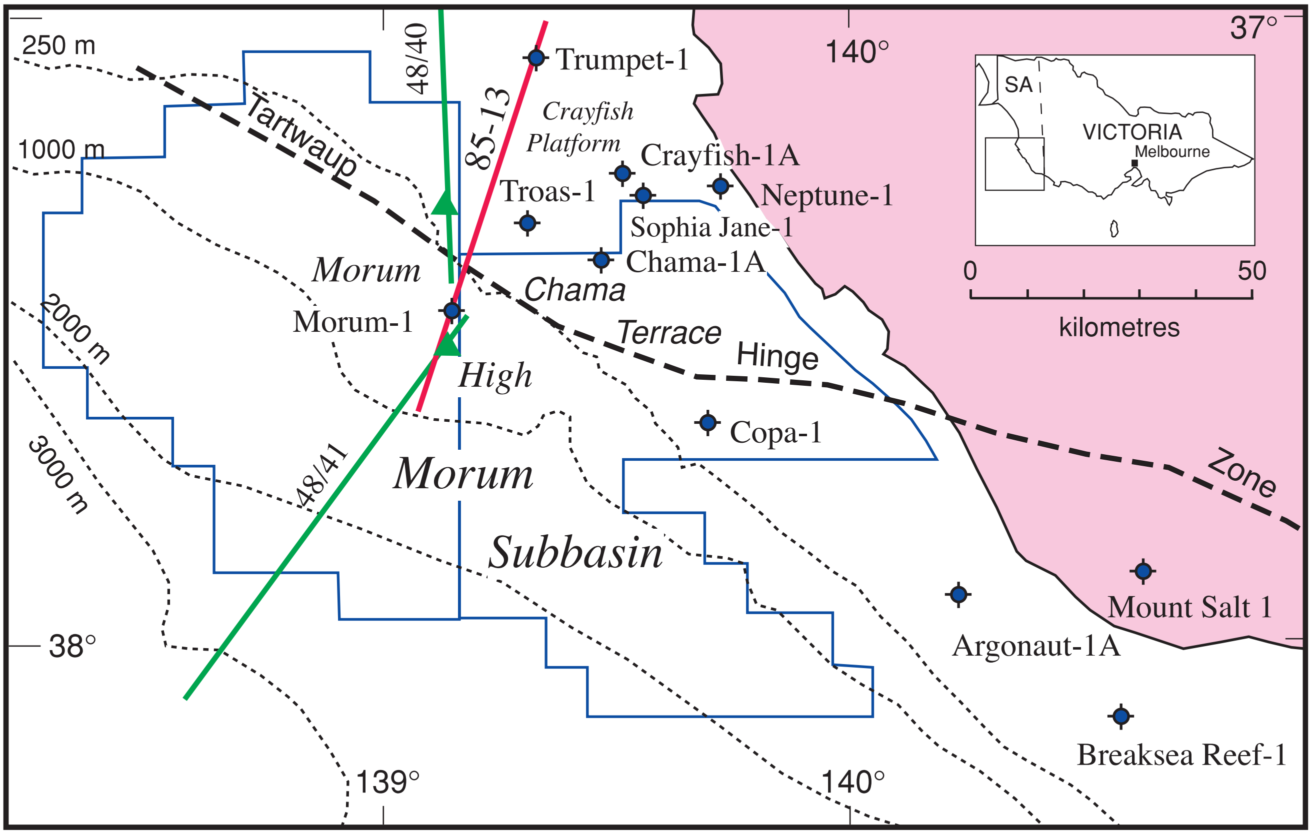

Figure 1. Location map, Otway Basin, South Australia, showing location of the Morum–1 and Trumpet–1 wells on the 85-13 seismic line which form the main part of this study in relation to key structural elements; the Morum High, Crayfish Platform, Chama Terrace, Morum Subbasin and Tartwaup Hinge Zone. Generalised bathymetry shown by fine dashed lines. Green triangles show approximate locations of anomalous sediment wet gas contents along seismic lines 48/40 and 48/41 reported by O'Brien and Heggie (1989).

from maximum paleotemperatures at Morum–1. The results of these analyses are presented here. The thermal history of Trumpet–1 (Fig. 1) is also assessed on the basis of the available open-file VR data, with no new data presented in this study.

The thermal and burial histories reconstructed for Morum–1 and Trumpet–1 are used for the calibration of a Temis 2D hydrocarbon generation and migration model along seismic line 85-13 (Fig. 1) following the basic work flow set out in Duddy and Erout (2001). The results of this model are used to provide insights into some of the key elements influencing hydrocarbon prospectivity around the Morum High in the SA offshore Otway Basin and its deepwater frontiers.

GEOLOGICAL HISTORY

A generalised stratigraphy applicable to the South Australian Otway Basin and used in this paper is shown in Figure 2 (after Morton et al, 1994, Duddy and Erout, 2001). The lithostratigraphic terminology used in South Australia is very similar to that used in Victoria with the main differences being the recognition of the Copa Formation as the basal unit to the Sherbrook Group, distinct from the Waarre Formation recognised more widely in Victoria. In addition, the Gambier Limestone forms the local equivalent of the Miocene Port Campbell Limestone. In most other respects, the lithostratigraphy and timing of the main breaks in the depositional succession are remarkably similar throughout the Otway Basin of South Australia and Victoria.

The key features of this history have been discussed in detail recently by Duddy and Erout (2001) and are not repeated here. In terms of the structural development of the basin, six major regional unconformities are recognised across the basin:

- Barremian-Aptian, separating the Crayfish Group from the overlying Eumeralla Formation in the western Otway Basin,
- mid-Cretaceous, separating the Otway Group from the overlying Sherbrook Group,
- Maastrichtian-Paleocene separating the Sherbrook Group from the Paleocene-Eocene Wangerrip Group (in the eastern Otway Basin, this episode probably encompasses two or more separate episodes),
- mid-Eocene separating the Wangerrip Group from the Eocene-Oligocene Nirranda Group,
- mid-Oligocene separating the Nirranda Group from

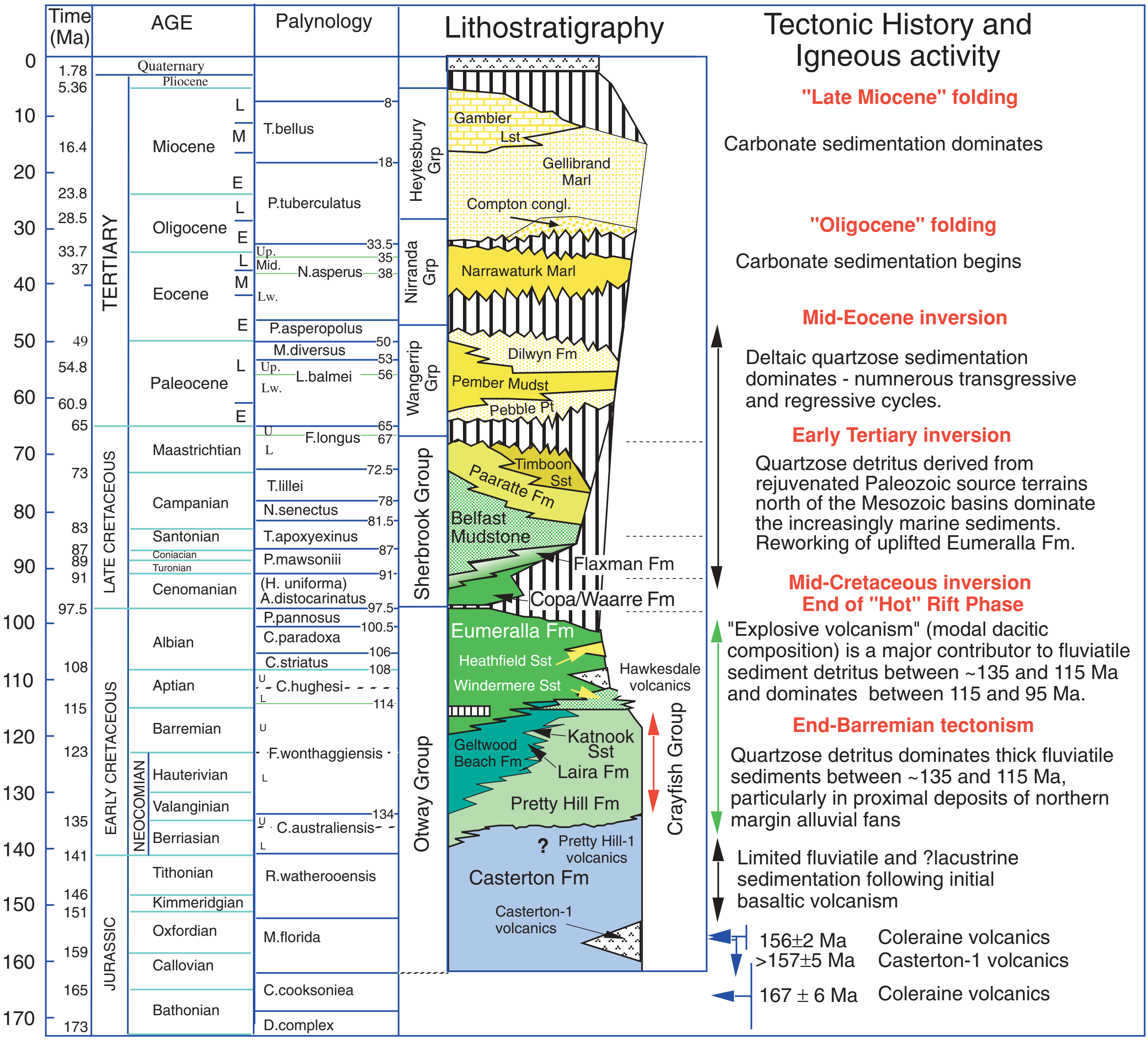

Figure 2. Generalised stratigraphic column for the Otway Basin and a summary of the tectonic history (after Duddy and Erout, 2001).

the Miocene Heytesbury Group,

- Late Miocene separating the Heytesbury Group from Pliocene volcanics and sediments.

Kilometre-scale uplift and erosion has been extensively documented, associated with the mid-Cretaceous and Late Miocene episodes (e.g. Duddy, 1994; 1997; Trupp et al, 1994; Dickinson et al, 2002) and associated with either of the mid-Eocene or mid-Oligocene episodes around the Mussel Platform of the eastern Otway Basin (Duddy and Erout, 2001). Similar high magnitudes of denudation have not been proposed for any Tertiary unconformity in the South Australian Otway Basin, with the development of most unconformities generally attributed to minor tilting or the effects of eustatic rise in sea level. Thus, the possibility of kilometre-scale erosion post-Sherbrook Group on the Morum High, noted above, based on the open-file vitrinite reflectance data, would necessarily be treated with some scepticism, and has resulted in the present study.

STRUCTURAL ELEMENTS

In South Australia offshore (Fig. 1), the Tartwaup Hinge, a zone of closely-spaced en echelon WNW–ESE trending Late Cretaceous faults, separates the Crayfish Platform and the structurally transitional Chama Terrace to the north from the Morum Sub-basin in the south (Tupper et al, 1993). The faults in this zone show clear

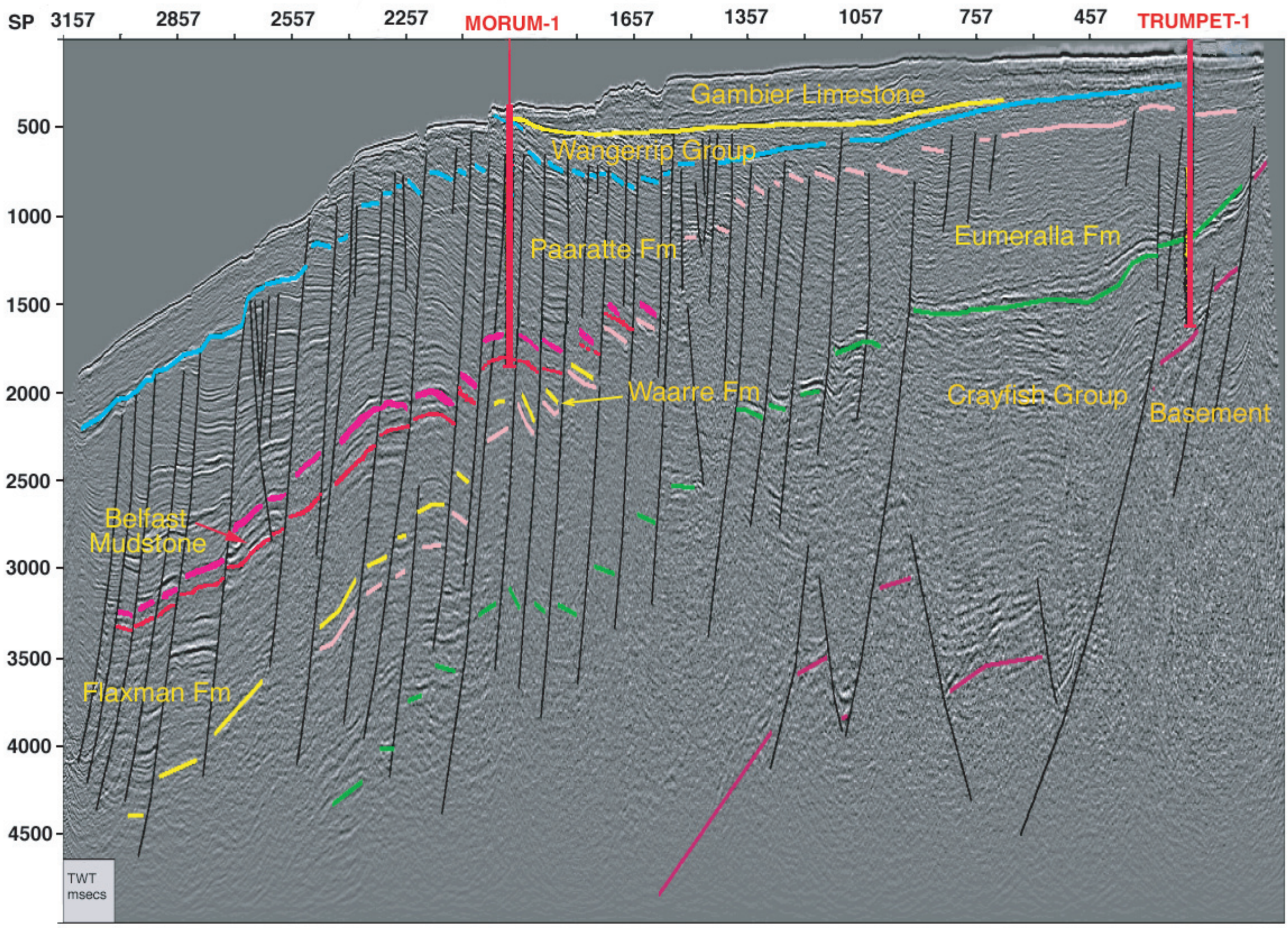

Figure 3. Seismic line 85-13 and interpretation used in the study. See Figure 1 for line location.

evidence of post-Late Cretaceous re-activation which can be readily seen south of Morum–1 in line 85-13 (Fig. 3). In contrast to the Crayfish Platform where Late Cretaceous sediments are thin and Early Tertiary Wangerrip Group sediments are thin or absent, the Morum Sub-basin is a major fault-controlled Late Cretaceous depocentre. The Morum High represents a distinct structural element that has the appearance of extending the Crayfish Platform to the south of the Tartwaup Hinge, to the extent of producing a bulge in the bathymetry (Fig. 1). Repeated uplift, truncation and the creation of angular unconformities is observed to the northeast of Morum–1. Onlap of possible Wangerrip Group foresets across the Maastrichtian-Paleocene unconformity is also seen.

METHODS AND BASIC DATA

Default thermal history analysis

In assessing the thermal history of a drilled section we compare measured thermal history data, generally vitrinite reflectance and AFTA data, with values predicted from a base thermal history derived from the preserved stratigraphy and the present-day thermal parameters (geothermal gradient and surface temperature), referred to as the Default Thermal History (DTH) analysis. Vitrinite reflectance is predicted using the kinetic descriptions of Burnham and Sweeney (1989) and the AFTA parameters are based on a multi-compositional kinetic model developed by Geotrack (Green et al, 1996) and representing a modification of the Laslett et al (1987) model. If the observed parameters can be explained on the basis of the DTH, then sediments throughout the section are likely to be at their maximum post-depositional temperatures at the present day, preserving no information on the past thermal history.

The use of this default thermal history analysis allows a simple assessment of the paleo-thermal history to be made in terms of the mechanisms of heating and cooling, as described in detail in publications by Green et al (1989), Bray et al (1992), Duddy et al (1994) and Green et al (1996). Duddy and Erout (2001) provide more details of this approach as applied in a number of Otway Basin wells.

Estimating the in situ present temperature for each AFTA and VR sample is essential for rigorous thermal history calibration. In this study, bottom hole logging temperatures (BHT) are corrected by an empirical procedure (after Andrews-Speed et al, 1984), whereby BHT data are corrected by increasing the difference between the sea-bed temperature (assumed to be 10°C in this study) and the uncorrected BHT by 20% for uncorrected temperatures below 66°C (150°F), and by 25% for uncorrected temperatures above 66°C. Where more than one BHT measurement is available at any one depth, the value with the shortest time since circulation is used. On this basis, a present-day geothermal gradient of 29.2°C/km is estimated for Morum–1 (derived from a single corrected BHT value of 74.7°C at 2,435 m) and 37.2°C/km for Trumpet–1 (derived from corrected BHT values of 94.4 and 91.2°C at 2,225 and 2,243 m).

Vitrinite reflectance

Vitrinite reflectance data are presented in Table 1. Several data sets are available for Morum–1; two open file data sets from the PEPS database comprising 13 and six determinations, respectively, a single value from Mehin and Link (1997) and the quality control data set comprising three new determinations carried out for this study. For Trumpet–1, only a single open file data set is available from the PEPS database.

AFTA®

The AFTA apatite fission track analysis technique is a well established tool for reconstruction of constrained thermal histories in sedimentary basins, based around the radioactive decay of naturally occurring uranium in apatite which allows both the magnitude and timing of maximum paleotemperatures to be determined (e.g. Green et al, 1989, 1995).

New AFTA results were collected on two samples from Morum–1, a Paaratte Formation sample from Core 1 and a composite cuttings sample from the Belfast Mudstone near TD (Table 2). Ideally, three or four samples would be processed for a well that is around 2,500 m deep, but for Morum–1 very little material is available from Primary Industries and Resources South Australia (PIRSA) or Geoscience Australia (GA) for sampling. Fortunately, PIRSA permitted the core tray to be swept of disaggregated sand and rubble enabling an AFTA sample to be obtained. The cuttings sample was obtained from GA with the permission of PIRSA by compositing small splits of individual dry cuttings samples over a 100 m interval. Excellent yields of detrital apatite were recovered from both samples, sufficient to carry out AFTA of both samples and (U-Th)/He apatite dating on the shallower Paaratte Formation sample.

No AFTA data were obtained for Trumpet–1.

(U/Th)/He apatite dating

(U/Th)/He apatite dating is a novel thermochronological technique based on the accumulation and diffusive loss of radiogenic helium produced by the alpha decay of trace amounts of uranium and thorium in apatite grains. Heating progressively reduces the (U/Th)/He age of an apatite grain due to diffusive loss of He, such that at around 80°C (maintained for millions of years), all He is lost and the age is reduced to zero. On cooling, He is again retained in a systematic way, and using the appropriate kinetic description, the resulting age can be interpreted. In practice, (U/Th)/He data is more useful when integrated with both AFTA and VR data (Green et al, 2002; Crowhurst et al, 2002), and has the potential to provide more precise low temperature thermal history constraints to be established for sediments heated to between 50° and 80°C. One important aspect of the technique is that very small samples can be used, sometimes a single grain, due to low blank levels available in the laser heating system employed at the CSIRO North Ryde facility used in this study. More details of the technique and modelling procedures used are provided in Farley (2000).

The results of the (U-Th)/He apatite dating from Morum–1 are presented in Table 3. Data are presented for four subsamples, each comprising between 1 and 4 grains.

1D WELL CALIBRATIONS

Morum–1 thermal history reconstruction

The Default Burial History for Morum–1 derived from the preserved stratigraphy is shown in Figure 4. A plot of the measured vitrinite reflectance data and equivalent VR data derived from the AFTA and (U-Th)/He results (see below) against depth is presented in Figure 5, together with a predicted VR profile derived from the Default Thermal History (i.e. a combination of the Default Burial History and the present-day geothermal gradient of 29.2°C/km and 10°C sea-bed temperature).

Inspection of Figure 5 clearly shows that new VR results are highly consistent with the equivalent VR levels (VRE) derived from AFTA and (U-Th)/He dating, and are also reasonably consistent with those in the larger (Amdel) open-file data set, while the results from the other open file data set (Padley) are generally much lower throughout most of the section, and are considered here to be incorrect. In detail, the Amdel data tend to be slightly higher than the new data, but this mismatch is considered to be minor in the context of the overall similarity of the trends of the data.

Furthermore, the reliable open file data and the new data plot consistently above and roughly parallel to the default history profile, clearly indicating that the entire Sherbrook Group section has cooled from maximum paleotemperatures higher than present temperatures.

Table 1. Vitrinite reflectance data and maximum paleotemperature estimates.

Average Depth (m)	VR (%)	Number	Max PT (°C)	Analyst [*1]	Source [*2]
Morum-1					
New data					
1336	0.41	25	75	ACC	This paper
1498	0.43-0.49	16	80-88	ACC	This paper
2435	0.60	25	100	ACC	This paper
Open file data-set 1					
541	0.34	-	60	AM	PEPS
651	0.36	-	65	AM	PEPS
806	0.37	-	67	AM	PEPS
916	0.42	-	78	AM	PEPS
1053	0.42	-	78	AM	PEPS
1200	0.41	-	75	?	VIMP 43
1236	0.44	-	81	AM	PEPS
1419	0.45	-	83	AM	PEPS
1551	0.50	-	90	AM	PEPS
1698	0.47	-	86	AM	PEPS
1861	0.51	-	92	AM	PEPS
2013	0.57	-	102	AM	PEPS
2140	0.62	-	110	AM	PEPS
2304	0.67	-	120	AM	PEPS
Open file data-set 2					
1113	0.32	-	Not used	DP	PEPS
1314	0.29	-	Not used	DP	PEPS
1817	0.41	-	Not used	DP	PEPS
2060	0.36	-	Not used	DP	PEPS
2380	0.29	-	Not used	DP	PEPS
2435	0.29	-	Not used	DP	PEPS
Trumpet-1					
503	0.40	-	72	AM	PEPS
672	0.40	-	72	AM	PEPS
809	0.42	-	78	AM	PEPS
919	0.40	-	72	AM	PEPS
1097	0.45	-	83	AM	PEPS
1276	0.47	-	86	AM	PEPS
1417	0.46	-	85	AM	PEPS
1571	0.45	-	83	AM	PEPS
1739	0.54	-	99	AM	PEPS
1891	0.57	-	102	AM	PEPS
1998	0.62	-	110	AM	PEPS
2089	0.61	-	108	AM	PEPS

[*1] ACC = Alan Cook, Keiraville Konsultants Ptd Ltd; .AM = AMDEL; DP = Dianne Padley, Sagasco
[*2] PEPS = PEPS database, Petroleum Group, PIRSA: VIMP 43 = Mehin and Link (1997).

Table 2. Summary of AFTA apatite fission track data in samples from Morum–1, Otway Basin.

Sample Number	Average depth (m)	Present temperature (°C)	Stratigraphic age (Ma)	Mean track length (μm)	Mean fission track age (Ma)
GC851-15	1498	45	87-70	13.25±0.23	136.7±13.0[*1]
GC851-32	2388	71	93-87	12.02±0.31	89.6±7.5[*1]

Note: All depths quoted are TVD with respect to KB.
[*1] P(χ2) <5%, indicating a significant spread in the individual grain ages.

Complete AFTA data set available from the senior author on request.

Table 3. Apatite (U-Th)/He age alpha particle ejection corrections—samples from Morum–1, Otway Basin.

Sample Number	Uranium (ppm)	Thorium (ppm)	Mean grain radius (μm)	Number of grains	FT*1 correction	Corrected He age (Ma)
GC851-15a	4.89	5.95	58	1	0.75	188.9 ± 7.2
GC851-15b	3.69	3.81	63	1	0.77	40.9 ± 2.4
GC851-15c	17.95	32.16	48	3	0.70	146.8 ± 5.5
GC851-15d	13.29	21.58	56	4	0.74	111.1 ± 4.1

*1 Grain-size dependent correction factor to allow for ejection of alpha particles from grain periphery.

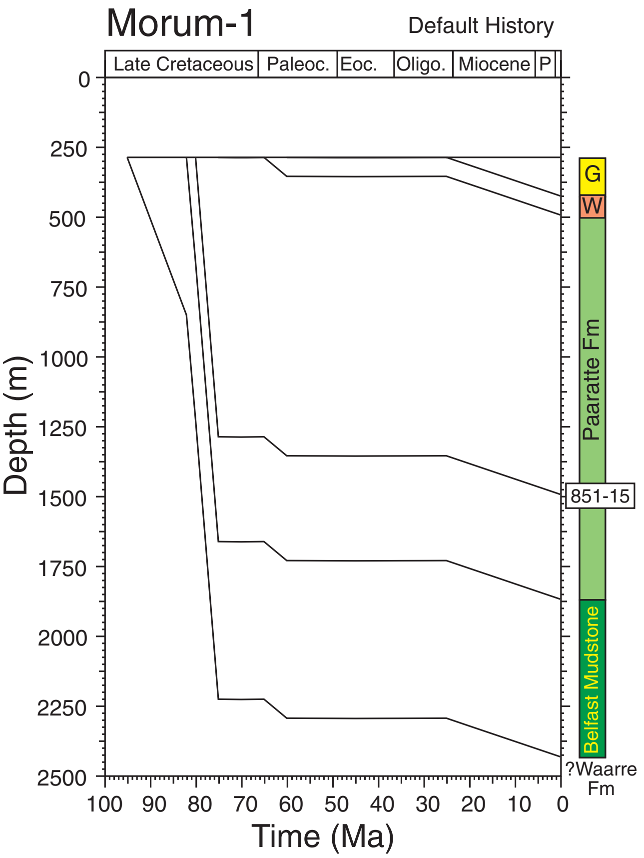

Figure 4. Default burial history for the Morum–1 well derived from the preserved stratigraphy. This history is combined with the present-day geothermal gradient to determine the Default Thermal Histories for each AFTA and VR sample.

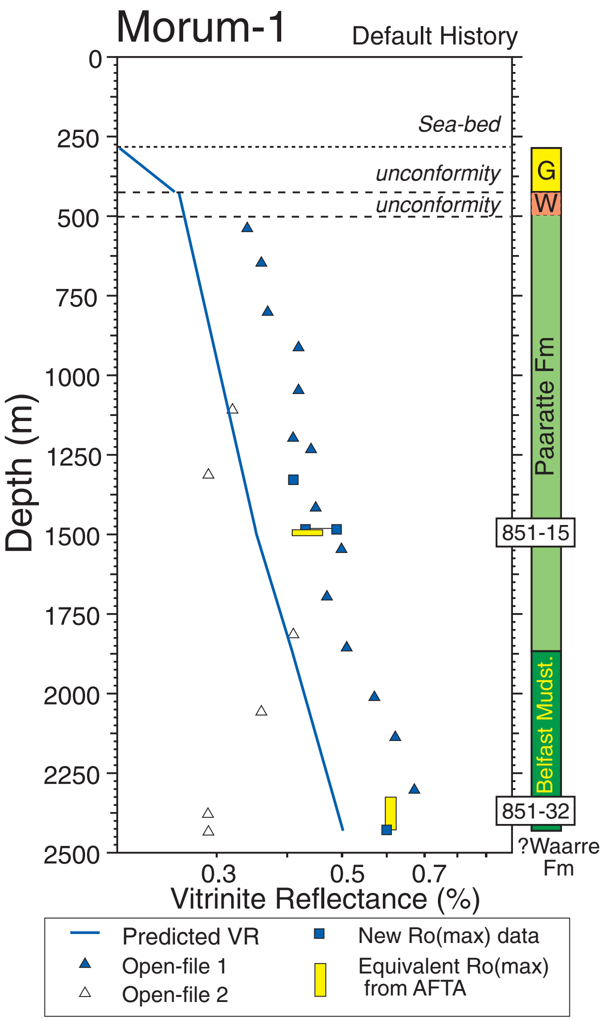

Figure 5. Measured vitrinite reflectance data with respect to depth in Morum–1 together with equivalent VR levels from AFTA. The solid line shows the VR profile calculated on the basis of the Default Thermal History which is derived from the preserved stratigraphy and present-day thermal conditions. All new values and those from open file dataset 1 lie well above the predicted profile, indicating the sampled sequence has been hotter than present temperatures since deposition. Values from dataset 2 are considered to be incorrect and are not used in reconstructing the History.

Therefore, the basic observation noted in the introduction that the Morum–1 well had undergone significant post-Sherbrook Group uplift and erosion made on the basis of the open-file VR data is confirmed. This implies that the Morum High represents a major structural inversion.

Kinetic modelling of the AFTA and (U-Th)/He apatite data allows quantification of the timing and magnitude of the post-Sherbrook Group inversion. Notional heating and cooling rates of 5 and 10°C/Ma, respectively, have been used in estimation of the maximum paleotemperatures. AFTA data in Paaratte Formation sample GC851-15 (1,493–1,503 m, present temperature 45°C), allow cooling from maximum paleotemperatures of 70–90°C at some time after Late Cretaceous deposition, and while the best-fit estimate for the time of cooling is 52 Ma, the range at 95% confidence extends from deposition at 83 Ma to the present day (Fig. 6). The maximum paleotemperatures of 70–90°C is equivalent to a VR level between 0.39 and 0.5%, which is highly consistent with the new VR result in the same sample of 0.43–0.49% (Table 1; Fig. 5). AFTA data in Belfast Formation sample GC851-32 (2,338–2,438 m, present temperature 71°C) provides a more defined constraint, requiring cooling from maximum paleotemperatures between 100 and 110°C at some time between 80 and 10 Ma (±95% confidence), with the best-fit estimate for the time of cooling at 44 Ma (Fig. 6). The maximum paleotemperatures of 100–110°C is equivalent to a VR level between 0.60 and 0.62%, again highly consistent with the new VR result of 0.60% R_o(max) in the same sample (Table 1; Fig. 5). The thermal history solutions are only resolvable by analysis of the apatite compositional range in these samples, with the results being highly dependent on the degree of annealing shown by the most easily annealed, chlorine-poor (fluorine-rich) compositional groups in each sample. Elsewhere in the Late Cretaceous section of the Otway Basin (e.g. Mussel–1 data in Duddy and Erout, 2001), apatites of this composition are almost exclusively derived from erosion of Paleozoic basement.

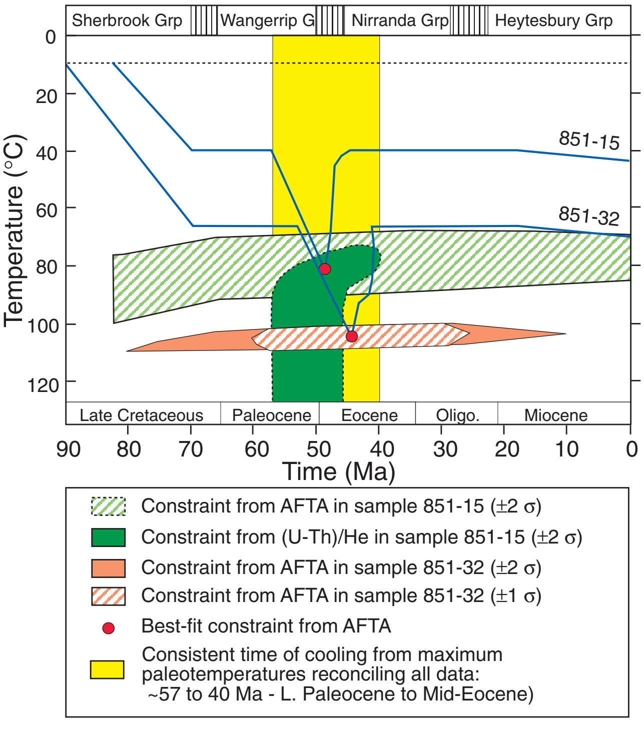

Figure 6. AFTA and (U-Th)/He dating thermal history solutions for samples 851-15 and 851-32 from Morum–1, showing the clear requirement for cooling from maximum paleotemperatures beginning at some time in the Late Paleocene to mid-Eocene, between 57 and 40 Ma (±95% confidence limits).

It is noteworthy that a broad range of chlorine is measured in detrital apatites from both the Paaratte Formation and Belfast Mudstone samples in Morum–1, with Early Cretaceous fission track ages in the more chlorine-rich groups. These characteristics are diagnostic of derivation of a high proportion of the apatite from the underlying Eumeralla Formation, erosion of which must therefore have formed an important provenance for these sediments for a significant period of time during the Late Cretaceous.

(U-Th)/He apatite dating in Paaratte Formation sample GC851-15 (1,498 m) provides greater precision than AFTA on the time of cooling owing to the greater sensitivity of this technique at relatively low paleotemperatures, as noted above. There is significant variation in the (U-Th)/He ages of the four aliquots analysed, from 41 ± 2.5 Ma–189 ± 7.5 Ma (Table 3). The conventional interpretation of (U-Th)/He apatite ages attributes the only source of age variation to differences in the size of apatite grains (Farley, 2000), in that all apatites of the same grain-size are regarded as behaving identically in terms of He diffusion, regardless of variation in other parameters such as atomic structure or chemical composition. Inspection of the data in Table 3 shows that there is no significant variation in size of the grains analysed so the cause of the age variation must lie elsewhere. The most obvious cause relates to the provenance of Otway Basin apatites which typically show derivation from a range of Paleozoic source terrains as well as apatite reworked from the Eumeralla Formation, as is the case for samples GC851-15 and 32 in Morum–1.

Kinetic modelling of these samples on the basis of the maximum paleotemperature constraints of 70–90°C provided from the AFTA and VR data, shows that the observed range of (U-Th)/He apatite ages can be matched for apatites with a range of typical Otway Basin provenance ages (notionally, 350–100 Ma), heated to maximum paleotemperatures between 70 and 80°C, the higher temperature just sufficient to totally de-gas the most sensitive apatite. We consider a variation of 10°C in the temperature of total degassing for different apatites at 70–80°C is not unreasonable at this stage in the understanding of the (U-Th)/He technology, although we concede that this does not accord with current practice which assumes grain-size exerts the only significant control of He diffusion (Farley, 2000).

Thus, in our interpretation, the youngest (U-Th)/He age is interpreted as indicating cooling from a maximum temperature of 70–80°C beginning at some time between ~57 and 40 Ma which is highly consistent with the best-fit timing estimates for both AFTA samples, as illustrated in Figure 6. In this interpretation, the older (U-Th)/He ages come from apatite grains derived from a Paleozoic provenance that were not quite totally degassed at this time.

In summary, the thermal history results indicate that the Late Cretaceous section in Morum–1 began to cool from maximum paleotemperatures at some time between 57 and 40 Ma, in the Late Paleocene to mid-Eocene, prior to deposition of the overlying Gambier Limestone in the Miocene. This timing compares very well with a regional unconformity in the mid–Late Eocene (Fig. 2), and suggests that this unconformity is associated with a major period of structuring, as discussed further below.

Morum–1 burial history reconstruction

All reliable maximum paleotemperature estimates for the Late Paleocene to mid-Eocene thermal episode identified in Morum–1 (Table 1) are plotted against depth in Figure 7, where they clearly define a linear profile sub-parallel to the present-day thermal gradient of 29.2°C/km. Fitting a line to these paleotemperatures using the methods of Bray et al (1992) indicates a maximum likelihood paleogeothermal gradient of 26°C/km, with a range from 21–31°C/m allowed at 95% confidence as shown in Figure 8. The allowed range of gradient encompasses the present-day level of 29.2°C/km. This indicates that heating due to simple additional burial without change in basal heat flow, and with cooling due solely to uplift and erosion is the most reasonable explanation of the results. Indeed, the upper limit of 31°C/km places a tight upper limit on the maximum allowed paleo heat flow for the Late Paleocene–mid-Eocene.

Extrapolation of the paleogeothermal gradient in the preserved section to a Late Paleocene to mid-Eocene surface temperature (assumed to be 10°C) allows the magnitude of section removed as a result of uplift and erosion to be quantitatively estimated. The result of this is shown in Figure 8, with a best-fit value of 1,850 m and allowed range from 1,400–2,600 m of section removed, corresponding to the allowed range of paleogeothermal gradient. Also shown in Figure 8, is a cross plot of removed section versus paleogeothermal gradient which permits estimation of the magnitude of removed section required for any value of allowed paleogeothermal gradient. This shows that for any given value of paleogeothermal gradient there is an uncertainty of ±150 metres in the removed section estimate. Thus for a paleogeothermal gradient of 29.2°C/km, equal to the present day value, ~1500 ± 150 m of additional burial is required on the top-Sherbrook Group unconformity to match the paleotemperature constraints. It is an explicit assumption of this methodology that the reconstructed missing section was comprised on the same average thermal conductivity as the preserved Sherbrook Group. If the missing section was more shalely then the magnitude of erosion will be lower or conversely if it was more sandy, then the require magnitude will be higher, but in either case, kilometre-scale erosion beginning in the Late Paleocene–mid-Eocene is necessary. This aspect of the study is further addressed with development of a regional heat flow history for use in the Temis 2D model discussed below.

A representative reconstructed burial history for Morum–1 is shown in Figure 9. This shows 1,500 m of additional Late Cretaceous–Eocene burial prior to removal of this section beginning at 45 Ma, within the range 57–40 Ma defined by the AFTA and (U-Th)/He results. While erosion is illustrated as occurring in a single episode, burial is shown in two notional phases, with around 500 m of burial during the Late Cretaceous

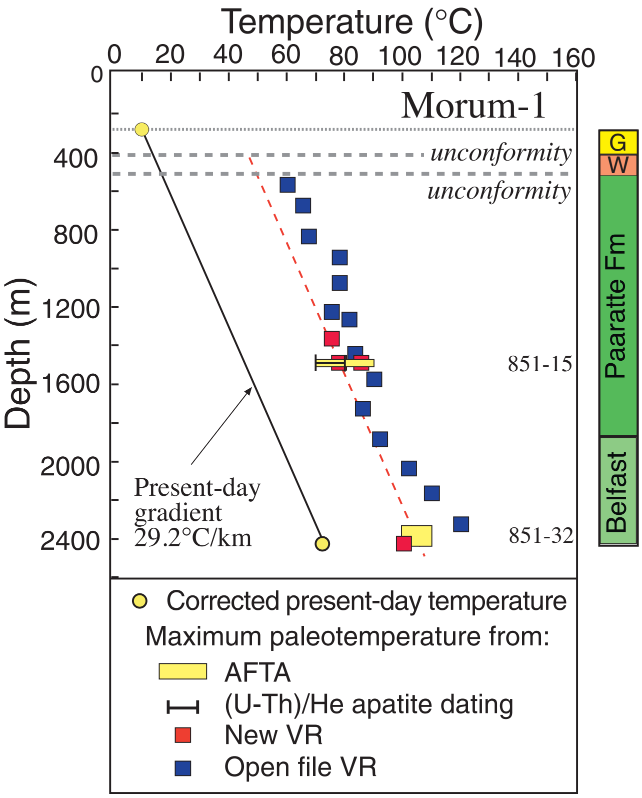

Figure 7. Paleotemperature-depth plot for Morum–1 with constraints from AFTA, (U-Th)/He apatite dating and vitrinite reflectance data. The new data define a paleotemperature profile (dashed line) sub-parallel to the present-day geothermal gradient of 29.2°C/km, indicating cooling was due largely to uplift and erosion. The open file data define a similar trend to the new data and while they plot at slightly higher values, they support the conclusions made from the new data.

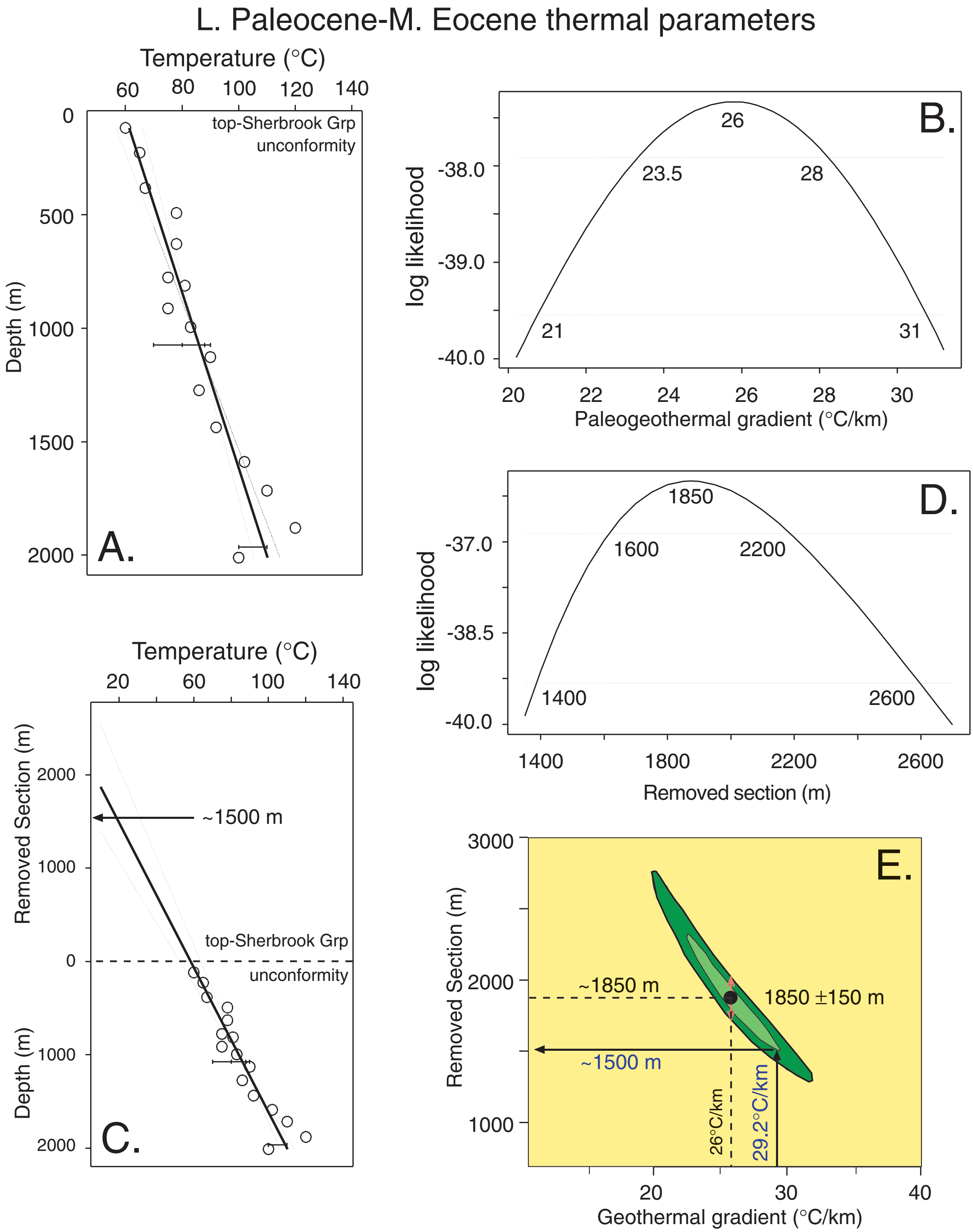

Figure 8. Maximum likelihood plots for paleogeothermal gradient and removed section for the mid-Eocene cooling episode identified in Morum–1. A. Linear paleogeothermal gradients fitted to maximum paleotemperature estimates showing best fit (solid line) and ±95% confidence levels (dashed lines) B. Maximum likelihood profile of linear paleogeothermal defined in A. C. Extrapolation of the paleogeothermal gradients shown in A. to a mid-Eocene paleo-surface temperature of 10°C in order to estimate the magnitude of section removed since the mid-Eocene. D. Maximum likelihood profile of removed section defined by the linear extrapolations shown in C. E. Cross-plot of total section removed from the top Sherbrook Group unconformity against paleogeothermal gradient, showing the ranges of paired values compatible with the paleotemperature constraints (±95% confidence level). This plot shows that a mid-Eocene paleogeothermal gradient equal to the present-day gradient of 29.2°C/km is allowed by the data, combined with additional burial by 1500 m of section.

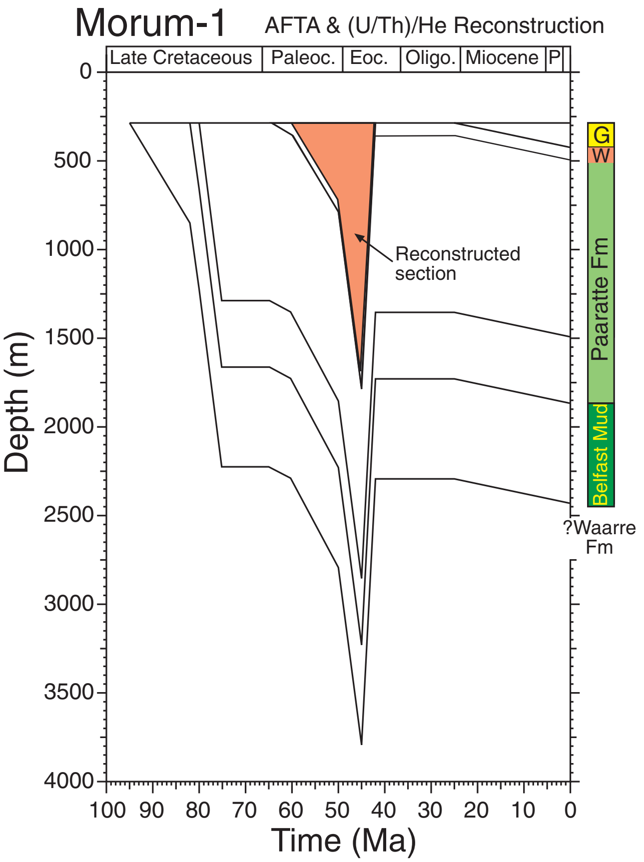

Figure 9. Reconstructed burial history for Morum–1 derived from the thermal history constraints and showing 1500 m of additional Paleocene to mid-Eocene burial removed by uplift and erosion commencing at 45 Ma.

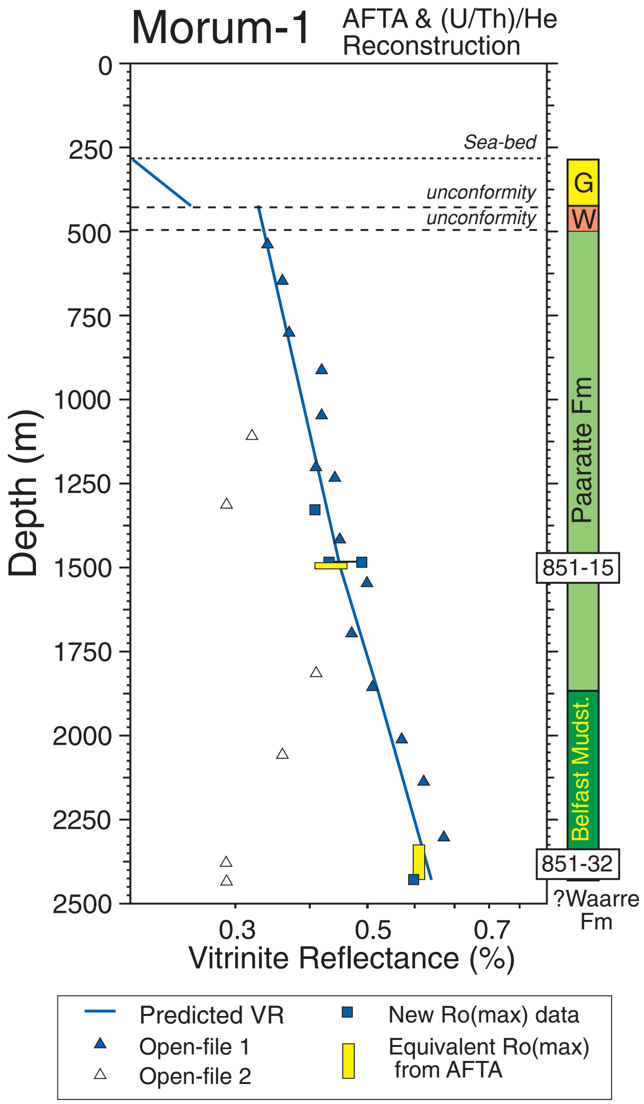

Figure 10. Measured vitrinite reflectance in Morum–1 and the predicted VR based on the reconstructed thermal and burial histories. The majority of the measured data shows a good match to the predicted profile confirming a valid calibration. VR results from dataset 2 are considered to be incorrect.

and Paleocene and 1,000 m in the Early Eocene. These burial and uplift rates match the heating and cooling rates used in determination of maximum paleotemperatures from the AFTA and VR data. Furthermore, the Eocene burial rate is similar to that indicated by the preserved Wangerrip Group section in the Portland Trough (Holdgate et al, 1986), as discussed in the following sections.

Figure 10 shows the match between the measured VR and VRE data and the VR profile derived from the reconstructed thermal and burial histories, emphasising the excellent constraints provided by the data in Morum–1.

Trumpet–1 thermal and burihistory reconstruction

Trumpet–1 was drilled on the Crayfish Platform (Fig. 1) at the northern end of seismic line 85-13 (Fig. 3). Figure 11 shows the Default Burial History for Trumpet–1 derived from the preserved stratigraphy. A plot of the open file vitrinite reflectance data against depth is presented in Figure 12, together a predicted VR profile derived from the default thermal history analysis (i.e. a combination of the default burial history and the present-day geothermal gradient of 37.2°C/km and 10°C surface temperature). In the deeper part of the well, represented largely by the Crayfish Group, the VR data show a good match to the predicted profile suggesting that this section is currently at, or close to, maximum post-depositional temperatures. Shallower data, largely from the Eumeralla Formation, plot above the profile, being increasingly divergent shallower in the section. No new VR data were collected for this study, although new data collected by Geoscience Australia (C. Boreham, pers. comm., 2002) suggest the open file Eumeralla Formation data are anomalously high, and that the true maturity trend is closer to the default history profile. On this basis, we

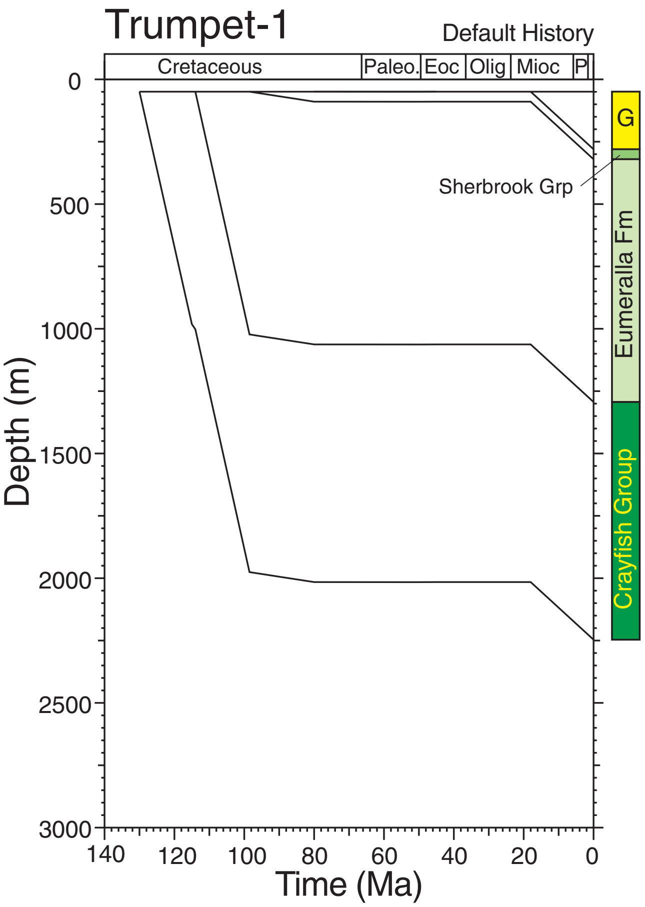

Figure 11. Default burial history for the Trumpet–1 well derived from the preserved stratigraphy. This history is combined with the present day geothermal gradient to determine the Default Thermal Histories for each AFTA and VR sample.

interpret the entire drilled section as being at maximum temperatures at the present-day. Most importantly, we infer that there has been little, or no, post-Eumeralla Formation or post-Sherbrook Group, uplift and erosion at this Crayfish Platform location.

A second predicted VR profile (dashed) is shown in Figure 12, resulting from applying our regional thermal history constraints for the Otway Basin (e.g. Duddy, 1994, 1997; Duddy and Erout, 2001), i.e. a mid-Cretaceous paleogeothermal gradient of 55°C/km, declining to the present-day level of 37.2°C/km by 80 Ma. This profile plots marginally above the DTH profile in the deeper part of the well, but is still consistent with the measured data. Thus, even though the data from this well shows no direct evidence for elevated mid-Cretaceous heat flow, it conforms to the thermal history constraints requiring such a regional thermal episode. Incorporation of elevated mid-Cretaceous heat flow is fundamental to understanding the timing of hydrocarbon generation from Eumeralla Formation source intervals (Duddy, 1997), and is a key requirement of rigorous 2D basin modelling studies in the Otway Basin.

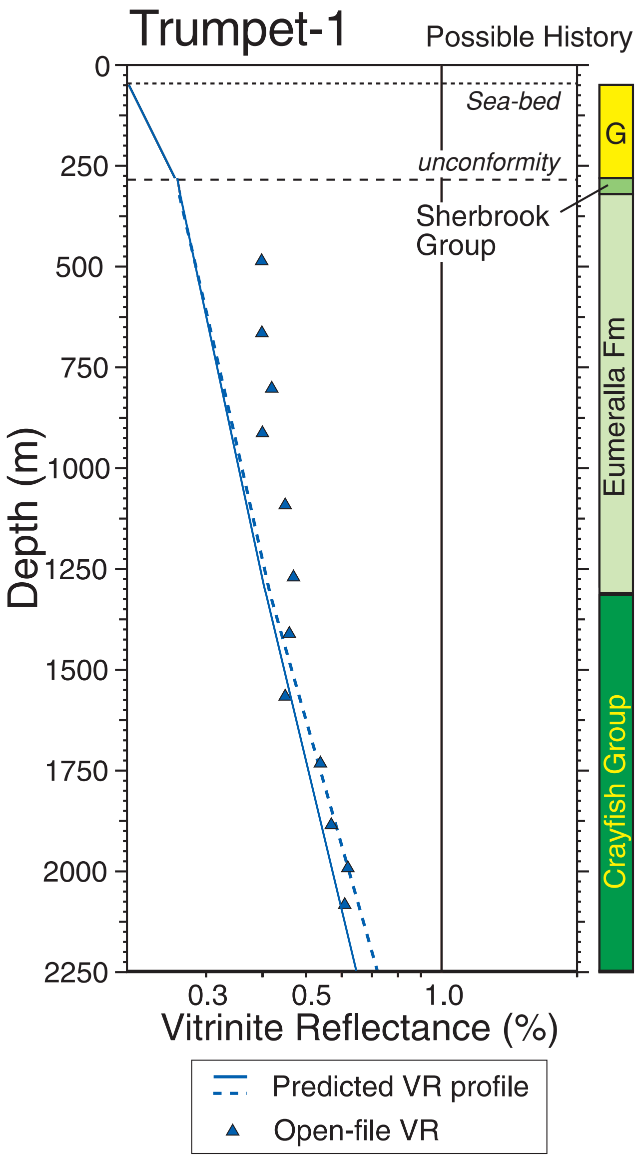

Figure 12. Measured vitrinite reflectance with respect to depth in Trumpet–1. The solid line shows the VR profile calculated on the basis of the Default Thermal History which is derived from the preserved stratigraphy and present-day thermal conditions. Deeper values lie close to the predicted profile indicating the sampled section is at or close to maximum paleotemperatures at the present-day. Shallower values lie slightly above the predicted profile, which is attributed largely to inaccurate measurement on the basis of new VR data (C. Boreham, pers. comm., 2002). The dashed VR profile, which is essentially indistinguishable from the default history profile, is predicted from a thermal history using an elevated geothermal gradient of 55°C/km at 95 Ma derived from regional constraints—see text.

Previous 1D basin modelling studies

Williamson et al (1996) provided burial history models with VR iso-reflectance contours for Morum–1 and Trumpet–1, as well as several other offshore SA wells in the region (Argonaut–1, Crayfish–1, Neptune–1, Chama–1). Few details of the modelling parameters are provided; in particular, no information was provided on the underlying thermal history used. In addition, for both Morum–1 and Trumpet–1, no VR data were used for calibration and for Morum–1 it was assumed that there was no uplift and erosion at any time during the history. It is clear that the resulting predictions of variation of VR with depth and time obtained from these models should be considered unreliable. Furthermore, for some of those wells with VR data, significant mismatches are evident between the measured VR data and the predicted profile, especially in Argonaut–1 and Crayfish–1 which passed without comment, but which clearly indicate significant problems with either the data or the modelling approach.

Tupper et al (1993) presented a model for Chama–1A (Fig. 1) based on matching of a suite of VR data assuming a basal heat-flow history declining from 65 mWm–2 at 120 Ma to 35 mWm–2 at 70 Ma thence constant to the present-day. While the details of such a history differ from the AFTA-constrained regional results for the Otway Basin (Duddy, 1994; 1997), the effect is similar to that assessed in detail by Duddy (1997) in that maximum maturity in the Eumeralla Formation source-rock interval was reached in the mid-Cretaceous, with no active maturation since that time.

TEMIS 2D GENERATION AND MIGRATION MODELLING

Introduction

Our approach to the Temis 2D modelling (e.g. Burrus et al, 1992a, 1992b) follows the strategy presented by Duddy and Erout (2001), involving depth conversion of the time seismic section, incorporation of the thermal and burial history calibration results at each well location as described above and definition of a suitable mesh for the 2D model, while balancing computation time with geological accuracy. The Temis2D model incorporates basin geometry, lithofacies, erosion and faulting and once calibrated, predicts through time, parameters such as compaction, water flow, temperature and pressure fields, hydrocarbon generation, migration pathways and saturation.

Our interpretation of seismic line 85-13 is shown in Figure 3. Key features of our interpretation are the recognition of a Post-Sherbrook Group and pre-Gambier Limestone package immediately north of the Morum–1 well, and our depth to basement pick, which differs significantly from recent interpretations of regional seismic.

The stratigraphic age of the section eroded at Morum–1

Pollock et al (2001) report the presence of Wangerrip Group of Paleocene *L. balmei* age in Morum–1, between ~527 and 555 m (their Figure 12) based on data from Stoian (in press). The biotstratigraphic compilation for Morum–1 in the PEPS data base (PIRSA) shows the youngest dated units are Maastrichtian-Campanian aged *T. lillei* (~509–554 m) belonging to the Paaratte Formation, and does not recognise the presence of the Wangerrip Group. Partridge (1996) reports the top of *T. lillei* within the Timboon Sand at 509 m. Stoian (in press) reports the presence of *L. balmei* zone between 527 and 555 m and *L. balmei* to upper *F. longus* between 555 and 583m, based on cuttings samples. We prefer this interpretation of top-Cretaceous below 555 m, as it appears that sample identifications based on cuttings in Partridge's (1996) original report are mis-reported in PEPS as SWC's, thus giving false credibility to a pick of the top-Cretaceous above 1790 feet (546 m).

We identify the presence of a Wangerrip Group package close to Morum–1 on line 85-13 (Fig. 3) and it would not be surprising if a thin Wangerrip section is present between the Gambier Limestone and Paaratte Formation within the interval ~424–555 m. The presence of Paleocene-aged Wangerrip Group (Pebble Point Formation equivalent) implies, when combined with the thermal history constraints indicating that cooling began between 57 and 40 Ma, that the missing section must be wholly composed of Wangerrip Group older than ~40 Ma, comprising the Dilwyn Formation and the Pember Mudstone.

Depth to basement

Moore et al (2000) divided the western Otway Basin into the Inner Otway Basin, the Morum Sub-basin and the Hunter Sub-basin. They published a key cross-section based on seismic line 137-03 in which they showed a fairly uniform thickness of both undifferentiated Lower Cretaceous–Jurassic and Late Cretaceous sediments beyond the present day shelf. They believed the Robe Trough was the only place along this section where the underlying transparent upper crust had undergone abnormal extension and caused tectonic subsidence in the form of a half graben. Their estimation of maximum sediment thickness in the Morum Sub-basin was 4.4 s TWT. A series of reflectors, which we have interpreted to be Casterton Formation on top of Basement, were described by Moore et al (2000) as volcanics within the transparent upper crust. Morton et al (1994) described the Casterton Formation as mixed sandstone shale and volcanics. Volcanics are also known to be dominant within the Casterton Formation in several wells in Victoria (e.g. Casterton–1; Lavin, 1997).

Teasdale et al (2002) used Moore et al's (2000) published sections to calibrate the offshore section of their estimate of depth to basement. At the Breaksea Reef–1 location (Fig.1), basement was predicted to be at 4,200 mss despite the well having reached a total depth of 4,446 mss in Late Cretaceous sediments. The nearest well to Breaksea Reef–1 where the Eumeralla Formation was intersected is Caroline–1, some 35 km distant, while the nearest location where the base of the Eumeralla Formation has been mapped with confidence, at greater than 2 km thickness, is only 45 km away. Given that the Eumeralla Formation:

- is present throughout the Otway, Gippsland and Bass Basins;
- has been found to be of fairly consistent thickness along a strike length of greater than 600 km, and
- generally thickens to the south west; and,
- the assumption that there is no Lower Cretaceous section near Breaksea Reef–1 is, in our opinion, fairly radical and casts some doubt on Moore et al's (2000) basement pick.

Moore et al (2000) also published a section through the Eastern Otway Basin based on seismic data which was later published by Palmowski et al (2001). Both of these sections showed marked necking of the crust which allowed a series of Lower Cretaceous–Jurassic, Late Cretaceous and Tertiary depocentres to evolve at the position of the present day continental slope.

We believe that the Morum Sub-basin, which we have mapped across the entire 137 survey in the western Otway Basin and modelled in seismic line 85–13 (Fig. 3), may also contain necked crust and resulting separate depocentres of Lower Cretaceous totalling up to 5.5 s TWT in thickness. On top of this there may have been a further one second, or more, TWT thickness of Early Tertiary sediment accumulated in short-lived transtensional basins developed along the northern boundary fault system to the Morum Sub-basin, which has subsequently been eroded during accelerated sea-floor spreading commencing in the Middle Eocene (~45 Ma).

Basic modelling parameters

DEPTH CONVERSION AND THE GEOLOGICAL MODEL

The time-seismic section (Fig. 3) was converted to a depth section using Easydepth®. Open-file velocity information obtained from the relevant well completion reports was used to calibrate the average velocities in the major stratigraphic units required for the simple depth-conversion. Through a series of iterations, minor modifications were made to the velocities within the measured ranges enabling good ties of the depth-converted section to the formations tops identified in the well completion reports.

Figure 13 shows the final geological model derived from seismic line 85-13 with nine main horizons representing the Basement, Crayfish, Eumeralla, Waarre, Belfast, Paaratte, Wangerrip, Nirranda and Heytesbury Groups, subdivided into 30 horizons with around 150 vertical markers placed to capture any structural complexity, giving a mesh of over 4,500 cells. A number of models were run investigating sensitivity to grid size and this size was found to give a reasonable balance between computational time and the desired structural configuration. Faults were modelled as essentially vertical structures of high porosity and permeability.

Coal-rich intervals within the lower part of the Eumeralla Formation have characteristics of both Type III and rarer Type II kerogens with oil-prone liptinite exceeding 10% (Tupper et al, 1993). In the model, we assume a standard IFP gas-prone Type III source rock in two 500 m thick intervals towards the top and near the base of the Eumeralla Formation, simulating the general distribution of Eumeralla source rocks in wells on the Crayfish Platform.

HEAT FLOW HISTORY

Heat flow along the line has been calibrated at the present day using the corrected BHT data from Morum–1 and Trumpet–1, with thermal conductivities derived from generalised lithologies assigned to each stratigraphic package as shown in Figure 14, which has resulted in a consistent estimate of basal heat-flow of ~55 mWm-2. The underlying heat-flow history is the same as that used by Duddy and Erout (2001) derived from AFTA and VR results from Otway and Gippsland Basin outcrops and wells (Duddy et al 1991; Duddy and Green, 1992; Duddy, 1997; Mitchell, 1997; Duddy and Erout, 2001). At commencement of rifting at ~145 Ma, heat flow is assumed to have been equal to the present day values, increasing to a peak in heat flow double present-day levels at 95 Ma, and thence decaying to the present-day level by 80 Ma and remaining at that level to the present-day. The thermal history reconstruction results for Morum–1 presented in this study, provide further verification of this regional heat flow history, providing tight constraints on the upper limit of the Late Paleocene–Middle Eocene paleogeothermal gradient and hence heat flow, being very similar to the present-day value.

SECTION REMOVED IN THE MIDDLE EOCENE

The 1,500 m of eroded Wangerrip Group at Morum–1 determined from the thermal history reconstruction has been incorporated into the 2D model and has been extended along the section as shown in Figure 15, a stratigraphic section reconstructed at the time of maximum burial, immediately prior to the onset of erosion commencing at 45 Ma. The extent of Tertiary sedimentation away from Morum–1 is speculative, but is based on the general dimensions of the Portland Trough, a relatively narrow and deep Early Tertiary depocentre in Victoria bounded to the north by the Tartwaup Fault.

Holdgate (1981) described the Wangerrip Group in the Portland Trough as consisting of multiple overlapping

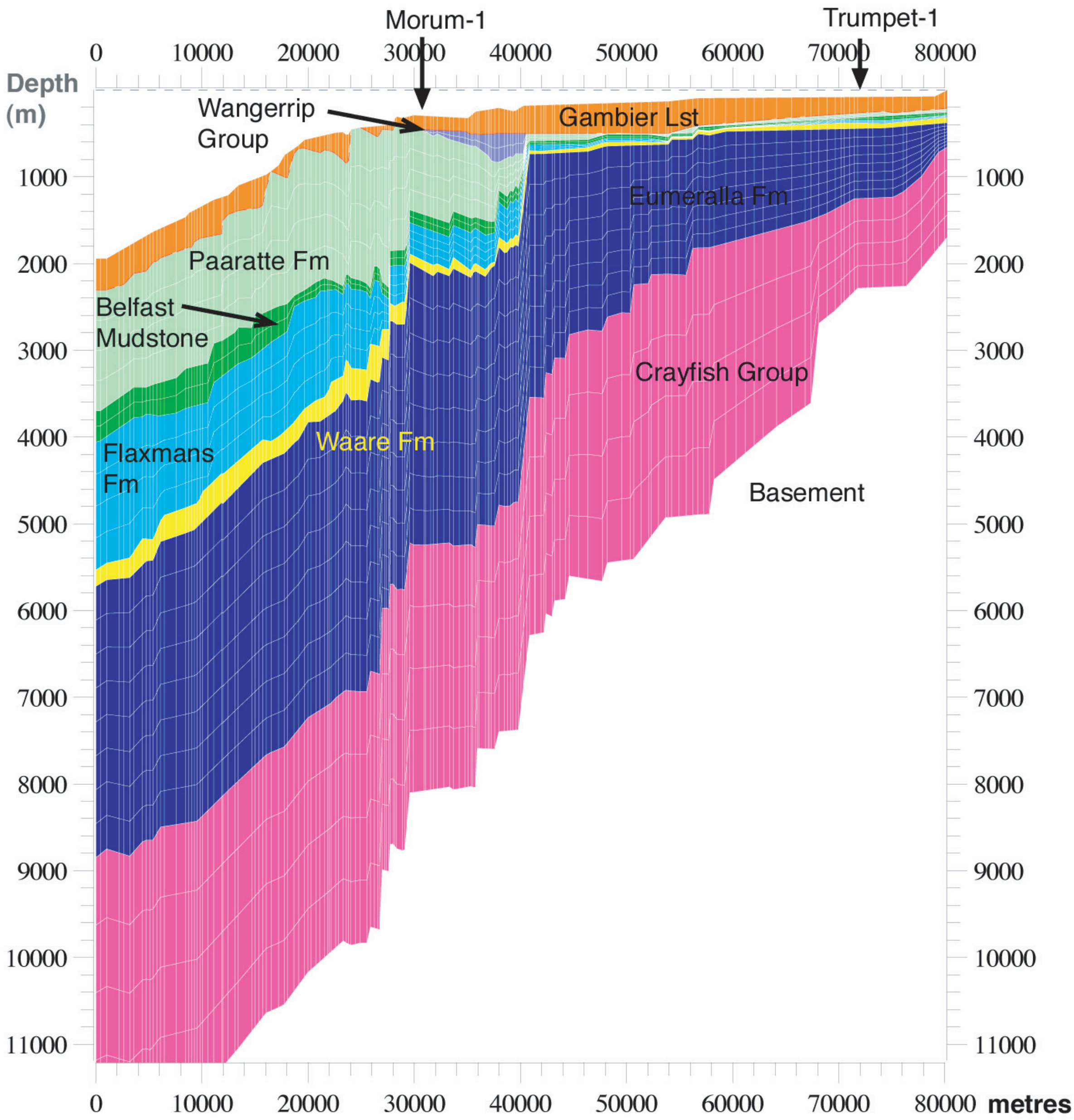

Figure 13. Depth-converted seismic line 85-13 showing major stratigraphic units defined for the 2D modelling.

depocentres which accumulated thick deltaic sediments of the Pember Mudstone and Dilwyn Formation, overlying the generally thin, restricted marine, Pebble Point Formation. In the axis of the trough, more than 1 km of deltaic section was deposited in less than 3 Myr during the Early Eocene *M. Diversus zone* (Holdgate et al, 1986), indicating a subsidence and basin fill rate of >300 m/Myr, rivalling the subsidence rate during deposition of the Early Cretaceous volcanogenic sediments of the Eumeralla Formation during active rifting. The onshore part of this Eocene depocentre with more 800 m of preserved Wangerrip Group stretches from Portland to the Gambier Sub-basin in South Australia and is ~90 km long and 30 km wide, as shown in Figure 16. This figure also shows a generalised isopach of the Dilwyn Formation in the Portland Trough based on well data (after Lavin and Naim, 1995), and a notional Paleocene-Eocene basin of the same dimensions centred on the Morum–1 well. We believe that the existence of a Wangerrip Group depocentre of similar dimensions, previously located south of the Tartwaup Fault in the vicinity of Morum–1, provides the most likely explanation for the nature to the missing section required by the thermal history results described here. Thus, even if a thin basal Wangerrip

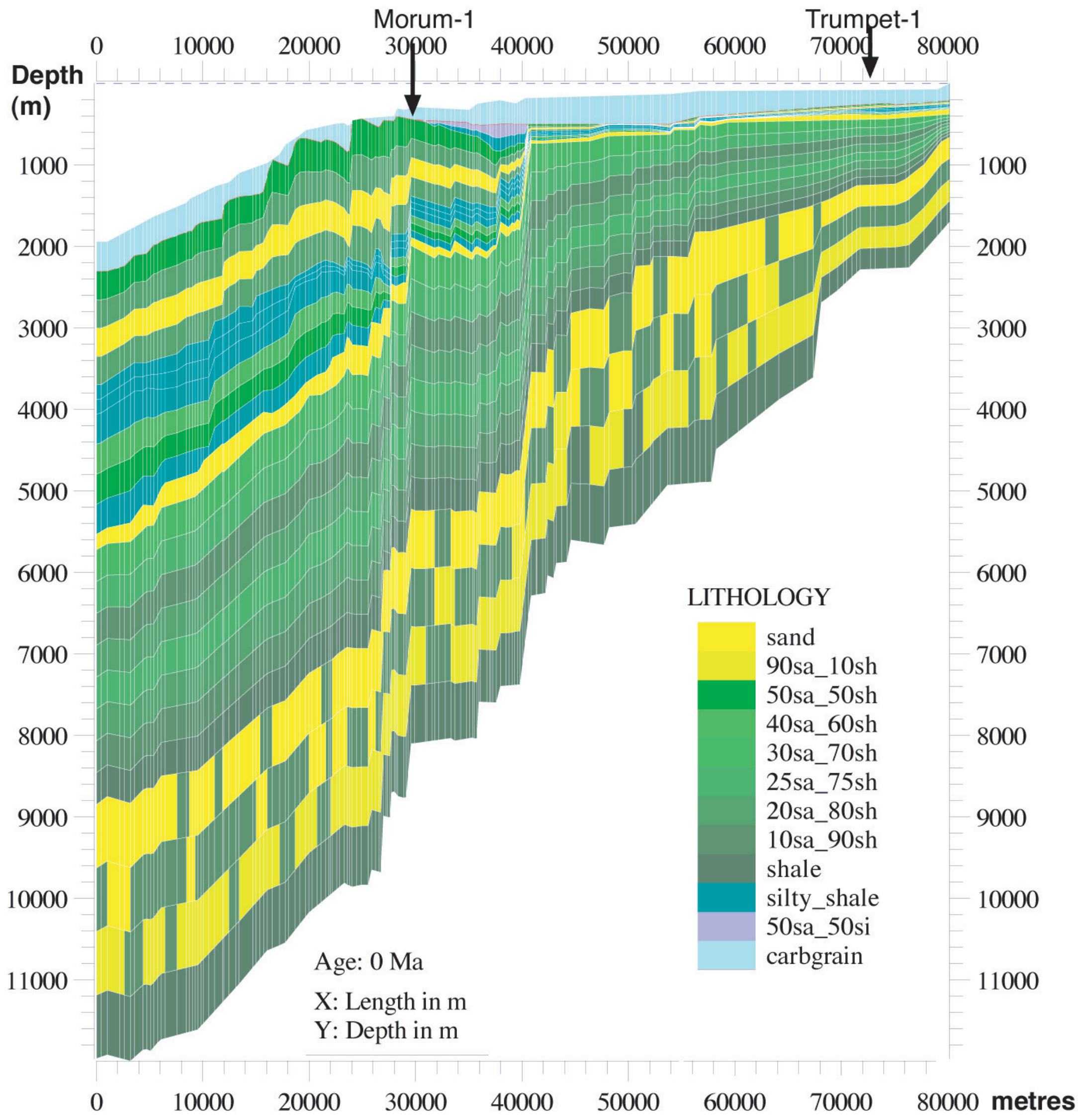

Figure 14. Depth-converted seismic line 85-13 showing lithologies assigned for the 2D modelling.

Group section is not present in Morum–1, which would allow some of the eroded section to have come from the upper Sherbrook Group, we argue that the bulk of the eroded section probably belonged to the Wangerrip Group, as the known upper Sherbrook in the region is too thin by itself to account for the missing section.

2D modelling results

SOURCE ROCK TRANSFORMATION AND HYDROCARBON MIGRATION

Figure 17 shows the predicted transformation ratio for the two Eumeralla source rock horizons at four key periods in the history: at 90 Ma—the approximate time of initial migration from the deeper Eumeralla Formation source rock; at 78 Ma—the approximate time of initial migration from the shallow Eumeralla Formation source rock; at 45 Ma—maximum burial immediately prior to inversion of the Morum High, and at the present day.

In the Morum Sub-basin (south of 27000 on the line), transformation of the deeper source rock is essentially complete (>90%) by ~78 Ma. Transformation in the shallow source rock is ~30–50% at this time. On the Crayfish Platform, transformation of the deeper source rock is ~70% –78 Ma, compared with <10% transformation in the shallow source rock.

Maximum transformation of all source rocks at all locations along the line was reached at the time of maximum burial, at 45 Ma, with the shallow source rock reaching 60–70% transformation in the Morum Sub-basin, and the deeper source rock reaching a similar

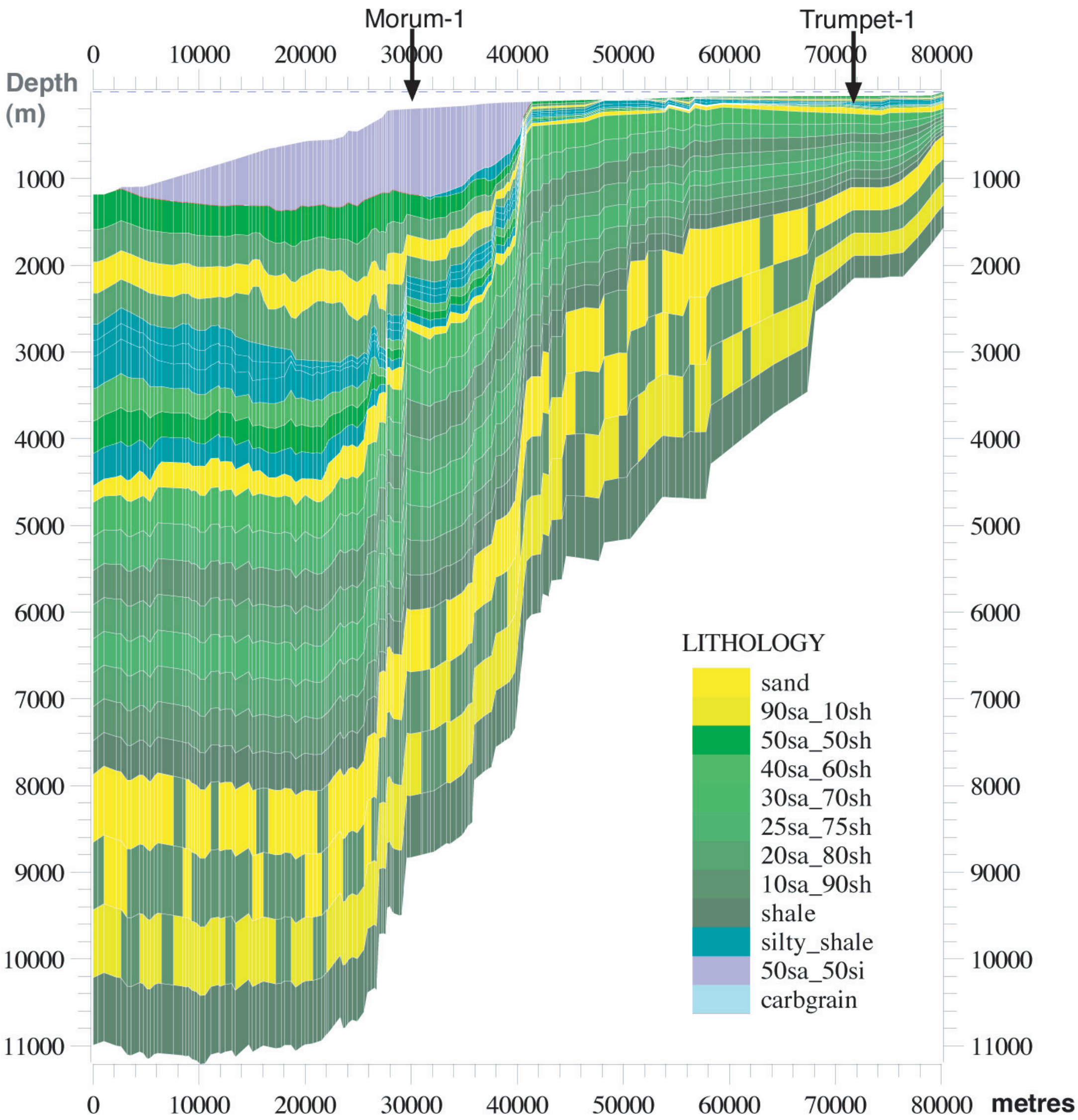

Figure 15. Seismic section 85-13 showing the postulated Wangerrip Group basin derived from the reconstruction of the uplift history of the Morum–1 well. The southward extend of the basin is highly speculative but there are strong indications of uplift on the seismic.

level of transformation in the Crayfish Platform. No significant additional transformation occurred in either of these source rock intervals at any location along the line after cooling commenced, which was induced by inversion of the postulated Early Tertiary basin (between ~2000 and 41000 along the line).

Figure 18 shows hydrocarbon true flow direction and magnitude arrows superimposed on the stratigraphy model for the same key periods as described above.

Hydrocarbon migration is complex, with vertical migration along faults from the deeper source rock beginning in the Albian, and with products starting to enter the potential Waarre Formation reservoirs in the Morum Sub-basin and at the margin of the Crayfish Platform during deposition of the Belfast Mudstone. Migration from the shallow Eumeralla Formation source rock horizon in the Morum Sub-basin had not commenced by the Albian, with no migration from either source rock interval on the Crayfish Platform. By end-Sherbrook time, significant migration had occurred from both source rock intervals in the Morum Sub-basin with the potential to move into possible reservoir intervals in the Paaratte Formation package. By 45 Ma, the time of maximum burial heating beneath the postulated early Tertiary basin, migration from both intervals was essentially complete in the Morum Sub-basin, but was still occurring in the region immediately south of Morum–1 (~30000-42000 on the line). Migration had not commenced on the Crayfish Platform.

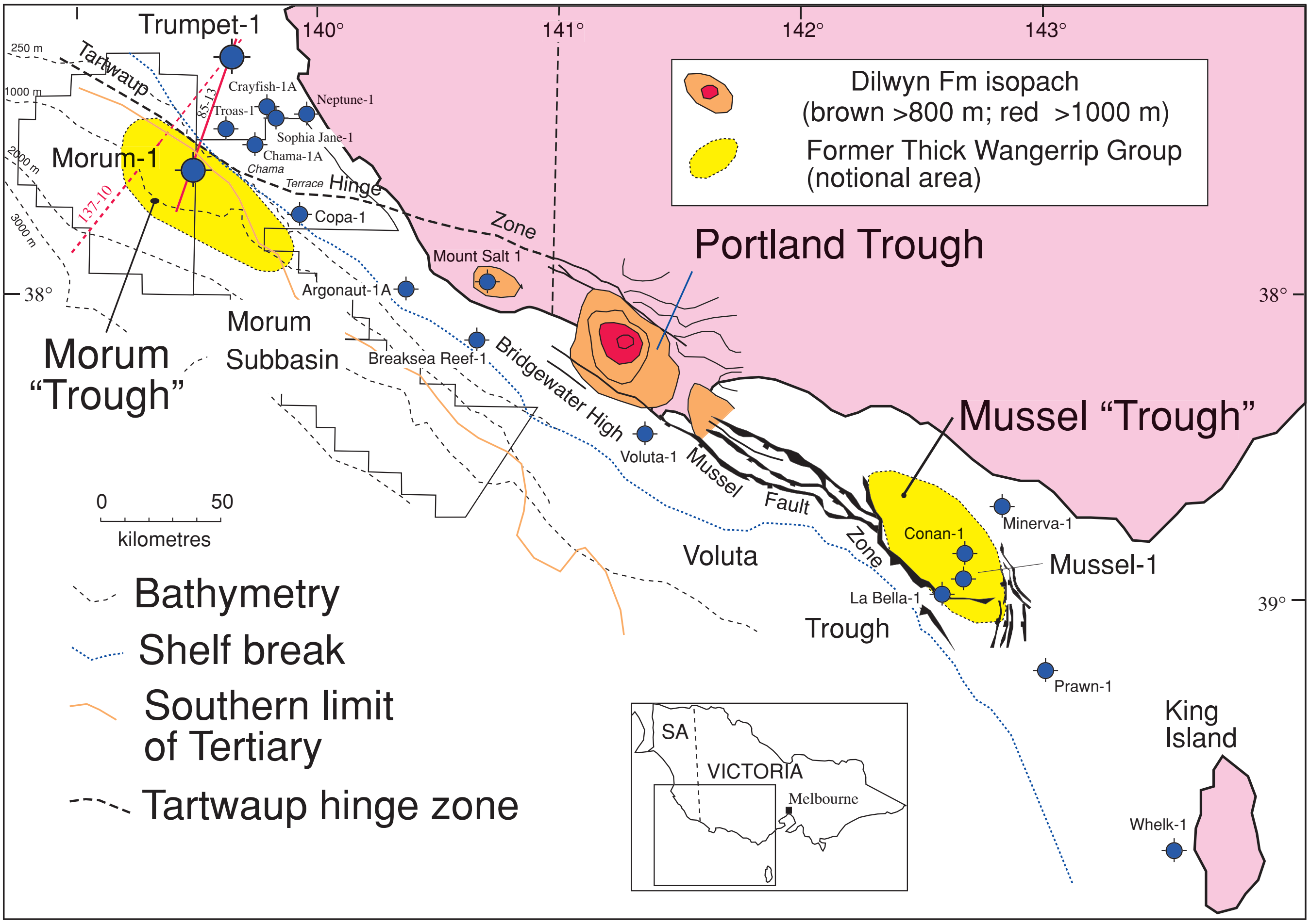

Figure 16. Location of the Portland Trough against the Tartwaup Fault, with over 1500 m of preserved Wangerrip Group sediment, including over 1100 m of Early Eocene Dilwyn Formation deposited in ~3 Myr (isopach data from Lavin and Naim, 1995). Based on the reconstructed burial history for Morum–1 a similar-sized Wangerrip Group basin, termed the Morum Trough, is shown in the position now largely occupied by the Morum High. It is also postulated that at least part of the Mussel Platform may have been the site of another former Wangerrip Group basin (area shown is notional) which was also largely eroded in the Eocene, as allowed by the thermal history reconstruction results from Mussel–1 presented by Duddy and Erout (2001).

The almost complete removal of the Early Tertiary basin between 45 and 40 Ma may have exerted a major control on the general direction of migration, with the potential for north to south migration in the vicinity of the Morum Sub-basin at 45 Ma, which reversed direction during inversion, to produce the current configuration with regional south to north migration.

The model also predicts the possible lateral migration of hydrocarbons source from the Morum Sub-basin along any potential basal Sherbrook Group sands onto the Crayfish Platform, into locations equivalent to the Troas–1 location (Fig. 1), from the early Late Cretaceous to the present-day.

At the present-day, migration is predicted to be continuing in both vertical and lateral conduits through the Eumeralla and Sherbrook Group sections, with the strong possibility of sea-bed seepage along penetrative faults.

INDICATIONS OF HYDROCARBONS AT THE PRESENT-DAY

O'Brien and Heggie (1989) reported anomalous sediment wet gas contents (~4–9 times background) along BMR seismic Line 48/41 just south of the Morum–1 location and also along BMR seismic Line 48/40 in a shallow basement location analogous to the Trumpet–1 location (Fig. 1).

This suggests the presence of an active hydrocarbon system in the area, consistent with the modelling predictions presented here, with fault active migration in the vicinity of Morum–1 and possible long distance lateral migration to Trumpet–1 like locations. Further the lack of any wet gas anomalies in eight additional samples in SW of Morum–1 suggests an effective seal may be present in this section with the complex faulting, further enhancing the prospectivity of the deeper water basin.

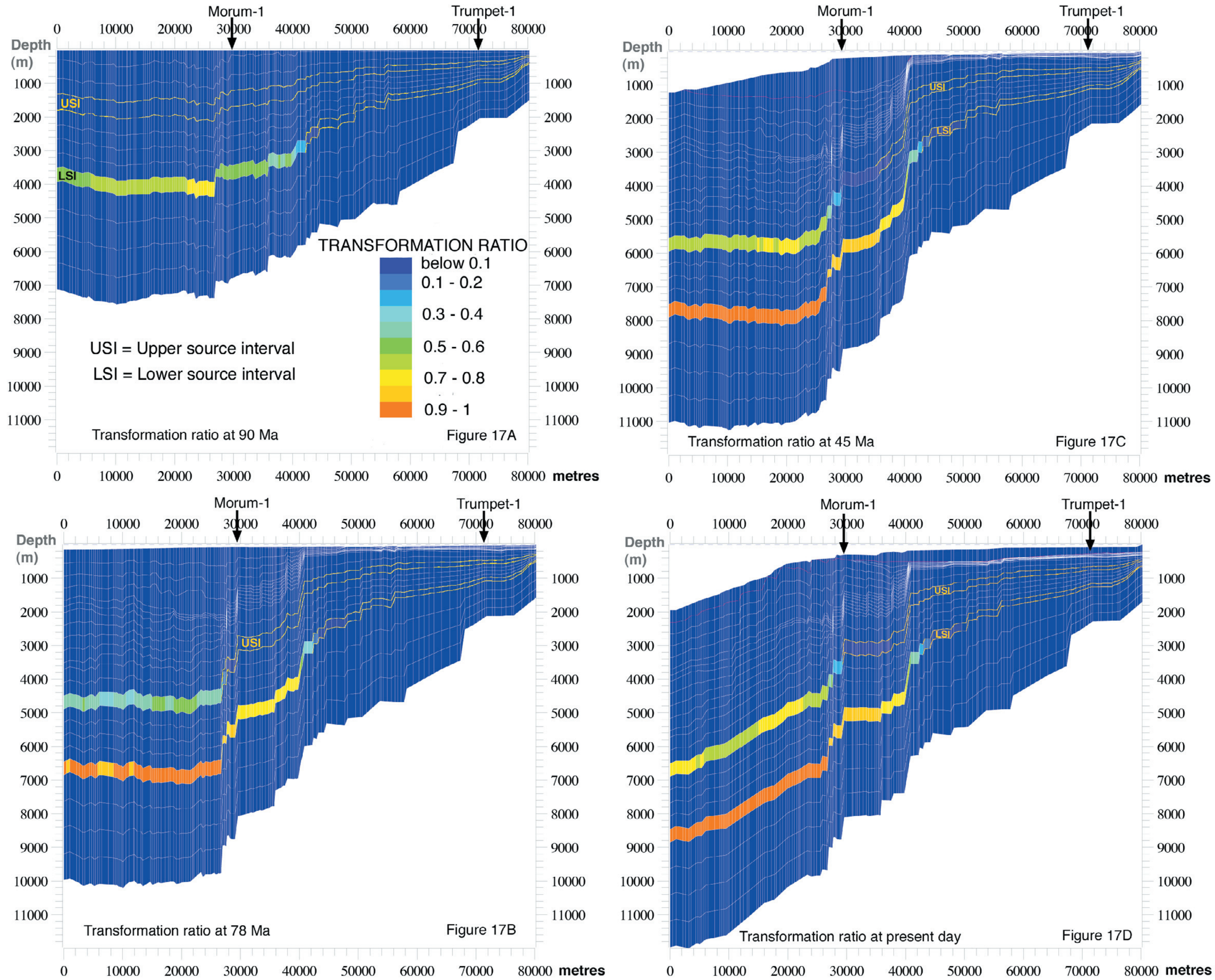

Figure 17. Modelled seismic line 85-13 showing the transformation ratio in the two Eumeralla Formation source rock intervals at four key periods in the history: **a.** 90 Ma—the onset of migration from the deeper Eumeralla Formation. **b**. 78 Ma—the onset of migration from the shallower Eumeralla Formation. **c**. 45 Ma—at the time of maximum burial of the Morum High. **d.** Present-day

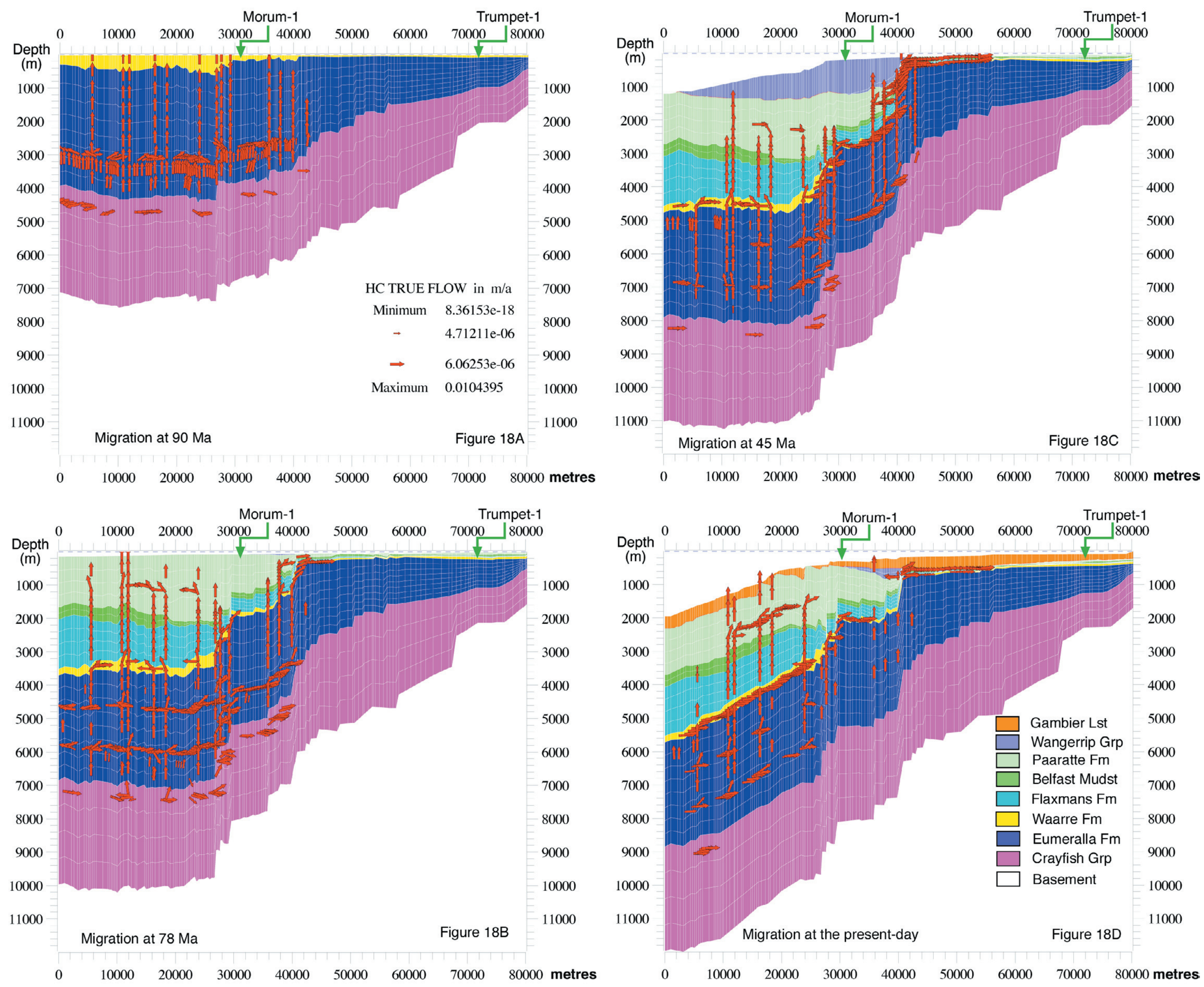

Figure 18. Modelled seismic line 85-13 showing hydrocarbon true flow direction and magnitude superimposed on the modelled stratigraphy at four key periods in the history: **a.** 90 Ma – the onset of migration from the deeper Eumeralla Formation. **b.** 78 Ma—the onset of migration from the shallower Eumeralla Formation. **c.** 45 Ma—at the time of maximum burial of the Morum High. **d.** The present-day

Asphaltites generated by, as yet undiscovered, Late Cretaceous source rocks (e.g. Boreham et al, 2001), which are regularly reported as strandings along the South Australian coastline south of Kangaroo Island, must be presently migrating. A Late Cretaceous package of deep water sediments has been identified in the vicinity of the Morum–1 well as part of our investigations. Only in a sub-basin of considerable thickness, such as identified in this paper, would migration leading to the asphaltite strandings still be occurring. Thus, the key to finding oil along the entire southern margin may be to find deep water Late Cretaceous sediments that are overlain by Tertiary depocentres.

POSSIBLE ACCUMULATIONS

Assessment of specific prospects is beyond the scope of this work. The model does point to the possibility of accumulations in suitably sealed tilted fault block reservoirs of the Paaratte package in the Morum Sub-basin immediately south of Morum–1, as well as potential Waarre reservoirs in the same general area (Figure 19). Potential shallow Waarre reservoirs on the southern boundary of the Crayfish Platform are also prospective. In this regard, Alan Cook (pers, comm., October 2002) reports the presence of rare dead oil rimming some sandstone grains and as abundant inclusions within a small proportion of grains in a cuttings sample of Belfast Mudstone near TD (2432.2–2438.0 m) in Morum–1. Given the maturity at this depth is 0.6% (Romax), and given the generally lean nature of the indigenous sediments in Morum–1 (McKirdy and O'Leary, 1984), this oil is considered here to be a migrated product, most likely from a more mature Eumeralla Formation source.

CONCLUDING REMARKS

Our modelling results serve to highlight only some of the main aspects of the hydrocarbon generation and migration history in this region of the Otway Basin. We have assumed that the Eumeralla Formation contains the only viable source rocks in the basin (as seems to be the case for known hydrocarbon discoveries—Duddy, 1997), and this is the major reason for the absence of generation for the Crayfish Platform. The presence of Crayfish Group source rocks beneath the Crayfish

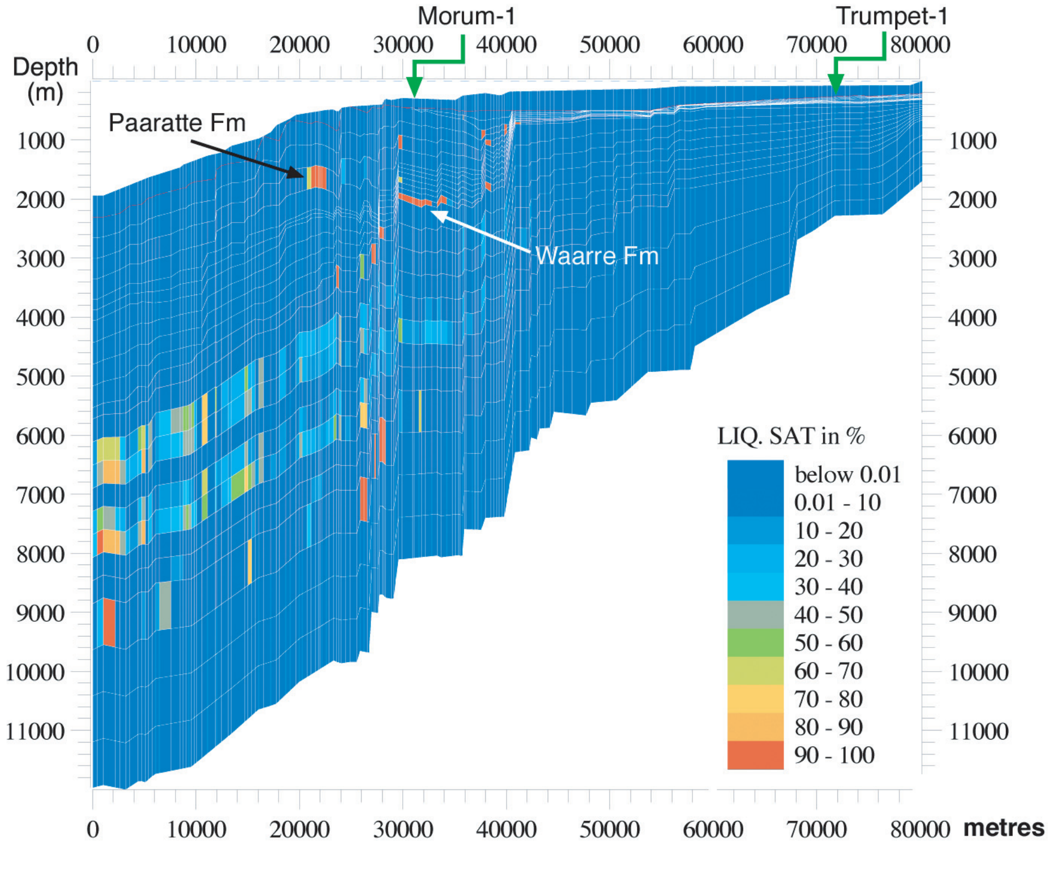

Figure 19: Modelled seismic line 85-13 showing predicted hydrocarbon saturation at the present-day. Locations of accumulations in the Waarre and Paaratte Formation in the Morum Subbasin is indicative only of the general possibilities in this part of the basin, as the model does not incorporate any detailed assessment of the distribution of potential reservoir lithologies.

Platform would change this picture, but the potential for significant accumulations from such rocks is significantly affected by elevated mid-Cretaceous heat flow which results in peak source rock maturation occurring prior to ~95 Ma in such locations (Duddy, 1997).

Inversion of the Morum High in the mid-Eocene stopped active hydrocarbon generation from Eumeralla Formation source rocks at that time, and there has been insufficient subsequent burial to re-start generation in the area of the inversion. We have postulated the almost complete removal of an Early Tertiary Wangerrip Group depocentre around the Morum High which covered an area similar to that still represented by the Portland Trough, but the actual extent of such a basin is completely speculative.

Duddy and Erout (2001) identified kilometre-scale erosion of the Mussel Platform, commencing at some time between 65 and 10 Ma as defined by AFTA. This episode was attributed to erosion on the Maastrichtian unconformity, but subsequent collection of new VR data from Mussel–1 suggests uplift more likely occurred on a post-Wangerrip Group unconformity. That being the case, it is possible that inversion of the Mussel Platform and the Morum High occurred more or less at the same time in the mid-Eocene and resulted in the erosional removal of a significant thickness of Wangerrip Group sediment at both locations as illustrated in Figure 16.

Tupper et al (1993) recognised a 'Mild Wrenching Phase' in the mid-Tertiary that resulted in local compression and fault re-activation along the southern margin of the Crayfish Platform. Our results suggest that there was a major episode of wrenching in the mid-Eocene (~45 Ma), preceded in the Early Tertiary by rapid local basin development that accumulated thick (> 1km) Wangerrip Group sediments. This episode of wrenching resulted in the almost complete removal of at least one of these wrench basins that developed along the Tartwaup Hinge zone in the vicinity of the Morum High, and possibly another in the eastern Otway Basin in the vicinity of Mussel–1 (Duddy and Erout, 2001). The Portland Trough represents another of these rapidly subsiding basins, bounded by the Tartwaup Hinge Zone to the north, but which escaped mid-Eocene inversion, although there is stratigraphic and structural evidence from Voluta–1 (Holdgate et al, 1986) that strongly suggests that the Wangerrip Group on the Bridgewater High forming the southern boundary of the Portland Trough (Fig. 16) was subjected to significant, potentially kilometre-scale, denudation at this time.

It is tempting to correlate these basin inversions with the onset of fast spreading in the Southern Ocean in the mid-Eocene, but given the limited number of direct AFTA timing constraints available, this is probably premature. Perhaps more importantly, the style of rapid Early Tertiary basin formation and equally rapid inversion implies development of a major strike-slip boundary between Australia and Antarctica with the possibility of significant inversion at other locations along the Tartwaup Hinge Zone and the Mussel and Sorrel fault systems bounding the Morum Sub-basin and the Voluta Trough.

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