AFTA®-calibrated 2-D modelling of hydrocarbon generation and migration using Temispack®: Preliminary results from the Otway Basin.

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ABSTRACT

Commercial hydrocarbon discoveries in the Otway Basin are currently limited to the Victorian Port Campbell Embayment, both onshore and offshore and the onshore Penola Trough in South Australia. Previous AFTA®-based studies have shown that the regional thermal history is a key factor controlling the distribution of these discoveries, the results of these studies providing a viable means of focussing exploration in the "thermally" most favourable regions of the basin. In simple terms, thermally favourable regions are those in which the negative effects of elevated mid-Cretaceous heat-flow have been overcome by sufficiently thick Late Cretaceous and Tertiary burial to re-start hydrocarbon generation from Early Cretaceous source rocks.

The offshore Port Campbell Embayment is such a favourable region but local structural complexity in this relatively small area provide significant challenges for predicting the location of additional hydrocarbon accumulations. Available open file organic maturity information from offshore wells (vitrinite reflectance, spore colour (TAI), T_{max}) suggests kilometre-scale uplift and erosion events in the area, but the timing of these events is very poorly constrained by the current data distribution. Similarly, seismic sections clearly show a number of post-early Cretaceous structuring episodes, but even the relative importance of these episodes on the generation and preservation of hydrocarbons is unconstrained.

In this study, Temispack 2-D basin modelling results are presented for a section through the La Bella and Minerva gas discoveries along seismic line OE80A-1056. A key aspect of this study is to provide viable explanations for the presence of gas accumulations at La Bella and Minerva as a guide to understanding the factors that control the petroleum system in the area.

Thermal history reconstruction using a combination of AFTA, VR and TAI data from Mussel-1, Minerva-1, Conan-1 and La Bella-1 provides evidence for a major period of post-Campanian – pre Miocene structuring on the Mussel Platform. A large area of the Mussel Platform is interpreted to have been buried by an additional ~1.5 km of Late Cretaceous and Paleocene section prior to inversion at ~60 Ma related to transpressional interaction between the Australian and Antarctic plates.

The calibrated 2-D model successfully predicts accumulations at Minerva and La Bella charged by hydrocarbons generated from the upper part of the Eumeralla Formation during the Tertiary and fault migrated. Minerva is locally sourced from the Shipwreck Trough whereas La Bella is sourced from the adjacent Voluta Trough. The model also predicts that all valid Waarre Formation traps in the zone of tilted fault blocks on the southern flank of the Mussel Platform flanking the Voluta Trough could potentially contain accumulations by fault migration pathways.

INTRODUCTION

In this study we present the results of 1-D thermal and burial history reconstructions of the Minerva-1 and Mussel-1 wells and a 2-D Temispack® reconstruction of the hydrocarbon generation and migration history along the associated OE80A-1056 seismic line (Figure 1).

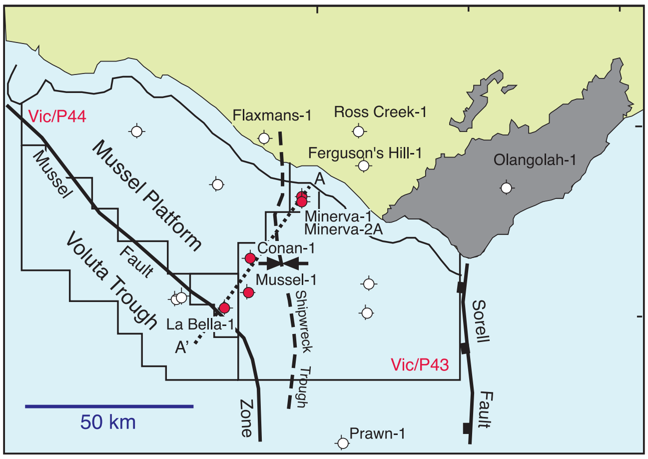


Figure 1. Location Map of the eastern Otway Basin showing the main structural provinces and locations of the wells and seismic line OE80A-1056 (A – A') referenced in the text.

The primary aim of this study was to try and understand the conditions responsible for reservoiring commercial and sub-commercial quantities of hydrocarbons at Minerva and La Bella, respectively. There are no published 2-D hydrocarbon generation and migration models for the Otway Basin and only one systematic study incorporating 1-D reconstructions (Duddy 1997). Duddy (1997) presented thermal, burial and source rock maturation histories derived from AFTA and vitrinite reflectance results for a number of wells in the Otway Basin, including a generalised history of the Minerva gas discovery. A key finding of this study was the definition of an offshore Otway Basin area, including Minerva-1 and the Shipwreck Trough, in which active hydrocarbon generation was interpreted to have begun in the Miocene and was continuing to the present day.

The basic work flow in this study involves:

- Calibration of the thermal history at each well location along the seismic line using measured BHT data, vitrinite reflectance, TAI and AFTA data. Calibration involves determination of the time of dominant structuring (using AFTA), magnitude of maximum paleotemperatures, amount of associated uplift and erosion and the magnitude of present and paleo-heat flow at the time of each thermal event revealed by AFTA.

- Simple depth conversion of the time-seismic section and the interpreted geological section.
- Defining a suitable “mesh’ for the 2-D model as a compromise between computation time and geological accuracy.
- The Temispack model (e.g. Burrus et al. 1992a) incorporates basin geometry, lithofacies, erosion and faulting and once calibrated, predicts through time, among other things, compaction, water flow, temperature and pressure fields, hydrocarbon generation, migration pathways and saturation.

The modelling results represented here are a work in progress and form part of a larger study reconstructing the geological history of Southeastern Australia for improving success in hydrocarbon exploration. However, the quantification of a structural episode with significant thermal effects on the Mussel Platform (Figure 1) was felt to warrant publication of the preliminary findings and some speculation as to the implications of the results for ongoing Otway Basin exploration.

GEOLOGICAL HISTORY

Chrono- and lithostratigraphic nomenclature together with a generalised tectonic history for the Otway Basin are presented in Figure 2. The key elements of the geological evolution are based on Duddy (1997) but also incorporates contributions of a large number of authors over several decades (see Duddy 1997; Lavin 1997; Geary & Reid 1998). The palynological zonation is largely based on the scheme of Helby et al. (1987) as used by Morton et al. (1994) although we note the currently unpublished work of Partridge (1997) which proposes that Cenomanian rocks are entirely absent from the Otway Basin. While this is a significant revision of the Late Cretaceous biostratigraphy, it does not materially affect the data-based thermal history reconstructions in the region.

Key features of the history

The deposition of the Eumeralla Formation through the Aptian-Albian is the oldest part of the history illustrated in Figure 2 as this unit incorporates the source rock horizons responsible for the all known Otway Basin discoveries (Duddy 1997). The non-marine Eumeralla Formation is comprised largely of high-energy, internally braided or anastomosing channel sandstones, in a spectrum of overbank shales and coals deposited during a period of active rifting. (Duddy 1983). The sediments are composed largely of dacitic volcanic fragments derived from contemporaneous volcanism (Gleadow & Duddy 1980), which is a major controlling factor for porosity and permeability destruction, and routes for subsequent hydrocarbon migration.

Eumeralla Formation fluvial deposition and contemporaneous explosive volcanic activity was abruptly terminated in the mid-Cretaceous (at ~95 Ma), associated with the initial separation of Australia and Antarctica, and involving rapid decline in heat flow and extreme, but localised, inversion of parts of the rift basin and adjacent basement blocks (Duddy 1994). Strongly uplifted blocks are bounded by re-activated Early Cretaceous normal and transfer faults with no evidence for reactivation of Paleozoic structures (c.f. Foster & Gleadow, 1993). The Otway Ranges and offshore extension to the uplifted basement of King Island, and the Paleozoic basement block on the northern flank of the onshore Port Campbell Embayment are major mid-Cretaceous inversions in the region. These uplifted blocks act to define the gross area of the Sherbrook Group depositional basin and localise deposition of the initially non-marine Waarre Formation Sandstones to the rapidly subsiding Port Campbell Embayment and the now offshore Shipwreck Trough (Figure 1).

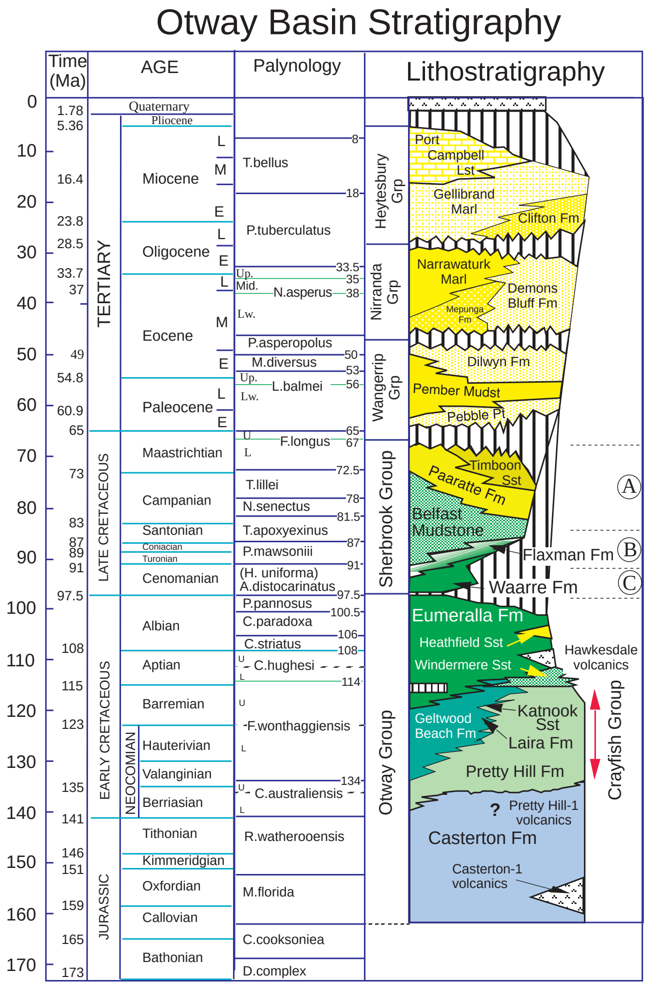


Figure 2. Chrono- and lithostratigraphy for the eastern Otway (after Duddy, in prep). A: Sherbrook Group; B: Upper Shipwreck Group; C: Lower Shipwreck Group (BHPP usage after Luxton, 1995).

Most importantly, the occurrence of Waarre Formation at the base of the Sherbrook Group is associated with no, or minimal, erosion of the underlying Eumeralla Formation in which the youngest Albian P. pannosus spore pollen zone (Figure 2) is usually preserved. In contrast, on mid-Cretaceous inversion structures the oldest sediments overlying the Eumeralla Formation are of Paleocene - Eocene age Wangerrip Group (Duddy 1997). The Waarre Formation was succeeded by the deltaic Flaxmans Formation and the thick interdigitating Belfast Mudstone, Paaratte Formation and Timboon Sandstone of Coniacian to Late

Maastrichtian age deposited in a near shore to open marine environments.

In the study area, Sherbrook Group deposition was terminated at the end of the Maastrichtian or early Paleocene by a period of uplift and erosion with significant truncation noted on some seismic lines (e.g. Geary & Reid, 1998) and with significant gaps in the palynological record identified in some key well intersections, particularly on the Mussel Platform, as discussed further below.

Deposition recommenced in the Paleocene with the Wangerrip Group, a prograding deltaic sequence of marine sandstones of the Pebble Point Formation overlain by mudstones, the Pember Mudstone, and a sandstone-shale sequence of the Dilwyn Formation. Deposition was terminated in the early Middle Eocene as a response to an apparently mild compressional episode. Uplift and erosion was apparently minor as deposition recommenced in the Middle Eocene with the Nirranda Group, a second prograding unit of nearshore to offshore marine basal clastics (Mepunga Formation), succeeded by the largely open marine carbonates and marls of the Narrawaturk Marl. Nirranda group deposition is terminated in the early Oligocene by the third significant post-mid-Cretaceous episode of compression.

In the middle Oligocene, shallow marine calcarenites of the Clifton Formation and the deeper water muddy limestone deposits of the Gellibrand Marl characterise the initial deposits of the Heytesbury Group. These deposits are largely replaced by the calcarenites of the Port Campbell Limestone by the Middle Miocene, with deposition terminated by a locally significant regional compressional episode in the latest Miocene-Pliocene (e.g. Trupp et al. 1994).

Other recent compilations of the geological evolution are broadly similar, but that of Lavin (1997) which forms that basis of that reported in the extensive study of Geary and Reid (1998), differs in a several important details. In the current context the most important difference is the attribution of the Late Cretaceous Sherbrook Group to a rifting episode incorporating high heat flow, with passive-margin thermal subsidence not beginning until the Paleocene. The results presented here do not support this model and favour more or less normal heat flow in the Maastrichtian-Paleocene at the time of development of the Maastrichtian unconformity.

Also note that BHP Petroleum developed an informal terminology for the basal Late Cretaceous units in offshore region (e.g. Luxton et al. 1995), restricting the Sherbrook Group to the Santonian to Maastrichtian section and introducing the term Shipwreck Group for the older section (Figure 2). Furthermore, the Shipwreck Group was subdivided into upper and lower units separated by an angular unconformity in the middle Santonian. The time gap represented by this unconformity is extremely small (less than ~1 Ma) and its structural significance is uncertain, but on the available data it appears to be of minor importance in the thermal history.

REGIONAL THERMAL HISTORY

Based on the regional thermal history derived from analysis of AFTA and VR results from Otway and Gippsland Basin outcrops and wells (Duddy et al. 1991; Duddy and Green, 1992; Duddy, 1997; and unpublished results), the following regional thermal history has been used for the 2-D basin model:

- Heat flow at the beginning of rifting (assumed to be ~145 Ma) was similar to present-day levels.
- Heat flow at ~95 Ma, the end of Otway Group deposition, was approximately double present-day levels. Thus, heating during deposition of the Otway Group was due to a combination of burial and elevated heat flow.
- Heat flow began to decline rapidly at ~95 Ma, the end of the thermal rift phase, reaching present-day levels by ~80 Ma (~mid Campanian). That is, heat flow during deposition of the Sherbrook Group was in decline, consistent with the offshore eastern Otway Basin during this time as a "strike-slip" basin that was not undergoing active, rift-related thermal extension.
- Heat flow from 80 Ma to the present day is assumed to have been the same as measured at the present-day. This indicates that heating of the stratigraphic section during deposition of the latter part of the Sherbrook Group, the Wangerrip, Nirranda and Heytesbury Groups was due only to burial.

METHODS

AFTA and VR-based thermal history calibration

Calibration of the section is the most important step in the modelling procedure. Thermal history reconstruction using AFTA and VR data and interpretation of paleotemperature profiles in terms of mechanisms of heating and cooling is described in detail in a series of publications by Green et al. (1989), Bray et al. (1992), Duddy et al. (1994) and Green et al. (1996) and are not repeated in detail here. A major aspect of this approach is the definition of the Default Thermal History (DTH) for each AFTA and VR sample as a starting point for interpretation. Interpretation begins by assessing whether the measured VR values and AFTA parameters in each sample could have been produced if the sample has never been hotter than its present temperature at any time since deposition.

DTH's are derived from the stratigraphy of the preserved sedimentary section, combined with constant values for paleogeothermal gradient and paleo-surface temperature that are the same as present-day values. Using these default thermal parameters, the variation of VR with depth (the VR profile) and AFTA age and length with depth is predicted for the whole well section for comparison with the measured data at each sample depth.

If a measured VR value is higher than the value predicted from the DTH (making due allowance for analytical uncertainty), the sample must have been hotter at some time in the past. In this case AFTA can be used to determine the time of this past heating.

If a measured VR value is the same as the value predicted from the DTH, then this indicates that the sample has not been exposed to paleotemperatures any higher than the present temperatures at any time after deposition. In other words, the section is at maximum temperatures now. In such a case, additional thermal history data (this includes AFTA, VR, biomarkers, Rock-Eval T_{max}, etc) cannot reveal any further details of the thermal history at this location.

If a measured VR value is lower than expected on the basis of the DTH, either the present temperature has been overestimated or temperatures have increased very recently. In such cases, the measured VR value may allow an estimate of the true present-day temperature. Alternatively the measured VR value may underestimate the true maturity for some other reason, e.g., suppression of reflectance in certain organic macerals, misidentification of true "in-situ" vitrinite, presence of caved material etc. Comparison of the VR data with inorganic thermal history tools, principally AFTA apatite fission track analysis usually allows such factors to be identified, and the real thermal history and the mechanism of heating and cooling to be determined.

The thermal histories reconstructed in this way form the fundamental calibration of the thermal and structural histories for the Temispack 2-D modelling.

Estimation of present temperatures

Determination of the in situ present temperature for each AFTA and VR sample is an essential element of rigorous thermal history calibration. In this study, BHT logging temperatures are corrected by an empirical procedure adapted from the literature, as unfortunately, present temperature data are often not recorded in sufficient detail to allow more sophisticated approaches, particularly in some of the 60's vintage wells in the Otway Basin region. Nevertheless, the correction procedure has been found to give very similar results to both Horner correction procedures and stabilised DST temperatures where they are available, and are probably accurate to ±5%. Raw BHT measurements from the well completion reports were corrected using a simplified correction procedure adapted from that of Andrews-Speed et al. (1984). Quoted BHT data are corrected by increasing the difference between the sea-bed temperature (assumed to be 10°C) and the uncorrected BHT by 20% for uncorrected temperatures below 66°C (150°F), and by 25% for uncorrected temperatures above 66°C. Note that where more than one measurement is available at any one depth, the value with the shortest time since circulation is used. Note all depths in this paper refer to measured depth below kelly bushing.

2-D Basin modelling approach

Details of the approach to 2-D modelling using the Temispack modelling software developed by Institut Francais Petrole (IFP) are given in Burrus et al. (1992a, 1992b) and Ungerer et al. (1990) with a more recent local example of its application provided by Vear (1998).

The basic steps in the approach involve depth-conversion of a time-seismic section to produce a geological cross-section that is then back-stripped, with quantitative allowance for compaction on the basis of user defined lithologies. This back-stripped history is combined with an underlying thermal model, user-defined thermal conductivities and source rock parameters to enable prediction of fluid flow, hydrocarbon generation and migration and pressure evolution along the line of section. In this study, we present results for hydrocarbon generation and migration along seismic section OE80A-1056 (Figures 1 and 3) from the mid-Cretaceous to the present-day.

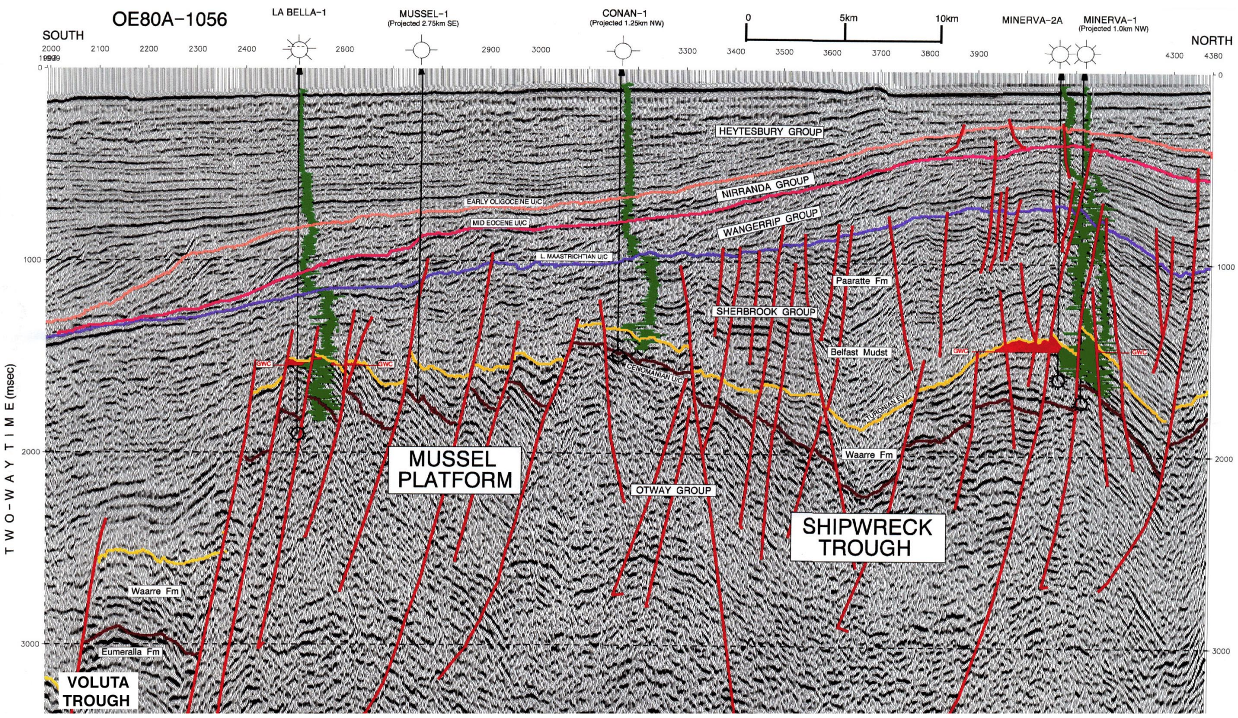


Figure 3. Seismic line OE80A-1056 (location in Figure 1) and interpretation from Geary and Reid (1998, VIMP 55).

1D WELL CALIBRATIONS

Mussel-1 thermal and burial history interpretation

Mussel-1 was drilled on the Mussel Platform and is offset a few kilometres to the SE from seismic line OE80A-1056 (Figure 1).

Two logging run temperatures at 416.1 m and 2286 m gave corrected temperatures of 43 and 82°C respectively, which give a present-day geothermal gradient of 35°C/km for a sea-bed temperature of 10°C. This is consistent with regional Otway Basin gradients which are typically between 30 and 35°C/km. Note however, that the shallower temperature lies well above the linear trend and cannot be explained by any reasonable distribution of rock thermal conductivities and it is therefore assumed to be anomalous. The geothermal gradient estimated from the deeper measurement only is 33°C/km and this is used to determine the DTH's from the preserved burial history illustrated in Figure 4. The burial history uses formation tops from the lithostratigraphic units in the well completion report and the most recent palynological data summarised by Geary and Reid (1998). The biostratigraphic data are consistent with a significant break at the top of the Sherbrook Groups between the Late Maastrichtian and the Early Eocene (~68 to 53 Ma), and smaller breaks at the top of the Wangerrip (~50 to 45 Ma) and Nirranda Groups (~30 to 24 Ma).

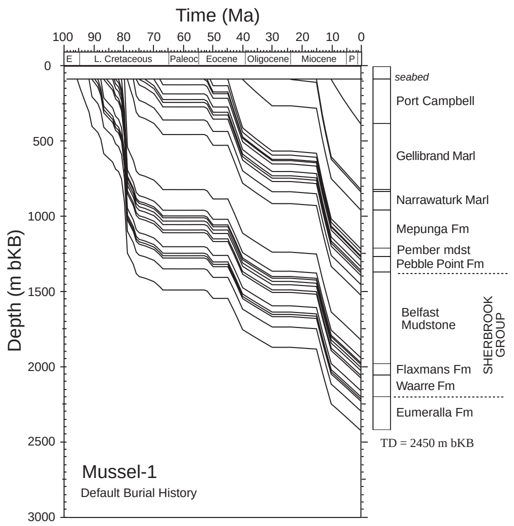


Figure 4. Default Burial History for the Mussel-1 derived from the preserved stratigraphy. This history is combined with the present-day geothermal gradient to determine the Default Thermal Histories for each AFTA and VR sample.

Figure 5 shows a plot of measured VR data from the Eumeralla Formation and basal Sherbrook Group (open file, DNRE), the majority of which is $R_o$max data from A.C. Cook (Keiraville Konsultants). Also shown is the profile of VR predicted from the DTH. The measured VR data all plot well above the predicted profile showing that the section has cooled from maximum paleotemperatures significantly higher than present temperatures. The time of cooling is only broadly constrained by the stratigraphic age of the shallowest VR data point (2013 m) as post-P. mawsonii spore pollen zone (< ~87 Ma).

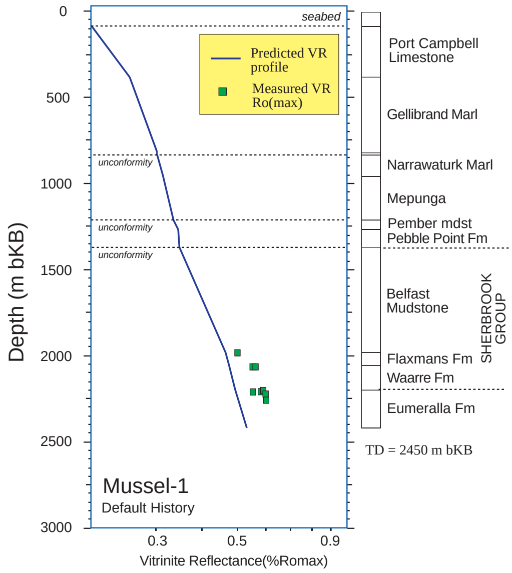


Figure 5. Measured and predicted vitrinite reflectance with respect to depth in Mussel-1. The solid square symbols denote VR data ($R_o$max) and the solid line shows the VR profile calculated on the basis of the Default Thermal History which is derived from the preserved stratigraphy and present-day thermal conditions. All values lie well above the predicted profile, indicating the sampled sequence has been hotter than present temperatures since deposition.

AFTA data in five samples from the Sherbrook Group and Eumeralla Formation are plotted against depth and present temperature in Figure 6, together with the profiles of fission track age and length predicted from the DTH's.

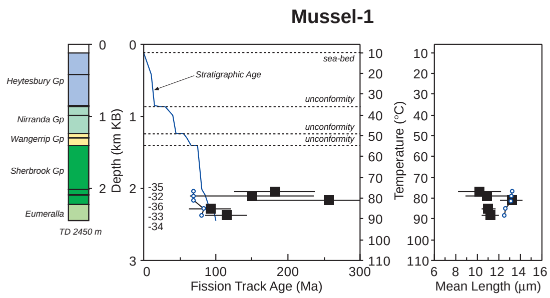


Figure 6. Measured AFTA parameters (square symbols) plotted against sample depth and present temperature for samples from Mussel-1. Average fission track age and length predicted from the Default Thermal History are shown as the open circles. The variation of stratigraphic age with depth is also shown, as the solid line in the central panel. A present-day geothermal gradient of 33°C/km and a sea-bed temperature of 10°C is used for the temperature scale.

At face value the mean values of age and length from each sample is similar to the value expected from the Default Thermal Histories. However, kinetic modelling of each sample, using the full range of apatite compositions present, clearly reveals that samples -33 and -34 have cooled from maximum paleotemperatures significantly higher than present temperatures after deposition of the Eumeralla Formation. Furthermore, the maximum paleotemperatures required by the AFTA data are consistent with those derived from the VR results in the same depth intervals. AFTA data from the three shallow Sherbrook Group samples (-32, -35 and -36 in Figure 6) are of lesser quality (particularly the track length data) due to poorer detrital apatite yields. The combined results from the three samples do not definitely require any additional heating, but allow a range of maximum paleotemperatures that incorporate those indicated by the VR results in this part of the section. Most importantly, integration of the AFTA and VR results from all samples, only provides consistent thermal history solutions if cooling from maximum paleotemperatures began at some time between 65 and 10 Ma. A thermal history solution derived from the AFTA and VR results from Eumeralla Formation sample -33 is presented in Figure 7.

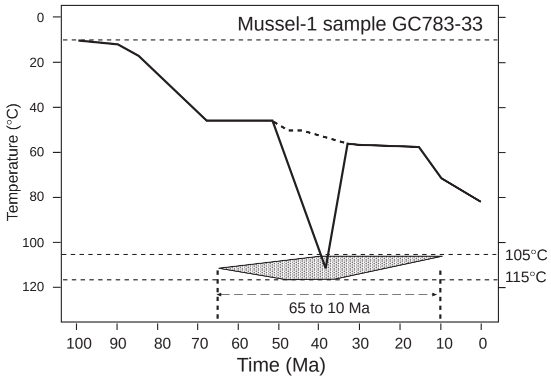


Figure 7. AFTA thermal history solutions for sample –33 from Mussel-1 at a present temperature of 89°C, showing the clear requirement from cooling from 105 to 115°C beginning at some time between 65 and 10 Ma (±95% confidence limits).

This allowed time of heating illustrated in Figure 7 is consistent with cooling associated with any of the top-Sherbrook Group, top-Wangerrip Group or top-Nirranda Group unconformities. Cooling associated with the top-Sherbrook Group unconformity is favoured, however, on the basis of the distinct breaks in the TAI (thermal alteration index from spore colour) profiles at this level in the nearby La Bella-1 well as illustrated in Figure 8 (TAI data from Morgan and Hooker, 1993). Unfortunately, while the break itself is undoubtedly significant (encompassing a time gap from ~80 to 52 Ma based on the palynology), the TAI data is not collected in a way that enables it to be used as a quantitative thermal history tool (Morgan, personal communication, 1999). TAI data are not available for Mussel-1.

The lack of a complete measured VR data set shallower than 2013 m in Mussel-1 means that the cause of heating cannot be directly assessed from the trend of the paleotemperature profile (see Duddy et al. 1991 & Bray et al. 1992 for an explanation of the interpretation of paleotemperature profiles). However, the distinct break in the La Bella-1 TAI profile (Figure 8) is a strong indication that heating was associated with uplift and erosion on the Maastrichtian unconformity rather than due to higher heat flow. If higher heat flow was the sole cause of the additional heating, then this would produce a change in slope of the TAI (or VR) profile without a distinct break. A more detailed analysis requires additional quantitative VR data from the complete drilled section.

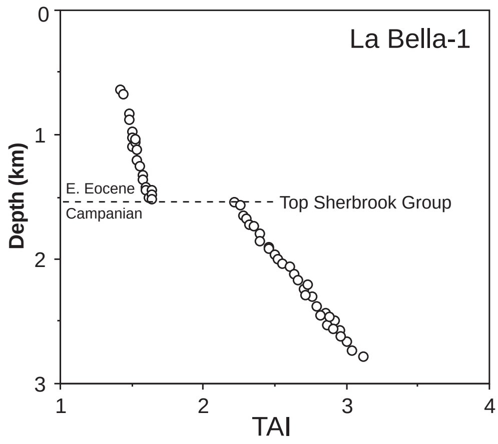


Figure 8. TAI (spore colour) versus depth in La Bella-1 showing the distinct break between the Campanian and E. Eocene, interpreted to be due to kilometre scale uplift and erosion beginning in the Paleocene (at ~60 Ma).

Figure 9 presents a reconstructed burial history assuming that cooling was due solely to uplift and erosion on the top-Sherbrook Group unconformity using a heat flow value adopted from the present-day level (~52 mWm^{-2}), and assuming that the eroded section was dominantly a fine grained shale and silt section like that currently preserved in the well. On this basis, burial and subsequent erosion of an additional 1.5 km of Late Maastrichtian to Paleocene section is required in order to explain the thermal history results. Uplift and erosion is assumed to have commenced at 60 Ma, within the time range 65 to 10 Ma defined by AFTA and 68 to 53 Ma represented by the "Maastrichtian" (top-Sherbrook Group) unconformity.

The VR depth profile derived from the reconstructed thermal and burial history for Mussel-1 is shown in Figure 10 where an excellent match is shown between the predicted profile and the measured VR values and the AFTA-derived equivalent VR values.

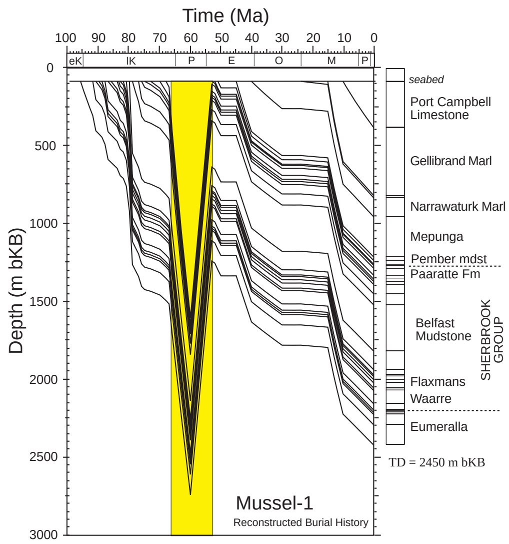


Figure 9. Reconstructed burial history for Mussel-1 derived from the thermal history constraints and showing 1.5 km of additional Maastrichtian to Paleocene burial removed by uplift and erosion between 60 and 52 Ma.

Conan-1 thermal and burial history interpretation

The open-file VR results from Mussel Platform well Conan-1 (Figure 1) are very similar to those described in detail for Mussel-1, and a similar thermal and burial history is considered appropriate for this well also. No AFTA data are currently available so direct information on the time of cooling is unavailable, but the shallowest VR value at 1575 m in the Belfast Mudstone constrains cooling to beginning at some time post-Campanian (Conan-1 well completion report, open-file, DNRE).

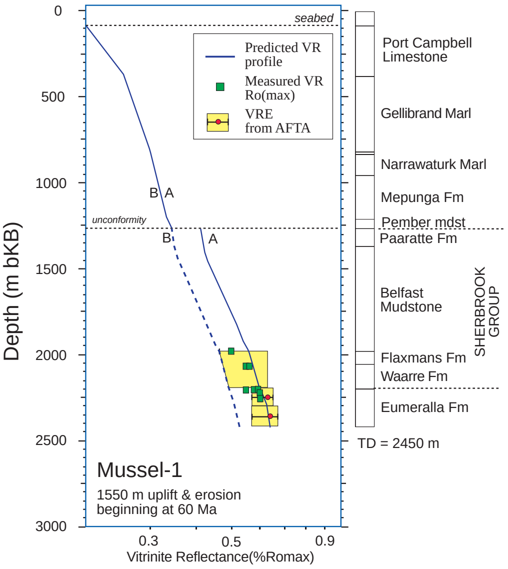


Figure 10. Measured vitrinite reflectance in Mussel-1 and the predicted VR based on the reconstructed thermal and burial histories. The measured data shows a good match to the predicted profile confirming a valid calibration. The dashed line shows the Default History VR profile (no additional heating) from Figure 5 for comparison.

Minerva-1 thermal and burial history interpretation

Minerva-1 was drilled on the north-east flank of the Shipwreck Trough at the northern end of seismic line OE80A-1056 (Figure 1). The default burial history derived from the preserved stratigraphy is shown in Figure 11.

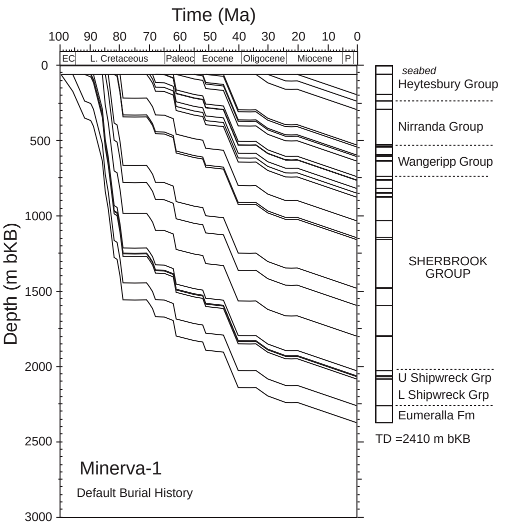


Figure 11. Default Burial History for the Minerva–1 derived from the preserved stratigraphy (BHPP terminology – see Figure 2).

Three logging run temperatures at 1834 m, 2019 m and 2419.5 m gave corrected temperatures of 89, 101.2 and 110°C respectively, which gives a linear present-day geothermal gradient of 43°C/km for a sea-bed temperature of 10°C. This is a little higher that regional Otway Basin gradients, which are typically between 30 and 35°C/km, but the three corrected values are very consistent and there appears to be no reason to see this as an anomalous gradient.

A plot of measured VR data from the Sherbrook Group and Eumeralla Formation (open file Keiraville Konsultants data, DNRE) is given in Figure 12. Also shown is the profile of VR predicted from the DTH. The majority of the measured VR data, from around 1500 m in the Sherbrook Group to the Eumeralla Formation at TD, plot on, or slightly below, the predicted profile, suggesting that this part of the well is at, or near, maximum paleotemperatures at the present-day. Three VR values from the Sherbrook Group between the shallowest sample at 1130 m and 1500 m plot consistently above the predicted profile, suggesting that this part of the well may have cooled from maximum paleotemperatures somewhat higher than present temperatures at some time after deposition of the middle N. senectus spore pollen zone (< ~80 Ma). One explanation for this difference in interpretation is that the upper part of the section was subjected to lateral heating due to transient flow of hot fluids through a confined aquifer(s) (see Duddy et al. 1994). A second possibility is that deeper VR values are geochemically suppressed and do not reflect the true thermal history. The AFTA results discussed below do not support geochemical suppression, as they clearly show that this part of the section is at or near maximum paleotemperatures at the present-day, in complete agreement with the measured VR values. A further explanation is that the present-day gradient is too high or has increased to the present-level in the very recent geological past (<1Ma), leading to a predicted VR profile that is too high throughout the well. On the available data we prefer the first explanation, and consider that the section is at maximum burial temperatures at the present-day and that the higher VR values shallow in the section results from transient heating, possibly due to flow of hot fluid. This transient heating episode is not considered further here.

AFTA data from three samples from the Sherbrook Group and Eumeralla Formation in Minerva-1 are plotted against depth and present temperature in Figure 13, together with the profiles of fission track age and length predicted from the DTH's.

Kinetic modelling using the full range of apatite compositions present in each sample shows that all samples are currently at, or close to, their maximum paleotemperatures since deposition, in good agreement with the interpretation of the VR results. Waarre Formation sample –12 for example is at a present temperature of 89°C, and clearly retains fission tracks from the sediment source terrains (Figure 13), with kinetic modelling showing that maximum paleotemperatures could not have exceeded 95°C at any time after deposition. Results from the other samples provide similar solutions.

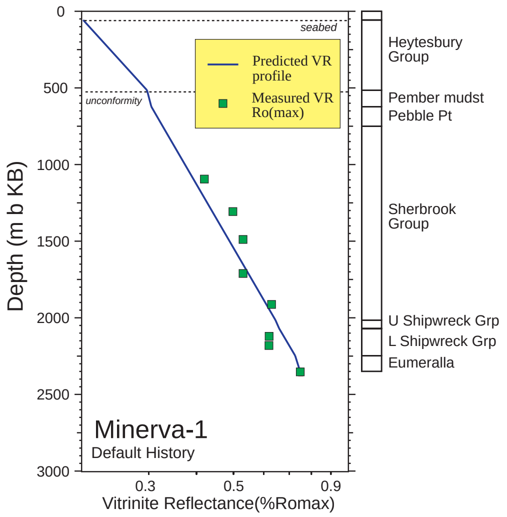


Figure 12. Measured and predicted vitrinite reflectance with respect to depth in Minerva-1. The solid square symbols denote high quality VR data ($R_o$max) and the solid line shows the VR profile calculated on the basis of the Default Thermal History which is derived from the preserved stratigraphy and 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 to local transient heating.

Thus, the available thermal history data do not require any *significant* periods of heating and cooling associated with additional burial and subsequent uplift and erosion at any time at the Minerva-1 location. This is in good agreement with the biostratigraphic results suggesting a fairly complete suite of Late Cretaceous palynological zones are recorded (summarised in Geary and Reid, 1998). Therefore, the default burial history illustrated in Figure 11 is considered to be a reasonable approximation to the true burial history for Minerva-1. Geary and Reid (1998) note pronounced folding is associated with the Late Miocene-Pliocene (top Heytesbury Group) unconformity and is clearly seen at the Minerva-1 location (Figure 3), although the thermal history reconstruction shows that it must have involved very limited cooling (<6°C) and therefore absolute uplift and erosion at this time is probably limited to less than a couple of hundred metres.

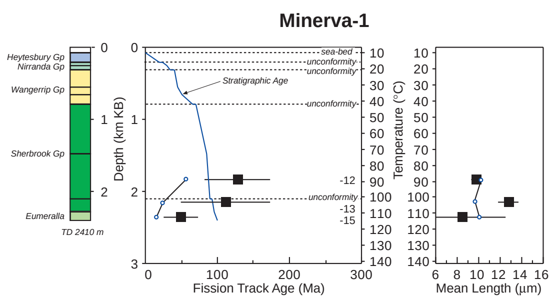


Figure 13. Measured AFTA parameters (square symbols) plotted against sample depth and present temperature for samples from Minerva –1. Average fission track age and length predicted from the Default Thermal History are shown as the open circles. The variation of stratigraphic age with depth is also shown, as the solid line in the central panel. A present-day geothermal gradient of 43°C/km and a sea-bed temperature of 10°C is used for the temperature scale.

TEMISPACK 2D MODELLING

The Temispack model incorporates basin geometry, lithofacies, erosion and faulting and once calibrated, predicts through time, among other things, compaction, water flow, hydrocarbon generation, saturation and migration and pressure distribution. In this initial study we are concerned only with the prediction of generation, saturation and migration.

The OE80A-1056 seismic cross-section

Seismic section OE80A-1056 was chosen for the modelling exercise as it provided a convenient regional dip line ~60 km long running approximately NE – SW through the Minerva and La Bella gas fields and a modern interpretation published in Geary and Reid (1998) was kindly made available by DNRE (Figure 3).

The section covers three of the main structural features of the offshore Port Campbell Embayment – the Shipwreck Trough, the Mussel Platform and the Voluta Trough and passes through or close to five exploration wells - Conan-1, La Bella-1 Mussel-1 and Minerva-1 and -2A (Figure 1), which have provided the basis for a rigorous calibration.

Depth conversion and the geological model

The time-seismic section was converted to a depth section using Easydepth®. Open-file velocity information was obtained from the relevant well completion reports for Conan-1, La Bella-1 Mussel-1 and Minerva-1 and -2A and 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. One important point here is that we favour the identification of the Eumeralla Formation in the Mussel-1, La Bella and Minerva-1 wells derived from the lithostratigraphy in the well completion reports rather than the attribution to the Waarre Formation presented in Geary and Reid (1998).

Figure 14 shows the final geological model derived from seismic line OE80A-1056 with seven main horizons representing the Basement, Otway, Waarre, Sherbrook, Wangerrip, Nirranda and Heytesbury Groups, subdivided to give 15 horizons and with around 150 vertical markers placed to capture any structural complexity, giving a mesh of over 2000 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. Source rocks (10% TOC) were assumed to be present in two regional horizons, each 500 m thick, within the Eumeralla Formation of the Otway Group. One horizon is placed 500 m below the top of the Otway Group and another 3000 m below the top, in order to investigate the relative importance of deep and shallow source rocks in terms of the complex heat flow history used. A standard IFP gas-prone Type III source rock was assumed. At this stage more sophisticated treatments of source rock distribution and type are felt to be unwarranted as the intention of the model is to investigate some of the factors controlling the known gas discoveries and not to carry out a detailed study of hydrocarbon type and volumes.

The heat-flow history used is derived from the regional thermal history described previously. Present-day heat-flow was calibrated using corrected present temperatures from the five wells on the line and default values of thermal conductivities based on the lithologies attributed to each horizon, with a value of ~52 mWm^{-2} giving an acceptable match at all locations. This level of heat-flow is assumed to have been operating from 80 Ma to the present-day increasing linearly to a heat-flow peak of ~104 mWm^{-2} at 95 Ma which is assumed to have operated since 115 Ma (base Aptian) which was chosen as the start time for the modelling.

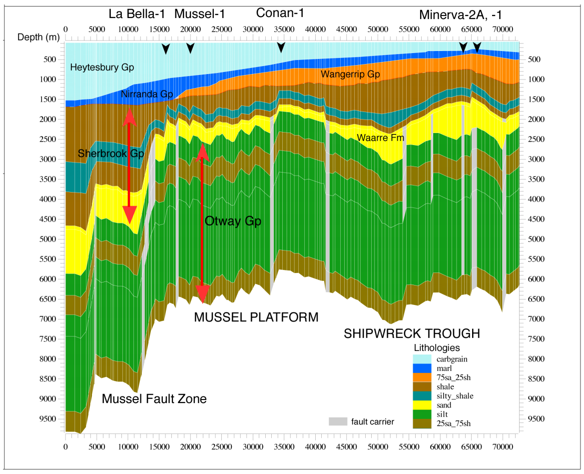


Figure 14. Depth-converted seismic section OE80A-1056 showing the lithologies of major units used for the 2-D modelling.

A major component of the model is the incorporation of a major basin inversion episode indicated by the calibrated thermal history reconstruction derived from the Mussel-1 AFTA and VR results, which suggest additional burial by ~1.5 km of Maastrichtian to Paleocene section prior to uplift and erosion beginning at ~60 Ma. Similar magnitudes of additional burial and erosion are allowed by the VR results from both Conan-1 and La Bella-1, and the model incorporates this additional burial (shale) and subsequent erosion for the entire Mussel Platform between the Mussel Fault Zone and the main western boundary fault of the Shipwreck Trough, (between position 5000 and 45000 in Figure 14). No additional burial is included for the Shipwreck Trough as indicated by the thermal history calibration results for Minerva-1.

Hydrocarbon saturation modelling results

Figure 15 shows hydrocarbon true flow direction and magnitude arrows superimposed on the stratigraphic model for four key periods in the history: at 71 Ma, 60 Ma – maximum burial, at 50 Ma, immediately following inversion of the Mussel platform, and at the present day. Predicted saturation at the present day is shown in Figure 16 without arrows showing flow, allowing the hydrocarbon-bearing traps to be easily observed.

Some key observations:

- There is a peak in generation and migration at 60 Ma in the Voluta Trough and on the Mussel Platform corresponding to the time at which the shallow Eumeralla source rock is reaching near complete transformation. This is also the time of maximum heating for the Mussel Platform due to the additional Maastrichtian-Paleocene burial.
- Active source rock transformation from shallow Eumeralla source rocks of the Mussel Platform ceased when cooling occurred due to uplift and erosion commencing at 60 Ma. No significant active maturation has occurred locally since this time but migration from this area continued with increasing re-burial to the present-day.
- The peak in generation and migration from the shallow Eumeralla source rock in the Shipwreck trough is at the present-day, as this area was not subjected to significant additional Maastrichtian-Paleocene burial.
- The model successfully predicts accumulations at Minerva and La Bella, charged by hydrocarbons generated from the upper part of the Eumeralla Formation in the Tertiary and fault migrated to the Waarre Formation reservoir. Minerva is locally sourced from the Shipwreck Trough, the majority of the charge emplaced since the Miocene, whereas La Bella is sourced from the adjacent Voluta Trough and received significant charge from the Late Cretaceous onwards.
- The model predicts no accumulation at Conan-1, as observed. The main reason for this appears to be a lack of local generation from the shallow Eumeralla Formation source rock, with migration from the Shipwreck Trough largely directed to the Minerva location to the north, while migration from the Voluta Trough to the south accumulates in the tilted-fault block structures on the southern flank of the Mussel Platform.
- As a consequence of successfully modelling the known accumulations at Minerva and La Bella, the model also predicts that the Waarre Formation in the tilted-fault block structures on the southern flank of the Mussel Platform, including the Mussel-1 location, and more deeply buried Waarre Formation in the Voluta Trough have had access to charge throughout most of the Tertiary, and all valid traps should contain significant accumulations.
- Hydrocarbons generated for the deeper Otway group source rock are mostly lost prior to deposition of the Waarre Formation reservoir, but may also have provided minor contributions to potential Waarre accumulations on the Mussel Platform and in the Voluta Trough.

- Eumeralla-sourced Wangerrip Group accumulations are possible, depending of fault migration and adequate seals.

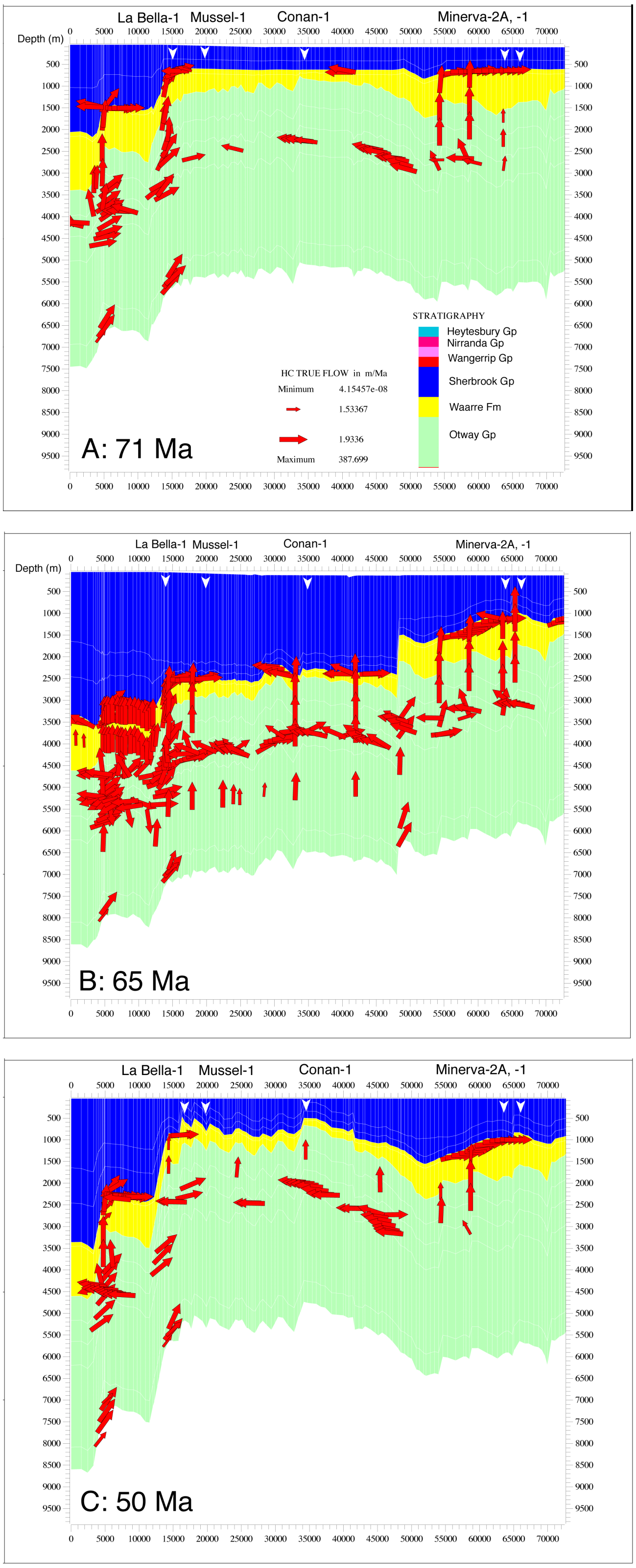


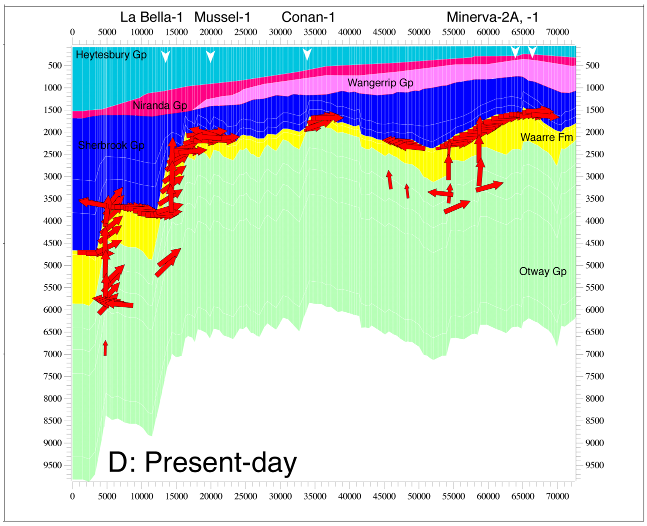
Figure 15. The modelled OE80A-1056 seismic section showing hydrocarbon true flow direction and magnitude superimposed on the modelled stratigraphy (legend in Figure A) at four key periods in the history:

A. 71 Ma - immediately prior to additional burial on the Mussel Platform.

B. 60 Ma – at the time of maximum burial of the Mussel Platform.

C. 50 Ma - immediately after inversion of the Mussel Platform.

D. The present-day



It is emphasised that the small number of modelling results presented here, while successfully predicting the known accumulations and the dry Conan-1 location, are dependent on the various assumptions concerning lithologies, thermal conductivities, source rock type and location, as well as the interpretation of the thermal history calibration data in terms of additional burial on the Maastrichtian unconformity. However, the available thermal history constraints are considered robust and the predictions of the time and extent of hydrocarbon generation, reliable. Migration directions, particularly along the Waarre Formation acting as a lateral carrier, and subsequent accumulation will clearly be influenced by our interpretation of inversion of the Mussel Platform.

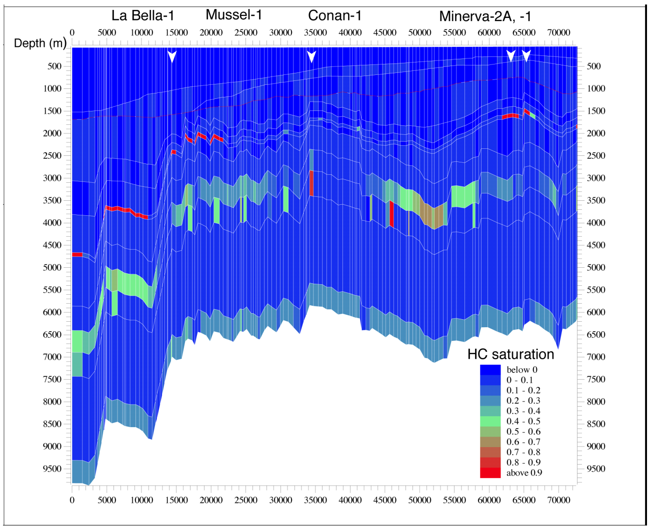


Figure 16. The modelled OE80A-1056 seismic section showing hydrocarbon saturation at the present-day. Accumulations in the Waarre Formation at the La Bella and Minerva locations are clearly seen, together with other potential accumulations in the tilted-fault blocks on the southern flank of the Mussel Platform and within the Voluta Trough. Confirmation of the lack of an accumulation at Conan-1 is also notable. Some saturation is present in the Eumeralla Formation source rock.

DISCUSSION AND CONCLUDING REMARKS

The new results from this preliminary study not only have significant implications for the structural history in the immediate area of the Mussel Platform and the local generation and migration of hydrocarbons in the eastern Otway Basin but also for the broader scale tectonic history associated with the protracted separation of Australia and Antarctica.

Hydrocarbon generation and migration from Eumeralla Formation source rocks commenced in the mid-Cretaceous but most of the products formed prior to Campanian were lost from the shallow Waarre Formation reservoirs. Accumulation in tilted fault block structures on the Mussel Platform is dominantly from the shallow Eumeralla Formation source rocks. La Bella-1 accumulations began in the Late Cretaceous, with product generated in the Voluta Trough to the SW. Accumulations in the Minerva structure were generated in the Shipwreck Trough, with a larger part of the charge emplaced since the Miocene, but with some charge migrating to the structure as early as the Maastrichtian.

Kilometre-scale uplift and erosion during the Maastrichtian-Paleocene interpreted from the AFTA and VR results at the Mussel-1 location, and from the VR and TAI data at Conan-1 is considered to reflect a widespread event effecting much of the Mussel Platform and at least some part of the Tasmanian west coast as suggested by the raw apatite fission track age results published by Dumitru et al. (1991). Inversion of the Mussel Platform exerts a significant control on the time of hydrocarbon generation from Eumeralla Formation source rocks and offers at least a partial explanation for the lack of a Waarre reservoir accumulation at Conan-1.

In this study, passive-margin thermal subsidence is considered to have begun in the Cenomanian, represented by the Sherbrook Group, with down to basin normal faulting attributed to local extension in a "strike-slip" regime and not to active, thermally driven rifting. Seismic evidence for significant transpressional structuring at the base-Tertiary unconformity was described by O'Callaghan (1993) in the vicinity of Eric the Red-1. Further south along the Sorell Fault zone, Hinz et al. (1986) attributed flower structures to Paleogene transpression and noted that "A huge sediment pile of largely Paleocene age was deposited locally in the Cape Sorell sub-Basin, probably as a result of transtension and rapid block subsidence in this part of the strike slip zone."

Thus the Maastrichtian unconformity is considered here to be represented by a series of localised inversions in a transpressional, strike-slip regime generated by significant mechanical interaction along the Sorell Fault Zone (Figure 1) between the Antarctic and Australian plates, due to the slow and perhaps punctuated opening on the southern ocean. Heat flow is considered to have been more or less similar to that measured at the present-day during the whole period since the Cenomanian, with no evidence for elevated basal heat flow driving a renewed period of rift-related crustal extension. The new results presented here provide further support for this view, but much additional work is needed to verify this conclusion, particularly the collection of complete VR profiles and additional AFTA results from the offshore eastern Otway Basin wells.

Several problems correlating published seismic picks with geological boundaries in the wells were noted during the course of the study and pointed to the need for additional litho- and biostratigraphic studies. The biostratigraphy of the Nirranda and Heytesbury Groups is urgently required to provide more accurate data on the burial induced heating rates since the Oligocene.

Only limited AFTA data was available for this study, and the sensitivity of the results of the complex interaction between thermal history and structuring highlights the need for additional accurate thermal history constraints incorporating VR and AFTA data, and the newly emerging (U-Th)/He technology which offers more precise control on the more recent thermal events in the basin's history.

Finally, this initial study uses only a generalised lithological distribution and generic source rock types. Future work should incorporate a more detailed lithofacies variation and specific source rock characteristics to enable modelling of the hydrocarbon composition and pressure distribution.

Acknowledgements

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