

# Basement and crustal structure of the Bonaparte and Browse basins, Australian northwest margin

Alexey Goncharov<sup>1</sup>

**Keywords:** North West Australian margin, Bonaparte and Browse basins, basement, crustal structure, seismic refraction.

## Abstract

The basement and crustal structure of the Bonaparte and Browse basins, which are located on the northwest Australian margin, are substantially different to each other. Depth conversion of the reflection seismic data, utilising calibration of stacking-derived velocities against those derived from ocean-bottom seismograph refraction/wide-angle reflection interpretation, suggests that the Bonaparte Basin contains up to 22 km of sediments compared to a maximum of 12–14 km in the Browse Basin. Despite the availability of high-quality seismic data, basement definition in the Bonaparte Basin is difficult, whereas it is relatively simpler in the Browse Basin. Sedimentation in the Bonaparte and Browse basins, unlike other basins on the northwest margin, was initiated in a region with a relatively thick crust. The two basins are located next to the Proterozoic Kimberley Block which has typical crustal thickness of ~40 km. This contrasts with the ~30 km crustal thickness beneath the Archaean Pilbara Block adjacent to the Carnarvon Basin. The relationship between the Moho and the basement in the Bonaparte Basin is unusual in that the deepest Moho is mapped directly beneath the deepest basement. The more typical inverse relationship between Moho topography and depth to basement is observed in the Browse Basin.

Crust adjacent to the outer boundary of the Browse Basin appears to be transitional, rather than oceanic. Generally, there appears to be an inverse correlation in the volcanic evolution of the northwest Australian margin. The presence of volcanics and intrusives in the upper crust is not accompanied by significant volumes of underplated lower crust (e.g., Scott Plateau). In contrast, the absence of significant volumes of upper crustal, magmatic material coincides spatially with underplated lower crust in the Roebuck/offshore Canning Basin. Underplating, which is often associated with large-scale extension of the crust, was not a major crustal forming event in either the Browse or Bonaparte basins.

## Introduction

The basement and its attendant architecture beneath the Bonaparte and Browse basins define the shape of the container in which the petroleum systems in the region evolved. In spite of the fact that these areas have been well-studied in regard to their petroleum prospectivity, relatively few studies have investigated the nature of basement and the crustal-scale processes in the area.

To address this, Geoscience Australia has undertaken an ocean-bottom seismograph (OBS) survey along the

northwest Australian margin to supplement the 35,000 km grid of deep reflection seismic studies, which have been acquired in the region (Goncharov *et al.*, 1998; Goncharov *et al.*, 2000a). The refraction/wide-angle reflection seismic data were recorded in the 1995–1996 OBS survey along five regional transects, with a total length of 2,764 km (Fig. 1). The project provided independent velocity information, so that depth conversion of the reflection profiles could be better constrained. Other objectives of the survey were to identify:

- the base of the sedimentary section, particularly in the deepest basins, where this cannot be resolved from the reflection profiles;
- major intra-crustal boundaries; and
- the crust-mantle boundary, so that changes in crustal thickness could be mapped.

Onshore recording stations were deployed together with the OBSs to link the offshore crustal structure with that onshore. All OBS transects (Fig. 1) coincided with previously recorded deep crustal reflection profiles (Fig. 2), thus enabling the joint analysis of both datasets.

In this paper, the main results of processing and interpretation of the OBS transects in the Bonaparte and Browse basins are presented, and are compared to the results of processing and interpretation of deep reflection data recorded along coincident profiles. Analysis of the entire northwest Australian Margin region was then undertaken to better understand the similarities and differences between the Bonaparte–Browse basins and other basins along the northwest Australian margin.

## Geological setting

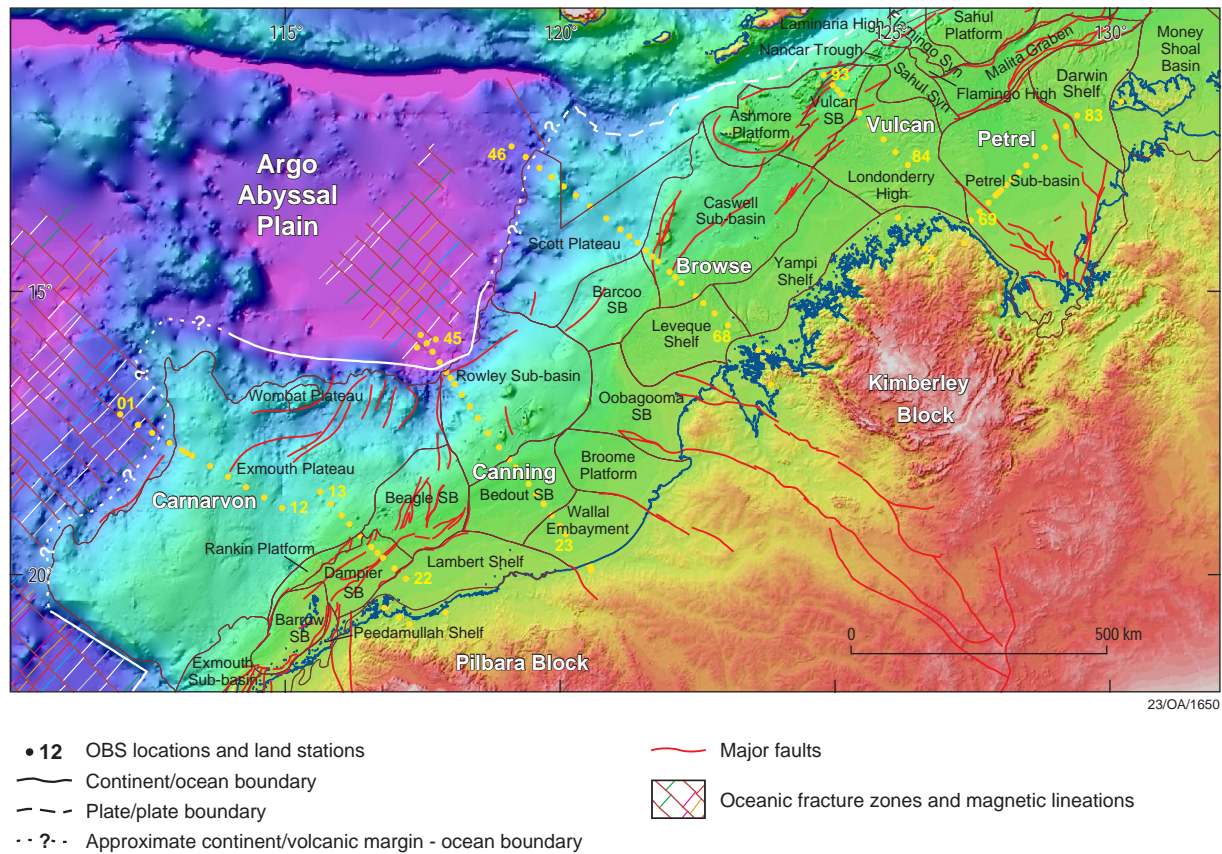
Australia's northwest margin is segmented into four discrete basins, which have distinct rift and reactivation histories (O'Brien *et al.*, 1999): the Carnarvon, offshore Canning/Roebuck, Browse and Bonaparte basins (Fig. 1). Of these basins, the Bonaparte Basin appears to have had the most complex history. This region is comprised of a number of sub-basin elements, which have widely varying ages and orientations (Fig. 1). Elements comprising the Bonaparte Basin, which are discussed in this paper, include the northwest-trending Palaeozoic Petrel Sub-basin and overprinting, Mesozoic elements such as the Malita Graben and Vulcan Sub-basin (O'Brien, 1993; O'Brien *et al.*, 1996, 1999).

The structural architecture of the entire northwest margin region is the product of a number of major tectonic events (AGSO North West Shelf Study Group, 1994) including:

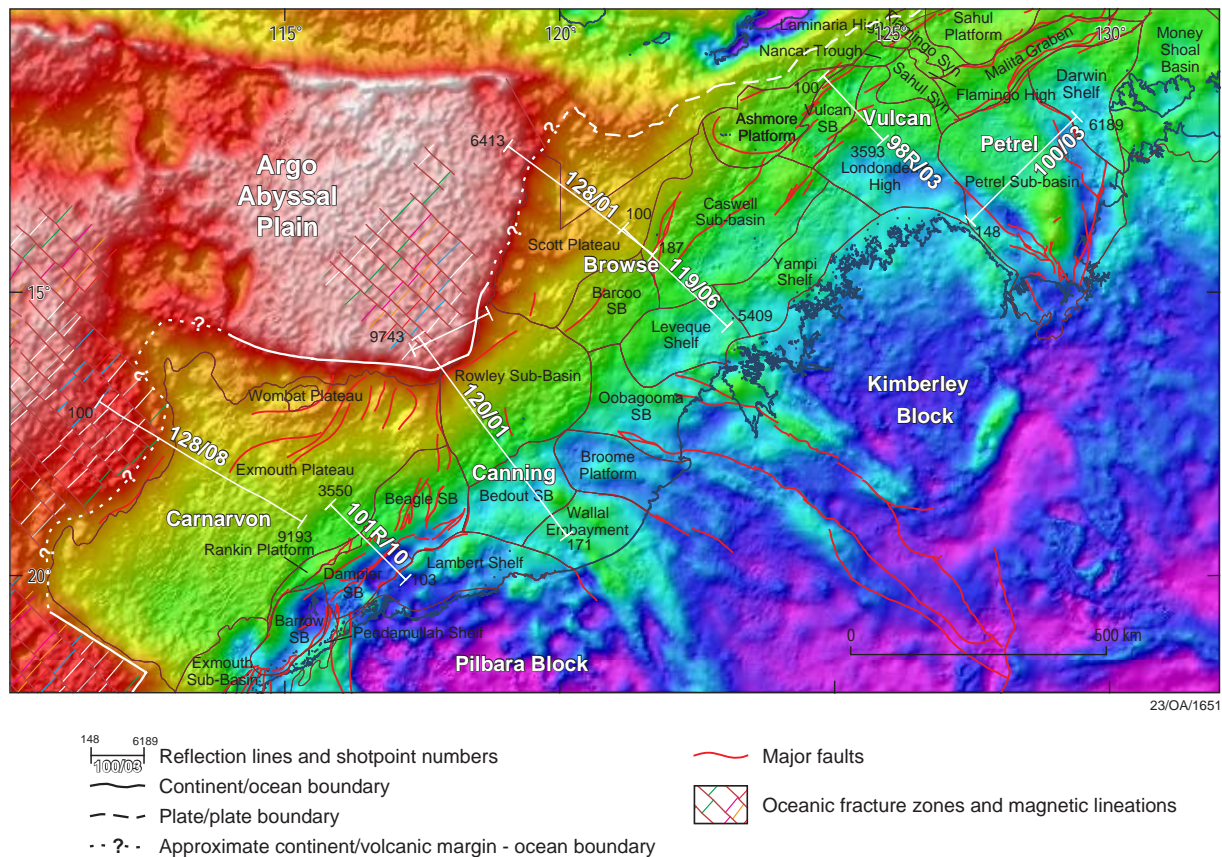
- Late Devonian northeast–southwest extension in the Petrel Sub-basin;

<sup>1</sup> Geoscience Australia, GPO Box 378, Canberra, ACT, 2601, Australia. Email: Alexey.Goncharov@ga.gov.au





**Figure 1.** Locations of Geoscience Australia's OBS profiles, major structural features, sub-basins and bathymetry of the Australian northwest margin.



**Figure 2.** Locations of Geoscience Australia's seismic reflection profiles coincident with the OBS profiles presented in Figure 1, major structural features, sub-basins and Bouguer gravity (at 2.67 g\*cm<sup>-3</sup> reduction density) of the Australian northwest margin. Shotpoint numbers are also plotted on top of each line in Figures 3, 4, 5 and 6.



- Late Carboniferous northwest–southeast extension in the proto-Malita Graben, Browse Basin and proto-Vulcan Sub-basin;
- Late Triassic north–south compression (Fitzroy Movement);
- Early–Middle Jurassic development of major depocentres in the Exmouth, Barrow and Dampier sub-basins, and extension in the Browse Basin;
- Middle–Late Jurassic breakup in the Argo Abyssal Plain, onset of thermal sag in the Browse Basin and extension in the Bonaparte Basin;
- Valanginian breakup in the Gascoyne and Cuvier abyssal plains, and onset of thermal sag in the Bonaparte Basin; and
- Late Miocene reactivation and flexural downwarp of the Timor Trough and Cartier Trough.

Many of these events may have involved processes of crustal extension (O'Brien *et al.*, 1999), and consequently, defining the style of crustal thinning related to extension is one of the purposes of this research.

Definition of basement in the region is critically important for understanding of crustal extension and basin formation. The Proterozoic Kimberley Basin and underlying Kimberley Block are generally regarded as basement to the Browse and Bonaparte basins (Symonds *et al.*, 1994). Onshore, the Kimberley Basin comprises 5–8 km of mildly deformed quartzose sandstone and other clastic rocks, tholeiitic basalts and dolerite sills, and is underlain by Archaean rocks of the Kimberley Block (Griffin and Grey, 1990; AGSO North West Shelf Study Group, 1994). The Kimberley Basin formed as a result of northeast-directed extension at ~1800 Ma, with associated west-northwest and northeast trends in fault sets (Etheridge and Wall, 1994). These fracture systems are ubiquitous in the Kimberley Block and continue offshore. O'Brien *et al.* (1996) suggested that both the development and architecture of the Palaeozoic to Mesozoic rift systems throughout the northern North West Shelf was controlled by these 'hard links' within the basement fabric.

Some difficulties in defining depth to Proterozoic basement in the Bonaparte and Browse basins are due to the presence of a thick Palaeozoic section, interpreted to have formed as a result of Late Devonian northeast–southwest extension in the Petrel Sub-basin (Gunn, 1988; O'Brien *et al.*, 1996) and Late Carboniferous to Lower Permian northwest–southeast extension in the proto-Malita Graben and proto-Vulcan Sub-basin (O'Brien, 1993; O'Brien *et al.*, 1996) and the Browse Basin (Struckmeyer *et al.*, 1998).

Thickness of the Palaeozoic section varies significantly between the Bonaparte and Browse basins: it may reach 18 km in the deepest part of the Petrel Sub-basin (Colwell and Kennard, 1996) compared to ~7 km in the Browse Basin (Struckmeyer *et al.*, 1998). Due to the great depth of burial of the Palaeozoic section, particularly in its lower part, a high degree of compaction is likely. As a result, seismic velocities in the lower part of the Palaeozoic succession may have become indistinguishable from those in the underlying Proterozoic basement. This may explain some of the difficulties in locating the true basement, as discussed in this paper.

## Data and interpretation

2D velocity models for individual profiles recorded in the OBS experiment, derived by forward modelling using the SIGMA ray-tracing software, which is based on the algorithm of Zelt and Smith (1992), were presented by Goncharov *et al.* (1998, 2000a); Pylypenko and Goncharov (2000); Fomin *et al.* (2000) and Petkovic *et al.* (2000). In this study, the velocity models for the Browse Basin, Vulcan Sub-basin and Petrel Sub-basin, originally developed in depth scale, were converted to two-way time to enable direct comparison with coincident reflection profiles (Figs 3, 4, 5, 6).

The deep seismic reflection data shown in the lower panels of Figures 3 to 6 were recorded by Geoscience Australia between 1990 and 1994, as part of a regional grid of 35,000 km of seismic lines. The collection of these data was aimed at investigating the structural framework of the northwest continental margin of Australia (AGSO North West Shelf Study Group, 1994). These data were initially interpreted by Geoscience Australia (e.g. Stagg and Colwell, 1994, Colwell and Stagg, 1994, Symonds *et al.*, 1994), and then integrated in collaboration with IKODA Pty Ltd. This latter work involved the consistent interpretation of 16 key horizons through the entire 35,000 km grid, supplemented in places by additional horizons depending upon the local geology, and the tying of over 100 petroleum exploration wells.

Of the 16 horizons mapped through the seismic reflection grid, six are of major significance in displaying the structural/tectonic architecture of the region and were therefore selected for integration and comparison with the velocity models developed along the coincident OBS transects. They are, from oldest to youngest:

1. "Basement": acoustic basement; in places, this horizon corresponds to crystalline or well-indurated Palaeozoic or Proterozoic "pre-rift" rocks.
2. Near top Permian: major regional carbonate marker bed produced by a widespread marine transgression.
3. Base of the Jurassic/top of the Triassic: major regional unconformity on structural highs, partly the result of regional north–south compression (Fitzroy Movement).
4. Callovian: widespread regional unconformity corresponding to continental breakup along the Argo Abyssal Plain margin.
5. Turonian: significant Late Cretaceous sequence boundary/global anoxic event.
6. Base of the Tertiary: major sequence boundary at the base of largely-prograding carbonate packages.

The main focus of this paper is on the basement and the crust beneath it. Clearly, acoustic (or 'reflection') basement, as defined above, may not correspond with the basement in a true geological sense (basement marks the bottom of non-metamorphosed sedimentary succession). Some remarkable mismatches resulting from this uncertainty will be discussed.

## Reflectivity of the crust and velocity models

The two major seismic technologies (reflection and refraction) used to image the crust of the Australian northwest margin 'measure' different properties of the crust. Imaging crustal reflectivity is a major aim of conventional seismic reflection

technology. These images are controlled by a combination of two factors: the stratification of the crust, and the spectrum of seismic signal penetrating the crust. Crustal stratification is determined by the thickness of layers and by contrasts in acoustic impedance (a product of density and velocity) between the layers. Layers of contrasting acoustic impedance may be of different thickness and they form various assemblages along a vertical profile through the crust.

Depending on in-phase or out-of-phase interference of reflections from individual boundaries, the total response of any depth interval may be amplified or attenuated. Therefore, thin layers (compared to a seismic wave length reaching hundreds of meters in the lower crust) can play a significant role in the formation of reflectivity pattern. Importantly, bulk seismic velocity above, beneath and even within finely stratified depth intervals, does not have to change significantly to produce a high-amplitude reflection response at near offsets.

Modern methods of velocity analysis in conventional reflection technology make use of the curvature of the reflection travel time curve. This curvature decreases rapidly with reflection time. As a result, sensitivity and accuracy of the velocity analysis degrade with depth. Consequently, in conventional reflection technology, seismic velocities are poorly constrained in the deep part of the crust.

In contrast, refraction/wide-angle reflection seismic technology utilises observations at much larger offsets than those available in conventional reflection studies, providing more accurate estimates of seismic velocity in the deep part of the crust. Due to the effects of fine (on a wavelength

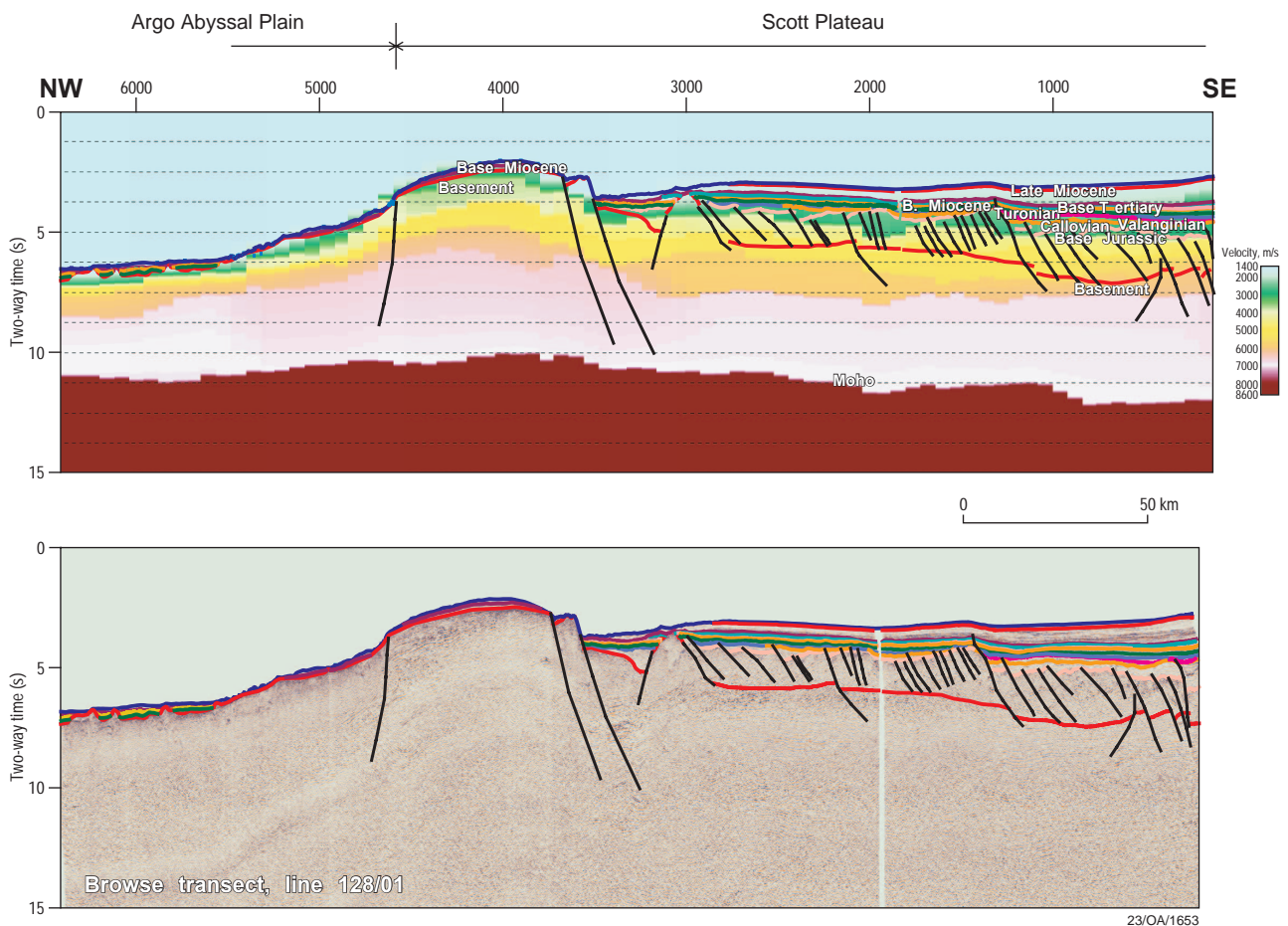
scale) velocity and density stratification of the crust, reflection horizons and changes in reflectivity patterns mapped by reflection technique will not necessarily coincide with velocity boundaries imaged by refraction/wide-angle reflection technology.

### *Browse Basin transect*

This transect incorporates two seismic lines: outer 128/01 (Fig. 3) and inner 119/06 (Fig. 4). These lines cross, from northwest to southeast: transition to oceanic crust imaged by the outer part of the profile 128/01 (Fig. 3), the Scott Plateau, the Browse Basin and the Proterozoic Kimberley Basin (Fig. 4).

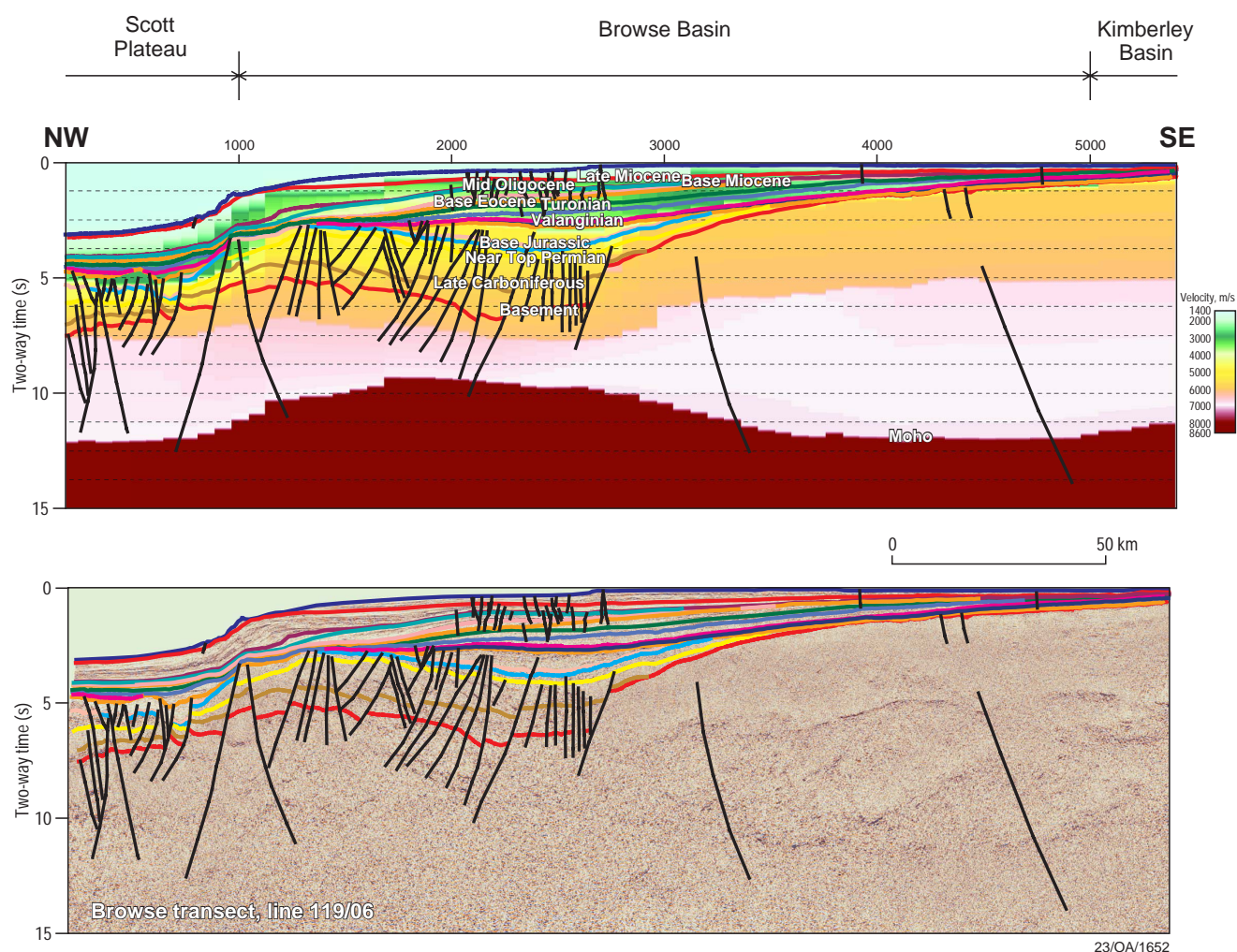
On line 119/06 (Fig. 4), the 'Basement' horizon shows little variation in velocity below it. It represents the top of the Kimberley Basin section and it generally conforms to 5.9–6.1 km/s iso-velocity contours, which is consistent with the basement definition on the joining part of the outer Browse line 128/01.

The 'Basement' horizon, interpreted from the reflection seismic data along the outer line 128/01, is characterised by significant velocity variation from ~6.0 km/s at shot points (SP) 100–1,000 to less than 3.0 km/s at SP 3,500 (Fig. 3). On the basis of velocity information, it is suggested that the true basement (bottom of non-metamorphosed sedimentary succession) to the northwest of SP 1,000 is located up to 2.5 s deeper than the 'Basement' horizon and probably follows the 6.0 km/s iso-velocity line. It is not clear how far towards the continent-ocean boundary this interpretation of



**Figure 3.** OBS-derived velocity model (upper panel) and seismic reflection section (lower panel) along the Browse line 128/01.





**Figure 4.** OBS-derived velocity model (upper panel) and seismic reflection section (lower panel) along the Browse line 119/06.

the basement can be extended. Such interpretation is more consistent with alternative interpretation of the reflection data along this line (Struckmeyer *et al.*, 1998).

The Browse Basin transect is the only one of the Australian northwest margin OBS transects where the expected inverse relationship between the depth to the Moho and depth to basement is observed. Maximum depression in the centre of the Browse Basin (SP 2,200–2,500, Fig. 4) corresponds to a clear Moho high beneath it. Reduction in total crustal thickness above that high is achieved by sub-equal thinning of both upper and lower crust (Fig. 4, upper panel).

#### ***Bonaparte Basin: Vulcan Sub-basin transect***

The most prominent structure imaged by the reflection data along this transect is the Cartier Trough and the basement low associated with it (SP 1,000–1,800, Fig. 5). Iso-velocity lines resulting from the interpretation of the OBS data are sub-horizontal beneath the trough and cut across reflection boundaries. Consequently, none of the reflection horizons is an iso-velocity surface.

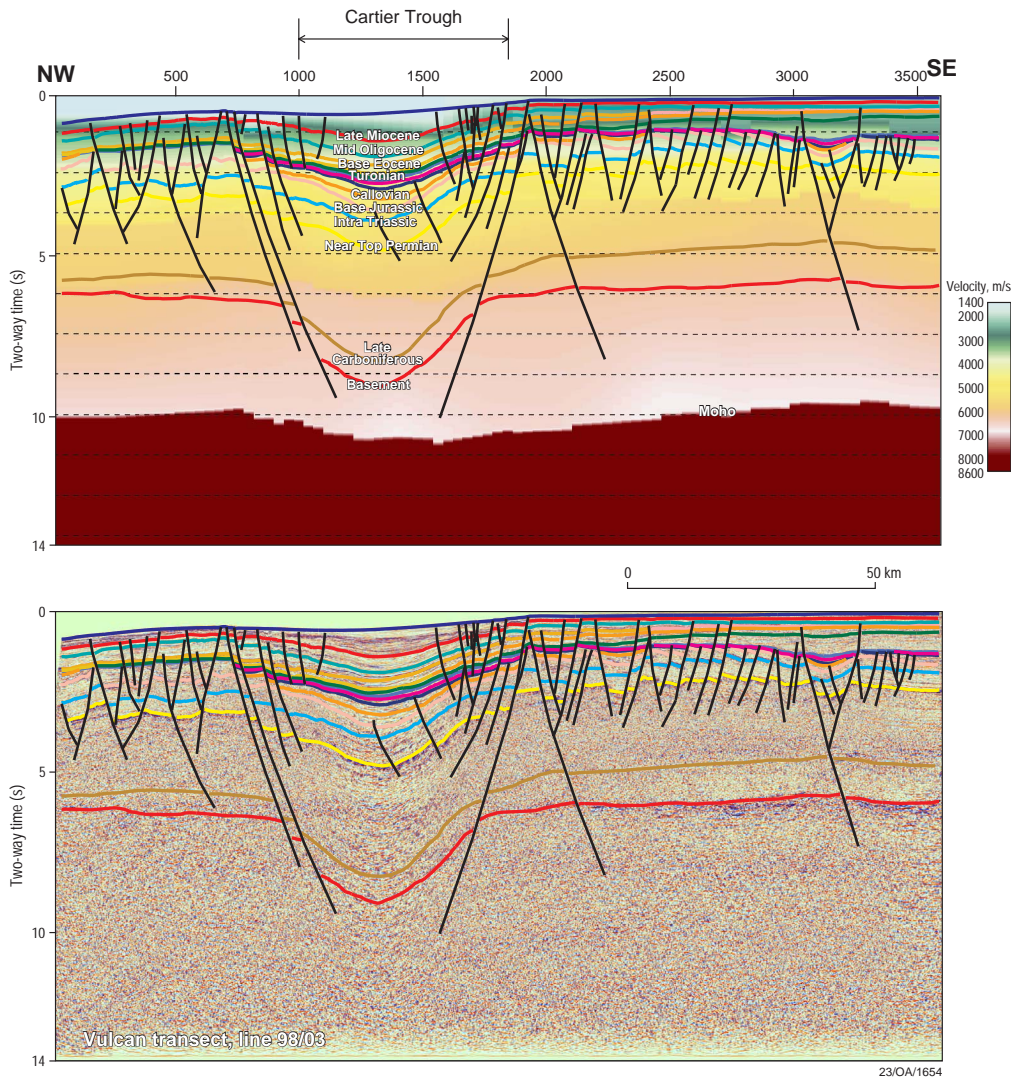
The ‘Basement’ horizon in the southeast part of the line corresponds to the prominent reflections at 6.0 s (Fig. 5, lower panel), but the OBS data show no significant velocity increase at this level (Fig. 5, lower panel). Therefore, the ‘6 s reflector’ on the Vulcan transect is most

likely to correspond to a finely stratified interval with several high- and low-velocity intervals, but bulk velocity below it does not increase significantly compared to the bulk velocity above it. Petkovic *et al.* (2000) have speculated that this feature may be a detachment surface, or sheet-like mafic intrusions. The question about the location of the true basement of sediments on the Vulcan transect cannot be unambiguously resolved on the basis of seismic data available.

However, according to the OBS-derived velocity model (Fig. 5, upper panel), seismic velocities at the depth level of the ‘6 s reflector’ (~6.2 km/s) suggest that this horizon is located close to the true base of sediments (top of the Precambrian Kimberley Basin), consistent with the earlier interpretation of Petkovic *et al.* (2000).

In the deep section beneath the Cartier Trough, the behaviour of iso-velocity contours is clearly not controlled by the structure imaged by the conventional reflection data. As a result, ‘reflection basement’ (red line, Fig. 5) and ‘refraction basement’ (change in colour from yellow to brown, Fig. 5, upper panel) deviate by as much as 2.5 s (~8.3 km). ‘Refraction basement’ is mapped not only by the velocity change, but also by a very distinct seismic phase recorded in the OBS experiment (Petkovic *et al.*, 2000).

One interpretation of this mismatch between the two ‘basements’ is to suggest that ‘refraction basement’ is the true base of the sedimentary succession, and the reflectivity



**Figure 5.** OBS-derived velocity model (upper panel) and seismic reflection section (lower panel) along the Vulcan line 98/03.

below it, which is clearly seen in the reflection image (Fig. 5, lower panel), is largely due to under-suppressed multiples and peg-legs. If this is correct, the reflection interpretation will overestimate depth to basement compared to the refraction interpretation. An alternative interpretation is that ‘reflection basement’ is the true base of sediments, and velocities in the lower part of the Palaeozoic section are indistinguishable from those characterising Precambrian basement to the southeast of the Cartier Trough, due to metamorphic changes at great depth.

Whichever interpretation is preferred, it is important to understand that accurate seismic velocity estimates below 6 s two-way time beneath the Cartier Trough suggest that this part of the section may have rock properties identical to those of the Precambrian basement interpreted to the southeast of the Cartier Trough. This conclusion may have a significant impact on the results of flexural isostatic modelling obtained before the accurate velocity model for the Vulcan Sub-basin transect has become available (Baxter *et al.*, 1997).

There is no evidence of the Moho in the reflection data (Fig. 5, lower panel). The OBS data contain very prominent Moho refractions and a significant velocity increase across the Moho (from 6.9 km/s in the lower crust to 8.1 km/s in the upper mantle) is required to explain these events (Petkovic *et al.*, 2000). The Moho, imaged as a change of colour from light- to dark-brown (Fig. 5, lower panel), deepens by ~1 s (3.5 km) under the Cartier Trough,

with a slight offset to the southeast. This observed behaviour of the Moho would not be predicted by commonly accepted models of crustal extension (McKenzie, 1978; Le Pichon and Sibuet, 1981).

#### *Bonaparte Basin: Petrel Sub-basin transect*

The unambiguous identification of basement in the reflection/refraction dataset in the Petrel Sub-basin is problematic, in a fashion similar to that described in the Vulcan Sub-basin transect above.

One of the most prominent events detected in the OBS data is the 6.0 km/s refractor, which was imaged not only by the travel time inversion, but also by the depth migration of the OBS data (Pylypenko and Goncharov, 2000). The 6.0 km/s refractor (corresponds to the change of colour from yellow to light brown in the upper panel of Fig. 6) shows rather poor correlation with the reflectivity of the crust imaged by the conventional reflection data, particularly in the centre of the line. It deviates significantly from the ‘Basement’ reflection horizon and cuts through the structure imaged by the reflection data. For example, near shot point 3,900, the 6.0 km/s refractor is ~2.5 s (7.7 km) shallower than the ‘Basement’ horizon. In fact, at this location the 6.0 km/s refractor coincides with the interpreted Late Carboniferous horizon (Fig. 6). Between shot points 2,500 and 4,500, the topography of the 6.0 km/s refractor conforms to that of the



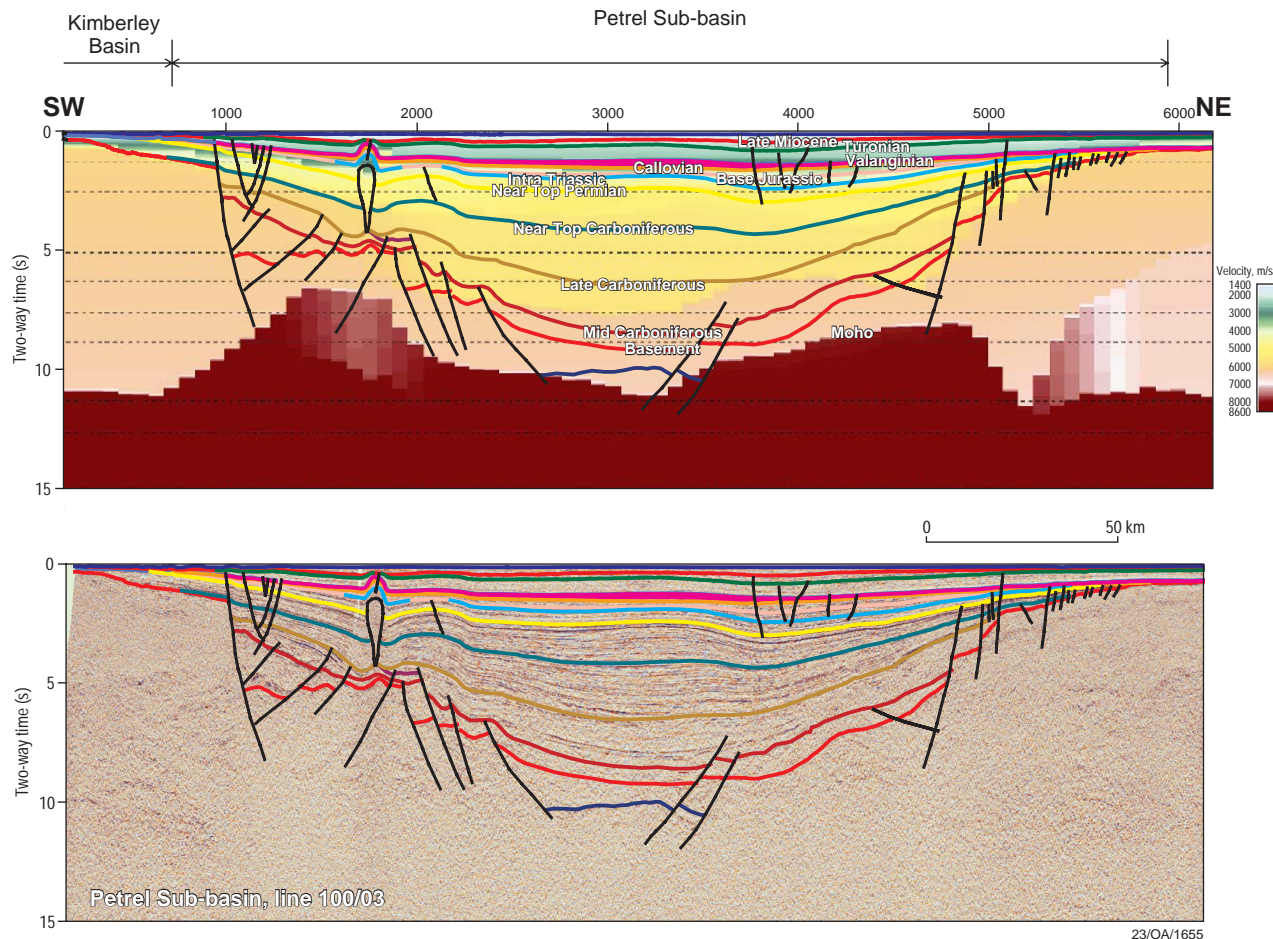
Moho (Fig. 6, upper panel). This observation suggests that the geological nature of the 6.0 km/s refractor is related somehow to the formation of the Moho topography. One possibility is to assume that the northeast high on the Moho (to the northeast of SP 3300) was formed after the deposition of the Late Carboniferous sediments, or even later. The presumed heat pulse associated with the formation of this prominent feature on the Moho might have produced some metamorphic change in the sediments above it, resulting in the gradual velocity increase with depth. If so, this velocity increase was superimposed on the original fine stratification of this part of the section. As a result, some reflections from this depth interval can still be observed (Fig. 6, lower panel), the origin of which is due to the fine stratification of the section. At large offsets, where the gradual changes in the bulk velocity become more important for the formation of the seismic response, high-amplitude refractions associated with the 6.0 km/s refractor are observed. This interpretation suggests that the 6.0 km/s refractor is the ‘high-velocity overprint’ rather than the base of the sedimentary succession.

Another possibility is that the 6.0 km/s refractor is the true base of the sedimentary pile. In that case, all reflectivity below it, including the middle Carboniferous and ‘Basement’ horizons (Fig. 6, lower panel), may represent under-suppressed multiples and peg-legs and therefore has no geological significance. High seismic velocities (higher than 5.0 km/s) and great depth of this part of the section favour this interpretation, because in such conditions it is difficult

to suppress multiples. However, more accurate modelling of seismic response, at near and large offsets, is required to determine which interpretation is the more likely.

If the 6.0 km/s refractor interpreted from the OBS data is taken to mark the bottom of sediments, then the maximum thickness of sediments along this line reaches 7.5 s (16 km) at SP 3,000, rather than 9.0 s (22 km) suggested by the interpretation of the reflection data. This is a significant difference that has to be considered when modelling the crustal extension in the Petrel Sub-basin. Earlier results of flexural isostatic modelling in the Petrel Sub-basin (Baxter, 1998) were based on the geometries defined purely by the reflection data, and have to be re-evaluated in the light of alternative interpretations presented in this paper. It is important to understand that basement-type physical properties can probably correspond to the deeper part of the sedimentary section, which was not taken into consideration when the results of Baxter (1998) were obtained.

Very little of the Moho is seen in the seismic reflection data. The only candidates, which could be Moho reflections, are some high-amplitude events at 9.0–11.0 s in the southwest part of the line (southwest of SP 1,000). Conversely, the OBS data document the Moho very well as a major velocity contrast (Fig. 6, upper panel). Sharp topography on the Moho, with two local highs reaching the amplitude of 10 km, is probably the most remarkable feature of the seismic velocity model along this line. In the earlier interpretation of this transect, which was based on



**Figure 6.** OBS-derived velocity model (upper panel) and seismic reflection section (lower panel) along the Petrel line 100/03.

geometries defined by reflection data and gravity modelling (Colwell and Kennard, 1996), flatter Moho was proposed. However, significant volumes of underplating and mafic intrusion into the lower crust are required to fill in the equivalents of the 'Moho highs' in the velocity model presented here.

The relationship between the Moho and the basement (regardless of whether the 'reflection' or 'refraction' definition of the basement is preferred) along this line is somewhat unexpected, in light of conventional ideas about crustal extension (McKenzie, 1978; Le Pichon and Sibuet, 1981). The deepest Moho is mapped directly beneath the deepest basement, although conventional models of crustal extension suggest an inverse topography relationship between these two boundaries. It is also worth noting that the two local Moho highs correspond to the steepest slopes of the basement as it approaches its deepest location in the centre of the basin (Fig. 6). A pre-existing zone of weakness in the crust is required to reproduce these observations in modelling crustal extension (Frederiksen and Braun, 2001; Frederiksen and Braun, 2001, personal communication).

## Depth to basement

### Approach

Two separate issues affect the definition of depth to basement. One is the difference in velocity characterisation of basement overburden coming from CDP reflection and OBS refraction/wide-angle datasets (Goncharov *et al.*, 2000a). Because conventional reflection technology constrains velocities in the deep part of the crust poorly, OBS-derived velocities are preferred for depth conversion of the basement and other deep horizons.

The second issue, which follows from the previous discussion for individual transects in the Bonaparte and Browse basins, relates to differences in the identification of basement in reflection and refraction datasets.

OBS-defined basement ('refraction basement') and OBS-derived velocities are available only for a few profiles in the Bonaparte and Browse basins. However, despite the limited OBS coverage, the results of this experiment are invaluable, because they provide an estimate of uncertainty of the depth to reflection- and refraction-defined basement.

Compilation and co-analysis of reflection stacking-derived and OBS-derived velocities enable much more accurate depth conversion of interpreted reflection horizons than the one illustrated above. In this study, only the reflection basement was depth-converted utilising calibration of reflection stacking-derived velocities against OBS-derived velocities. However, both the data compiled and approach developed enable depth conversion of any interpreted reflection horizons in the region.

Figure 7 shows the correlation between depth to basement, estimated from depth conversion of reflection basement using both stacking-derived and OBS-derived velocities. Approximately 2,000 selected locations at six coincident reflection/OBS profiles (including the four discussed above in the Bonaparte and Browse basins) were analysed to calculate linear regressions for individual profiles (Fig. 7).

The general rule, obviously followed in most cases below 5 km depth (Fig. 7), is that depth conversion based on

stacking-derived velocities over-estimates depth to basement. For example, a depth of 20 km estimated from OBS-derived velocities would translate into 25 km if stacking-derived velocities were used in the Petrel Sub-basin, resulting in a 25% overestimate.

Clearly, several less continuous trends can be detected in Figure 7, or even non-linear approximations may be considered for some areas (eg. Canning transect, Fig. 7b). However, the origin and spatial limits of applicability of corresponding regressions remain poorly understood at this stage and they were not used for depth conversion. Linear regressions are defined by the general equation:

$$(\text{Depth @ stacking-derived velocities}) = A \times (\text{Depth @ OBS-derived velocities}) + B$$

Spatial and two-way time limits of applicability of 6 main individual regressions presented in Figure 7 are illustrated in Table 1, as well as the values of coefficients *A* and *B*.

Depth conversion using these regression formulae leads to a maximum error of depth conversion of  $\pm 2$  km (Fig. 7). These six continuous linear regressions were utilised to calculate depth to reflection basement for all seismic lines in the region (Fig. 8).

### Results

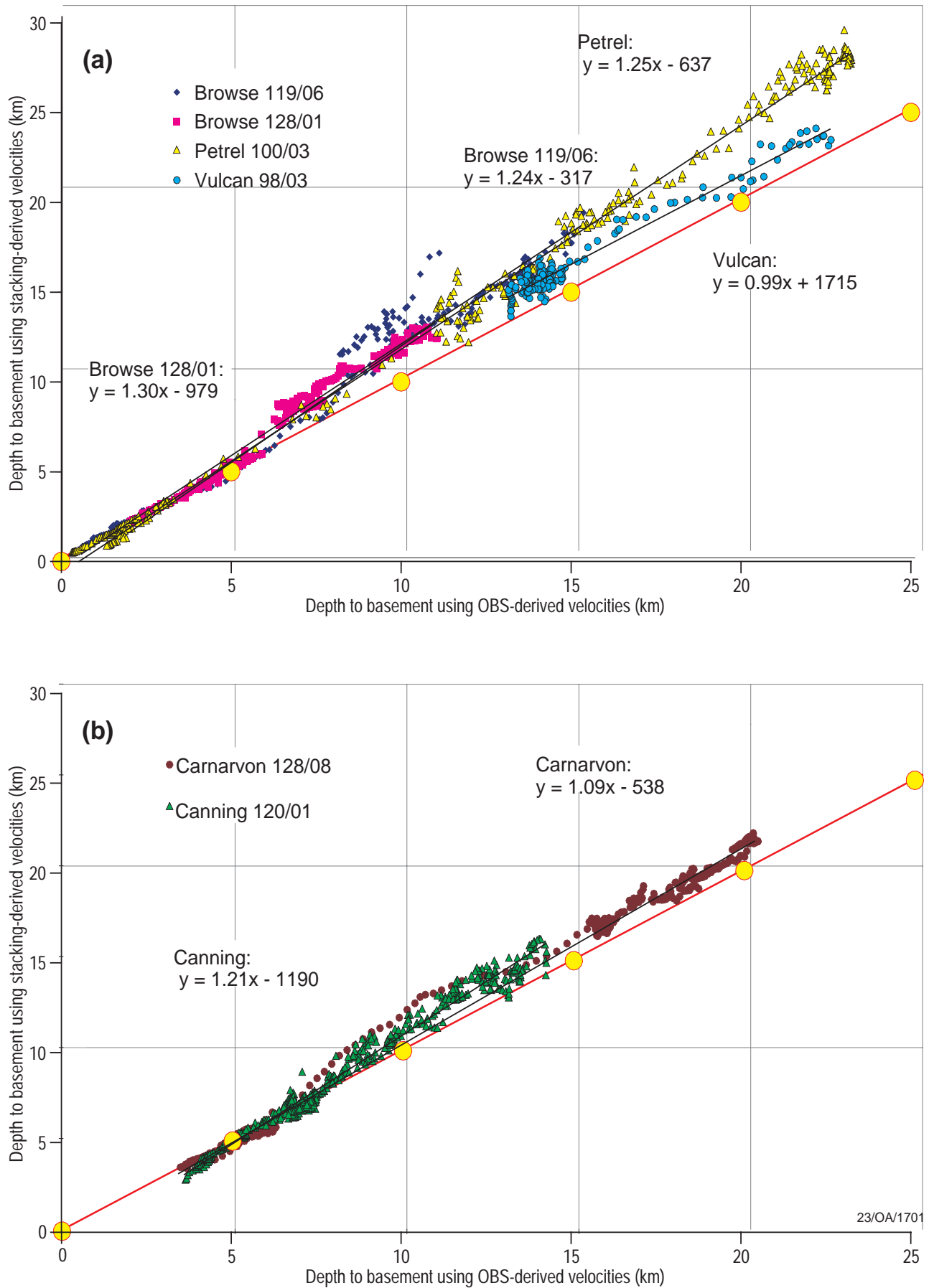
The resulting map of total sediment thickness at the Australian northwest margin shows that the Bonaparte Basin has up to 22 km of sediments compared to a maximum of 12–14 km in the Browse Basin (Fig. 8). The thickest sediments in the Browse Basin are present in the inboard part of the Caswell Sub-basin. The central part of the Barcoo Sub-basin contains in excess of 12 km of sediments, similar to the Caswell Sub-basin. The thickest sediments in the Bonaparte Basin occur within the Petrel Sub-basin, Sahul Syncline, Vulcan Sub-basin, Cartier Trough and Malita Graben. Maximum sediment thicknesses in the Sahul Syncline and Petrel Sub-basin are similar, up to 22 km.

At the level of the basement horizon, the inboard part of the Caswell Sub-basin appears to be continuous with the Vulcan Sub-basin. This southwest–northeast-oriented structure is broadly outlined by the 10 km sediment isopach (Fig. 8). Sediment thickness increases along the strike of this structure from 12 to 18 km.

It is important to estimate the possible differences in depth to basement due to different identification of basement using reflection versus refraction data. Again, it is necessary to emphasise that acoustic (or 'reflection') basement identified in the reflection data interpretation is not necessarily the basement in a true geological sense. Discussion below gives an indication of the magnitude of the uncertainty in total sediment thickness estimate arising from this ambiguity in identification.

The uncertainty due to differences in identification of basement in reflection and refraction datasets, as illustrated in Figures 3, 4, 5 and 6, varies from 0–2.5 s two-way time on the Petrel, Vulcan and outer Browse lines. Larger uncertainties are evident on the Scott Plateau, in the deepest part of the Cartier Trough, and to the northeast of the depocentre in the Petrel Sub-basin (at ~SP 3,900).





**Figure 7.** Correlation of depth to reflection basement calculated using stacking-derived and OBS-derived velocities in (a) the Bonaparte-Browse area, and (b) the Carnarvon-Roebeck-Canning area. Red line with yellow dots represents the 'no distortion' trend: points located above (below) it result from overestimation (underestimation) of depth at CDP stacking-derived velocities. Linear regressions presented in the charts were used to calculate sediment thickness presented in Figure 9. Reflection basement corresponds to red horizon in Figures 3, 4, 5 and 6.

Zone	Area	Limits	Coefficients	
			<i>A</i>	<i>B</i>
1	Carnarvon Basin	West of 117°E	1.09	-538
2	Canning Basin	117–120°E	1.21	-1190
3	North Browse Basin	120–121°E	1.30	-979
4	South Browse Basin	121–124°E	1.24	-317
5	Vulcan Sub-basin deeper than 11 km	Deeper than 11 km within the limits 124–127°E	0.99	1715
6	Petrel Sub-basin and Vulcan Sub-basin shallower than 11 km	Shallower than 11 km within the limits 124–127°E; all area east of 127°E	1.25	-637

**Table 1.** Subdivision of the Australian northwest margin into zones for basement depth conversion, utilising regressions between depth to basement, estimated at stacking-derived and at OBS-derived velocities.

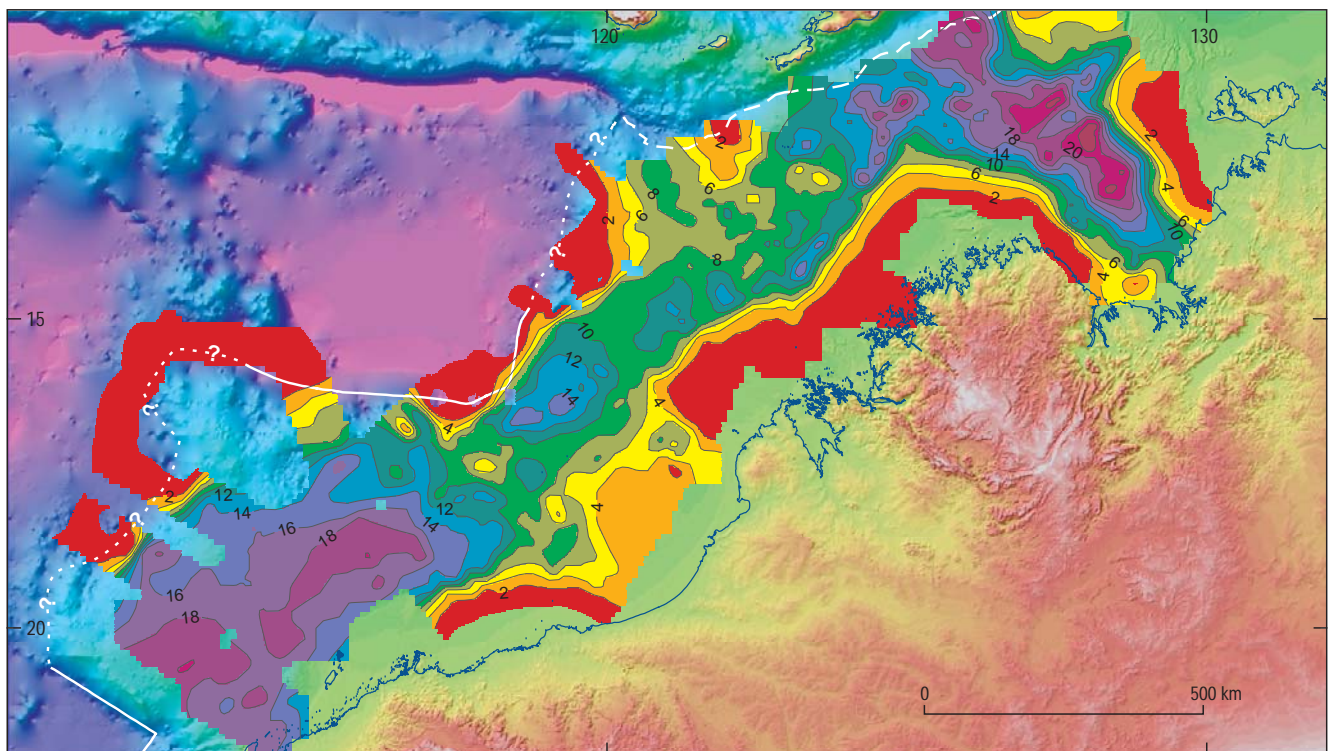
Unlike the effect of depth conversion using CDP stacking-derived velocities, which for depths below ~5 km result in erroneously deep basement depth estimates, ‘refraction’ basement can be shallower (Vulcan and Petrel transects, Figs 5 and 6) or deeper (outer Browse line, Fig. 3) than ‘reflection’ basement. The maximum depth deviation between ‘reflection’ and ‘refraction’ basement may reach  $\pm 8.0$  km in the Bonaparte and Browse basins.

### Crustal types and thickness of the crust

Crustal types in the Bonaparte-Browse region change from continental to transitional. The outer part of the Browse Basin

transect extended beyond the continent-ocean boundary identified on the basis of reflection seismic data interpretation (Sayers *et al.*, 2002), but it is unclear if it went into true oceanic crust. Crustal thickness in the Bonaparte-Browse region reduces seawards from ~38 km near the coast to 12 km (Fig. 9).

Australian northwest margin-wide analysis shows that the thinnest continental crust (28–29 km) onshore occurs near the coast at the Archaean Pilbara Block (Fig. 9). The thickest crust (38–45 km) is beneath the Proterozoic Kimberley Block. The zone of relatively thick continental crust associated with the Kimberley Block extends into the Browse and offshore Canning basins. The rate of crustal thinning of the Australian northwest margin varies



23/OA/1702

- Continent/ocean boundary
- - - Plate/plate boundary
- · ? · · Approximate continent/volcanic margin - ocean boundary

**Figure 8.** Total sediment thickness (km) at the Australian northwest margin.



significantly, with the most rapid thinning to the southeast of the continent-ocean boundary in the Rowley Sub-basin (Fig. 9). In this region, the crust thins from 34 to 13 km over a distance of ~100 km. The thinnest oceanic crust (8 km) is under the Argo Abyssal Plain.

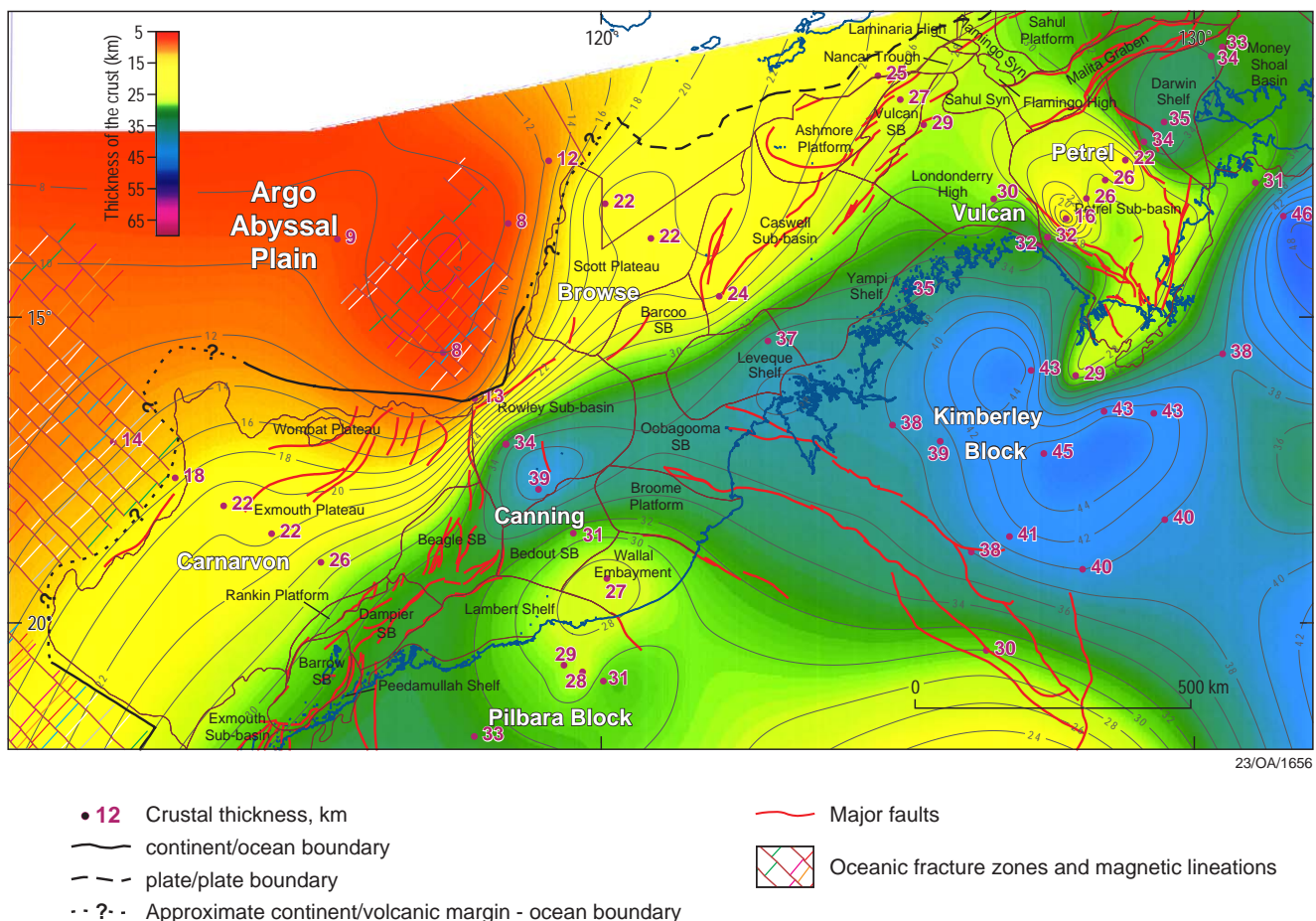
Generally, oceanic crust adjacent to the outer boundary of the Australian northwest margin (Fig. 10) is considerably thicker (9–13 km) and has lower velocities than in the global average model of oceanic crust (White *et al.*, 1992). The Carnarvon and Browse basins are characterised by particularly low velocities in the oceanic crust adjacent to their outer boundaries. Only on the Canning transect, along the northwestern margin of the Rowley Sub-basin, does oceanic crust approach the global average model of White *et al.* (1992). Velocity-depth functions characterising oceanic crust in the Carnarvon and Browse transects are intermediate between the global average oceanic and water depth-adjusted continental models (Fig. 10). Velocities typical for rocks of pure gabbro-type bulk geochemistry, estimated by the petrophysical modelling technique of Sobolev and Babeyko (1994), are considerably higher than those observed on the Carnarvon and Browse oceanic segments (Fig. 10). Therefore, based on velocity characteristics, the crust imaged by the outer parts of the Carnarvon, Browse and, to a lesser degree, Canning basin transects is not oceanic but rather transitional.

The results of this research enable some refinement of earlier ideas (O'Brien *et al.*, 1999) about the crustal thickness patterns in the region. On the basis of different bathymetric

expressions of the Bonaparte and Carnarvon compartments as opposed to the Browse and Canning compartments, O'Brien *et al.* (1999) suggested that these compartments belong to two distinctly different extensional systems: wide and narrow. The Bonaparte and Carnarvon compartments represent wide extensional systems, and the Canning and Browse compartments represent narrow extensional systems.

However, the present crustal thickness map (Fig. 9) suggests otherwise. The Browse compartment appears to follow the same trend of crustal thinning as the Carnarvon. The most rapid crustal thinning is detected in the Canning compartment (beneath the Rowley Sub-basin) and in the inshore margins of the Petrel Sub-basin. Therefore, from a crustal thickness perspective, wide extensional systems, marked by gradual crustal thinning, include the Carnarvon and Browse compartments. The Canning compartment certainly represents a narrow extensional system (rapid crustal thinning beneath the Rowley Sub-basin), as does the Petrel Sub-basin. There is insufficient crustal thickness data in the western part of the Bonaparte Basin (Vulcan Sub-basin) to reliably distinguish it from the Browse compartment, and accordingly it also appears to represent a wide extensional system (gradually thinned crustal region). The bathymetric compartments recognised by O'Brien *et al.* (1999) thus do not represent crustal thickness compartments.

The most obvious explanation to this is that variation in bathymetric load is not entirely compensated by opposite variation in crustal thickness over the same distance. Strength



**Figure 9.** Crustal thickness (km) of the Australian northwest margin and sub-basin outlines. Magenta dots show the locations where the Moho depth (km) was defined to produce a digital grid, supplemented by onshore and sonobuoy data from Collins (1991) and Collins and Drummond (2000).

of the crust appears to be sufficient to distribute compensating effect of rapid water depth changes over broader region (e.g. in the Browse compartment).

Also, in contrast to the underlying assumption of O'Brien *et al.* (1999), the present analysis suggests that pre-extensional crustal thickness was very different in different parts of the Australian northwest margin, ranging from less than 30 km underneath the Pilbara Block to more than 40 km underneath the Kimberley Block. Therefore, the Browse Basin adjacent to the Kimberley Block started to evolve in a thick crustal environment.

Finally, O'Brien *et al.* (1999) argued in favour of ~7 km thickness limit for extended crust at the point of continental breakup and formation of thin and rigid oceanic crust. The present analysis suggests that the extended crust at the time of breakup was considerably thicker (12–18 km, Fig. 9) and that the oceanic crust that formed adjacent to the Australian northwest margin was also thicker than global average models suggest (Fig. 10).

This can probably be explained by a low temperature regime that existed at the final stages of crustal extension, leading to the margin breakup and formation of oceanic crust. Under low temperature conditions, thicker crust is likely to break up, compared to break up occurring under a high temperature regime, when extending crust remains

sufficiently strong, even in the range of 7–12 km thickness. Under high temperature conditions, crust becomes more ductile and can become thinner in the process of extension before the break up occurs.

### Implications for volcanic evolution

A recent regional study of volcanic and magmatic manifestations of the entire Australian northwest margin has confirmed the presence of an extensive magmatic province, characterised by flood basalts, sill/dyke intrusions and high velocity lower crustal bodies interpreted to represent a combination of magmatic underplating and crustal intrusion. The nature, distribution and volume of the magmatic features have led to a classification of the margin as a transitional- or intermediate-type volcanic margin (Symonds *et al.*, 1998).

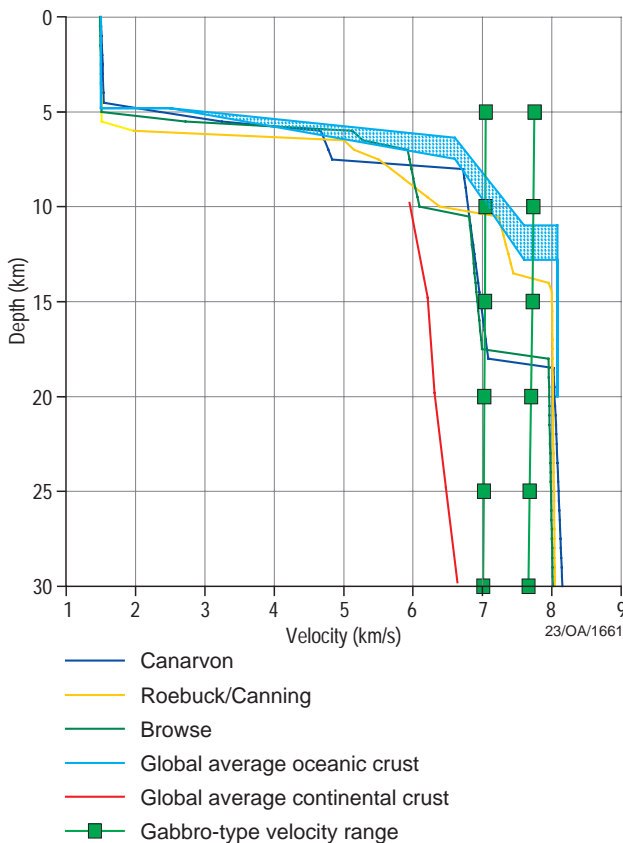
More specifically, in the Bonaparte/Browse region, the Scott Plateau is arguably the most compelling example of magmatic processes contributing significantly to the formation of the crust. Basalts have been dredged on the northern Scott Plateau, and landward flow subaerial basalts have been intersected by a number of wells in the Browse Basin. Lava flows have been interpreted in the northern Rowley Sub-basin, adjacent to the Scott Plateau in the west (Fig. 1). Three main volcanic provinces and facies types have been identified in reflection seismic data on the Argo margin segment, and are mainly associated with the Scott Plateau and northern Rowley Sub-basin:

- landward facies related to subaerial flood basalts in the southern Barcoo Sub-basin and throughout the Browse Basin;
- a rifted volcanic zone consisting of extensive flows, buildups and intrusives over much of the inner and central Scott Plateau; and
- a transition zone on the outer edge of the Scott Plateau consisting of volcanics and faulted continental blocks.

Many of the wells in the Browse Basin penetrated subaerial volcanics reaching several hundreds metres in thickness (Symonds *et al.*, 1998). Beneath the Scott Plateau, the landward lava flows cover an area of more than 20,000 km<sup>2</sup> and reach ~800 m in thickness. Stacking-derived interval velocities in these landward lava flows are ~4 km/s. In some instances (line 128/02, fig. 9 in Symonds *et al.*, 1998), total thickness of lava flows reaches ~3 km.

An overall conclusion of this brief summary is that the Argo margin has clearly been affected by voluminous magmatism that has modified and covered much of the Scott Plateau, and spread into the Browse Basin. The various volcanic facies and features produced extend throughout a 400 km-wide zone, and appear to have been emplaced around the time of Argo breakup in the Oxfordian (Symonds *et al.*, 1998).

Indications of volcanics in the Browse Basin velocity refraction model (Struckmeyer *et al.*, 1998) are somewhat uncertain because of the velocity value overlap between volcanics and host sediments in the upper 10 km of the crust. Intrusives in this part of the section are also difficult to detect on the basis of velocity information. Velocity of ~5.0 km/s in the upper part of intrusive body is close to the velocity at the bottom of overlying volcanics; velocity



**Figure 10.** Seismic velocity models of oceanic crust at the outer parts of the Browse, Roebuck-Canning and Carnarvon transects compared to global average models of oceanic (White *et al.*, 1992) and continental (Christensen and Mooney, 1995) crust. Global average models of oceanic crust are represented by a range of values limited by  $\pm$  one standard deviation from the median value at each depth level. A 4.8 km-thick water layer has been added at the top of the global average model of continental crust to enable comparison with oceanic models. Gabbro-type velocities as predicted by petrophysical modelling technique of Sobolev and Babeyko (1994).



of  $\sim 5.9$  km/s in the lower part of the intrusive body is undistinguishable from that typical for underlying basement. Only the presence of reliable indications of volcanics and intrusives in the reflection data enabled inclusion of the intrusives into the OBS-derived velocity model. The total thickness of interpreted volcanics and intrusives underneath the Scott Plateau, based on combined reflection and OBS data, reaches 5 km.

Finally, the possible presence of underplated crust in the region has to be addressed. Underplating of the extended continental crust can be suggested as one of the main crustal-forming processes in the region. Underplating can be defined as addition of mafic material at the bottom of the crust resulting from partial upper mantle melting during major tectonic episodes. It is important to evaluate if the OBS-derived velocity models show any evidence of underplated lower crust in the Bonaparte and Browse basins.

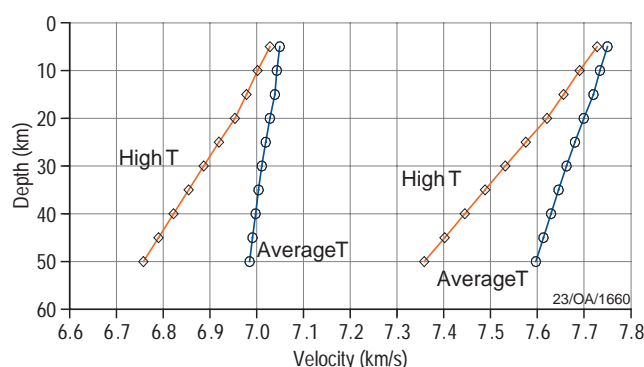
To answer a question about the possible presence of underplated material in the lower crust, an estimate of what seismic velocities would correspond to rocks of the gabbro-type bulk geochemistry under the modern pressure and temperature conditions in the region needs to be made. To interpret seismic velocities at any depth level in terms of the composition of the crust, the petrophysical modelling technique of Sobolev and Babeyko (1994) is utilised. This method predicts seismic velocities at depth for a range of assumed crustal compositions. Firstly, however, the effect of present day temperatures in the crust on seismic velocity needs to be accounted for.

The whole Australian northwest margin can be broadly subdivided into two domains – average and high heat-flow domains, according to the present day heat-flow distribution (Cull, 1991 supplemented by Cox, 2001, personal communication; Beardsmore and Altmann, 2002). The northeast Carnarvon, offshore Canning, Roebuck and southwest Browse basins, where the heat flow typically varies from 30–50 mWm<sup>-2</sup>, were included in the average heat-flow domain. The southwest Carnarvon, northeast Browse and Bonaparte basins, with heat flow in excess of 60 mWm<sup>-2</sup>, were included in the high heat-flow domain.

Geotherms proposed by Christensen and Mooney (1995) for average and high heat-flow conditions were utilised to define the seismic velocity ranges for gabbro-type rocks (Fig. 11 and Table 2).

Scans of the OBS-derived velocity models searching for the velocity values predicted by this technique and summarised in Table 2 do not reveal significant volumes of rocks with gabbro-type composition in the Bonaparte and Browse basins (Fig. 12).

Therefore, it is concluded that underplating was not a major crustal-forming event in this region. It was noted earlier (Symonds *et al.*, 1998) that little evidence of underplating is



**Figure 11.** Ranges of seismic velocities corresponding to gabbro-type rock composition under high and average temperature conditions of Christensen and Mooney (1995). Only the curves for end-member gabbros predicted by petrophysical modelling technique of Sobolev and Babeyko (1994) are presented, illustrating the lowest and highest possible velocity values at each depth.

particularly surprising for the Scott Plateau, given the significant magmatic character of this part of the Argo margin, deduced from reflection seismic and well data.

For comparison, the possible presence of gabbro-type rock is noticeable in the velocity scans of the Carnarvon Basin line 128/08 in depth ranges 10–20 km and 20–30 km, and in the velocity scans of the Canning Basin line 120/01 (Fig. 12). It is particularly interesting that the velocity model of the Roebuck and offshore Canning basins gives a clear indication of underplated material in the lower crust (Figs 12b, c and Goncharov *et al.*, 2000b). Upper crustal manifestations of volcano-magmatic activity in this region are poor (Symonds *et al.*, 1998).

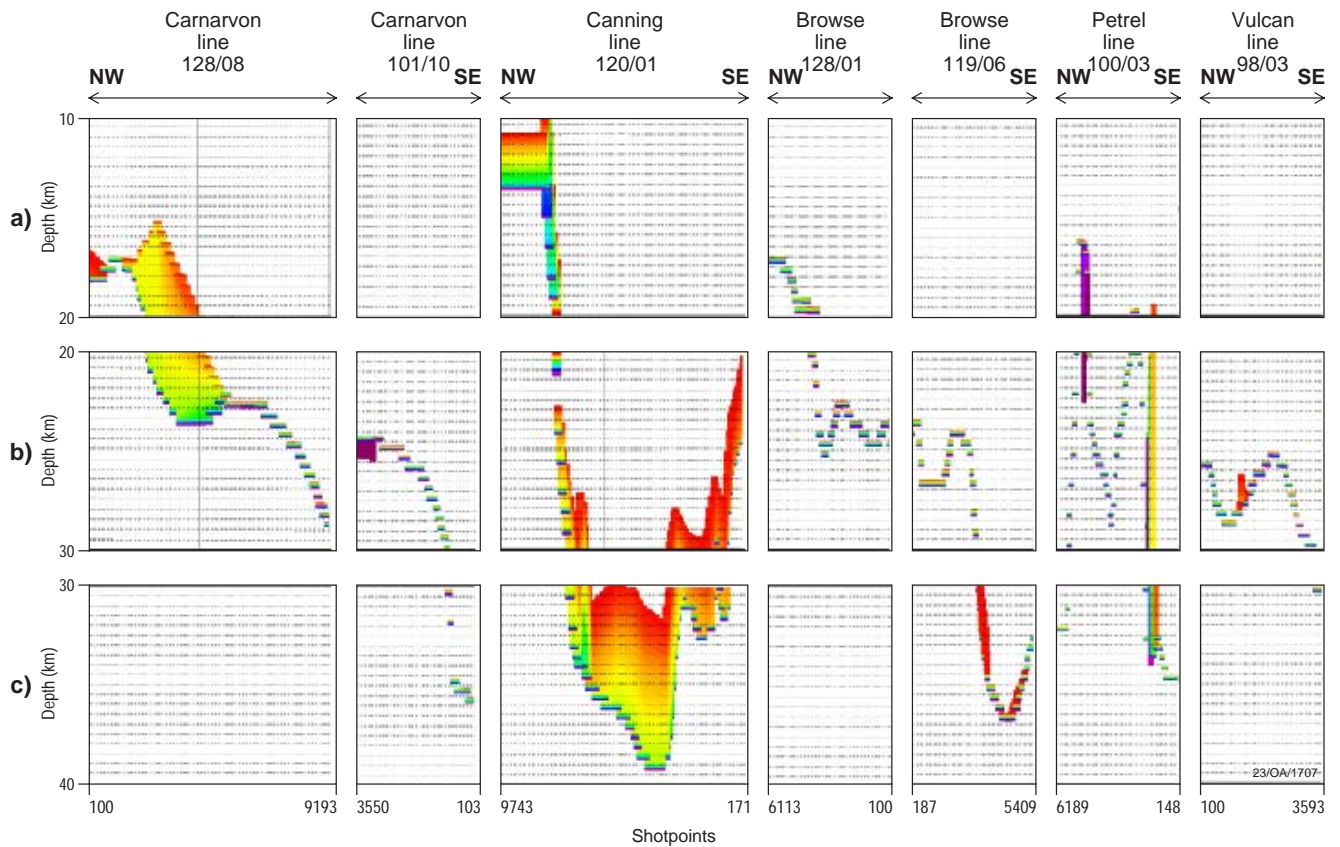
Therefore, there appears to be an inverse correlation in the volcanic evolution of the region: the presence of volcanics and intrusives in the upper crust is not accompanied by significant volume of underplated lower crust (e.g. Scott Plateau). In contrast, the absence of significant volumes of upper crustal magmatic material spatially coincides with underplated lower crust (e.g. Roebuck and offshore Canning basins).

## Conclusions

Basement is a difficult target for deep reflection profiling. In some cases (Browse Basin), velocity information derived from the OBS studies has helped to better define it, whereas some problems with basement identification remain unresolved in the Petrel and Vulcan sub-basins. One of the two options of basement definition on the Petrel Sub-basin transect leads to a decrease in estimated maximum total thickness of sediments from  $\sim 22$  km, suggested by the interpretation of the reflection data, to  $\sim 14$  km, if the velocity-based definition is preferred.

Depth range (km)	High heat-flow domain (SW Carnarvon, NE Browse and Bonaparte basins)	Average heat-flow domain (NE Carnarvon, offshore Canning, Roebuck and SW Browse basins)
10–20	6.98–7.66	7.04–7.72
20–30	6.92–7.57	7.02–7.68
30–40	6.85–7.48	7.00–7.65

**Table 2.** Upper and lower velocity limits (km/s) for gabbro-type rocks in different depth ranges under different temperature regimes, as predicted by petrophysical modelling technique of Sobolev and Babeyko (1994).



**Figure 12.** Seismic velocity scans of the OBS-derived models of individual profiles in depth ranges (a) 10–20 km, (b) 20–30 km and (c) 30–40 km. Upper and lower velocity limits for each scan are summarised in Table 2. Coloured areas represent possible gabbro-type rocks.

Accurate OBS-derived velocity models provide an invaluable source for calibration of CDP stacking-derived velocities for the purposes of depth conversion of deep seismic data. This calibration has been used to produce a map of depth to ‘reflection’ basement identified on ~35,000 km of seismic lines for the entire Australian northwest margin. The maximum possible overestimate of depth to basement, if uncorrected CDP stacking-derived velocities are used for depth conversion, may reach 25% for depths in excess of 20 km.

This study suggests that underplating, which is often associated with large-scale extension of the crust, was not a major crustal forming event in Bonaparte and Browse basins. Close spatial association of underplated crust with the narrow/high gradient type of margin in the Canning Basin, where rapidly necked crust was detected underneath the Rowley Sub-basin, leads to a suggestion that rapid thinning of the crust is a condition required for underplating to be triggered. In other basins, where the extension is more distributed, underplating has not happened, probably due to a different, probably higher temperature regime that existed there at the time of the extension.

Mostly, there are very poor manifestations of the Moho in the reflection data at the Australian northwest margin. OBS-derived velocity models have proven to be an invaluable source of information about the Moho. Crustal types in the Bonaparte–Browse region change from continental to transitional. The OBS data indicate that crust adjacent to the outer boundary of the Browse Basin is not purely oceanic, but rather transitional. This is similar to the Carnarvon, and, to a lesser degree, the Roebuck margins. Crustal thickness

in the Bonaparte–Browse region reduces oceanwards from ~38 to 12 km.

The results of this research enable some refinement of earlier ideas about the crustal thickness patterns in the region (O’Brien *et al.*, 1999). From a crustal thickness perspective, wide extensional systems, marked by gradual crustal thinning, include the Carnarvon and Browse compartments. The Canning compartment represents a narrow extensional system (rapid crustal thinning beneath the Rowley Sub-basin), as does the Petrel Sub-basin. The Vulcan Sub-basin appears to represent a wide extensional system (gradually thinned crustal region). The bathymetric compartments identified by O’Brien *et al.* (1999) thus do not appear to represent crustal thickness compartments, probably due to a significant effect of crustal strength on the style of isostatic compensation.

In the Bonaparte Basin, depth to Moho increases with increasing depth to basement, although conventional models of crustal extension suggest otherwise. The Browse Basin displays the conventional inverse relationship between depth to Moho and depth to basement. On the Petrel Sub-basin transect, local Moho highs correspond to the steepest slopes of the basement. These observations have to be accounted for by models of crustal extension.

### Acknowledgments

Tanya Fomin, Alexander Kritski, Peter Petkovic, Clive Collins and Jacques Sayers processed and interpreted the OBS data and developed original velocity models for individual transects in the Carnarvon, offshore Canning/Roebuck, Vulcan and Browse basins. Jim Colwell and John Kennard



contributed to the interpretation of the reflection data and provided summaries of their work for this paper. I thank Clive Collins, Jim Colwell, John Kennard, Peter Petkovic, Barry Willcox and Heike Struckmeyer for reviewing earlier versions of the manuscript, and Michael Morse for producing bathymetry and gravity field images. Brian Hack provided technical support in figures design. Thoughtful reviews by Geoffrey W. O'Brien and Peter Baillie helped me to improve the paper after its presentation at the Timor Sea Symposium. The paper is published with the permission of the Chief Executive Officer, Geoscience Australia. The Geoscience Australia Catalogue reference number for this paper is 41976.

## References

- AGSO NORTH WEST SHELF STUDY GROUP, 1994, Deep reflections on the North West Shelf: Changing perceptions of basin formation. In: Purcell, P.G and R.R. (Eds), 1994, *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1994, 63–76.
- BAXTER, K., COOPER, G.T., O'BRIEN, G.W., HILL, K.C. AND STURROCK, S., 1997, Flexural isostatic modeling as a constraint on basin evolution, the development of sediment systems and palaeo-heat flow: Application to the Vulcan Sub-basin, Timor Sea. *The APPEA Journal*, 37(1), 136–153.
- BAXTER, K., 1998, The role of small-scale extensional faulting in the evolution of basin geometries. An example from the late Palaeozoic Petrel Sub-basin, northwest Australia. *Tectonophysics*, 287, 21–41.
- BEARDSMORE, G.R. AND ALTMANN, M.J., 2002, A heat flow map of the Dampier Sub-basin. In: Keep, M. and Moss, S.J. (Eds), 2002, *The Sedimentary Basins of Western Australia 3: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 2002, 641–659.
- CHRISTENSEN, N.I. AND MOONEY, W.D., 1995, Seismic velocity structure and composition of the continental crust: a global review. *Journal of Geophysical Research*, 100, 9,761–9,788.
- COLLINS, C.D.N., 1991, The nature of the crust-mantle boundary under Australia from seismic evidence. In: Drummond B.J. (Ed.), *The Australian Lithosphere*. Geological Society of Australia Special Publication, 17, 67–80.
- COLLINS, C.D.N. AND DRUMMOND, B.J., 2000, Crustal thickness patterns in the Australian continent. In: Skilbeck, C.G. and Hubble, T.C.T. (Eds), *Understanding Planet Earth: Searching for a Sustainable Future*. 15th Australian Geological Convention 59, 91.
- COLWELL, J.B. AND STAGG, H.M.J., 1994, Structure of the Offshore Canning Basin: First impressions from a new regional deep-seismic data set. In: Purcell, P.G and R.R. (Eds), 1994, *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1994, 757–768.
- COLWELL, J.B. AND KENNARD, J.M. (EDS.), 1996, Petrel Sub-basin study 1995–1996: summary report. *The AGSO Record* 1996/40, 1996, 122p.
- CULL, J.P., 1991, Geothermal gradients in Australia. In: Drummond B.J. (Ed.), *The Australian Lithosphere*, Geological Society of Australia Special Publication, 17, 147–155.
- ETHERIDGE, M.A. AND WALL, V.J., 1994, Tectonic and structural evolution of the Australian Proterozoic. 12<sup>th</sup> Australian Geological Convention, 20–26 September 1994, Perth, Geological Society of Australia, Abstracts No. 37, 102–103.
- FOMIN, T., GONCHAROV, A., SYMONDS, P. AND COLLINS, C., 2000, Acoustic structure and seismic velocities in the Carnarvon Basin, Australian North West Shelf: towards an integrated study. *Exploration Geophysics*, 31, 579–583.
- FREDERIKSEN, S. AND BRAUN, J., 2001, Numerical modelling of strain localisation during extension of the continental lithosphere. *Earth and Planetary Science Letters*, 188, 241–251.
- GONCHAROV, A., COLLINS, C., PETKOVIC, P., FOMIN, T., PILIPENKO, V., DRUMMOND, B. AND LEE, C.S., 1998, Ocean-bottom seismograph and conventional reflection surveys in the Petrel Sub-basin: an integrated seismic study. *Exploration Geophysics*, 29, 384–390.
- GONCHAROV, A., O'BRIEN, G. AND DRUMMOND, B., 2000a, Seismic velocities in the North West Shelf region, Australia, from near-vertical and wide-angle reflection and refraction studies. *Exploration Geophysics*, 31, 347–352.
- GONCHAROV, A., KENNARD, J., COLWELL, J., FOMIN, T., KRITSKI, A., PETKOVIC, P., SYMONDS, P. AND SAYERS, J., 2000b, Towards improved understanding of the deep structure of the Australian North West Margin from combined refraction/reflection seismic studies. In: Skilbeck, C.G and Hubble, T.C.T. (Eds), *Understanding Planet Earth: Searching for a Sustainable Future*. Abstracts of the 15<sup>th</sup> Australian Geological Convention, 181.
- GRIFFIN, T.J. AND GREY, K., 1990, Kimberley Basin, In: *Geology and Mineral Resources of Western Australia*. Geological Survey of Western Australia Memoir, 3, 293–304.
- GUNN, P.J., 1988, Bonaparte Basin: evolution and structural framework. In: Purcell P.G and R.R. (Eds), 1988, *The North West Shelf, Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1988, 275–285.
- LE PICHON, X. AND SIBUET, J.C., 1981, Passive margins: a model of formation. *Journal of Geophysical Research*, 86, 3,708–3,720.
- McKENZIE, D.P., 1978, Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, 40, 25–32.
- O'BRIEN, G.W., 1993, Some ideas on the rifting history of the Timor Sea from the integration of deep crustal seismic and other data. *PESA Journal*, 21, 95–113.
- O'BRIEN, G.W., HIGGINS, R., SYMONDS, P.E., QUAIFFE, P., COLWELL, J. AND BLEVIN, J., 1996, Basement control on the development of extensional systems in Australia's Timor Sea: an example of hybrid hard-linked/soft-linked faulting? *The APPEA Journal*, 36(1), 161–201.
- O'BRIEN, G.W., MORSE, M., WILSON, D., QUAIFFE, P., COLWELL, J., HIGGINS, R. AND FOSTER, C.B., 1999, Margin-scale, basement involved compartmentalisation of Australia's North West Shelf: a primary control on basin-scale rift, depositional and reactivation histories. *The APPEA Journal*, 39, 40–63.

- PETKOVIC, P., COLLINS, C.D.N. AND FINLAYSON, D.M., 2000, A crustal transect between Precambrian Australia and the Timor Trough across the Vulcan Sub-basin. *Tectonophysics*, 329, 23–38.
- PYLYPENKO, V. AND GONCHAROV, A., 2000, Seismic migration in near-vertical and wide-angle reflection and refraction studies: Towards a unified approach. *Exploration Geophysics*, 31, 461–468.
- SAYERS, J., BORISSOVA, I., RAMSAY, D. AND SYMONDS, P.A., 2002, Geological framework of the Wallaby Plateau and adjacent areas. *Geoscience Australia Record* 2002/21.
- SOBOLEV, S.V. AND BABEYKO, A. Yu., 1994, Modelling of mineralogical composition, density and elastic wave velocities in anhydrous magmatic rocks. *Surveys in Geophysics*, 15, 515–544.
- STAGG, H.M.W. AND COLWELL, J.B., 1994, The structural foundations of the Northern Carnarvon Basin. In: Purcell, P.G. and R.R. (Eds), 1994, *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1994, 349–364.
- STRUCKMEYER, H.I.M., BLEVIN, J.E., SAYERS, J., TOTTERDELL, J.M., BAXTER, K. AND CATHRO, D.L., 1998, Structural evolution of the Browse Basin, North West Shelf: new concepts from deep seismic data. In: Purcell P.G. and R.R. (Eds), 1998, *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1998, 345–367.
- SYMONDS, P.A., COLLINS, C.D.N. AND BRADSHAW, J., 1994, Deep structure of the Browse Basin: implications for basin development and petroleum exploration. In: Purcell P.G. and R.R. (Eds), 1994, *The Sedimentary Basins of Western Australia: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1994, 315–331.
- SYMONDS, P.A., PLANKE, S., FREY, O. AND SKOGSEID, J., 1998, Volcanic evolution of the Western Australian Continental Margin and its Implications for Basin Development. In: Purcell P.G. and R.R. (Eds), 1998, *The Sedimentary Basins of Western Australia 2: Proceedings of the Petroleum Exploration Society of Australia Symposium*, Perth, WA, 1998, 33–54.
- WHITE, R.S., MCKENZIE, D. AND O'NIONS, R.K., 1992, Oceanic crustal thickness from seismic measurements and rare Earth element inversions. *Journal of Geophysical Research*, 97, 19,683–19,715.
- ZELT, C.A. AND SMITH, R.B., 1992, Seismic travel time inversion for 2-D crustal velocity structure. *Geophysical Journal International*, 108, 16–34.



**Alexey Goncharov** holds a PhD degree in Geophysics from the St Petersburg Mining Institute in Russia. His original research interests were mostly in studying the structure of the crust and upper mantle by various seismic methods. Alexey started his work processing and interpreting seismic data from the Baltic Shield, later he was involved in the seismic part of the unique super deep drilling project at the Kola peninsula in Russia. Teaching geophysics to students was Alexey's primary occupation for a number of years. In 1994, Alexey came to Australia where his research interests outgrew the bounds of Precambrian crust and he expanded his original seismic orientation to petrological interpretation of seismic data and potential field analysis. Alexey's main research projects in Australia have been deep crustal studies of the Mount Isa Inlier, ocean-bottom seismograph studies at the Australian northwest margin, integration of reflection and refraction/wide-angle seismic results at the

Australian northwest margin, production and analysis of unique gravity and magnetics grids for the continental margin of the Australian Antarctic Territory. Since 2001, Alexey has been a project leader of Basement and Crustal Studies at Geoscience Australia's Petroleum and Marine Division.