Crustal reflectivity and bulk seismic velocity: how close is the relationship?

Alexey Goncharov[1], Peter Petkovic[1], Tanya Fomin[2], & Phil Symonds[1]

Ocean-bottom seismograph (OBS) data acquired on Australia's North West Shelf suggest that prominent seismic reflectors and changes in reflectivity patterns in conventional reflection data do not necessarily correspond to significant bulk-velocity discontinuities. If conventional reflection surveys are not supplemented by refraction/wide-angle reflection seismic studies, erroneous interpretations are inevitable.

Technological considerations

Imaging crustal reflectivity is a major aim of conventional seismic reflection technology. These images are controlled by a combination of two factors: stratification of the crust, and the spectrum of seismic signal penetrating the ground.

Crustal stratification is determined by thicknesses of layers and by contrasts in acoustic impedance (a product of density and velocity) between 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, usually hundreds of metres in the lower crust) can play a prominent role in the formation of reflectivity pattern.

Importantly, bulk seismic velocity above, beneath, and even within finely stratified (in terms of acoustic impedance) depth intervals can remain unchanged, to produce a high-amplitude reflection response at near-offsets.

We have little independent information about thin density stratification of the crust, particularly in its deep part, and variations in acoustic impedance are commonly attributed to variations in seismic velocity alone. The underlying assumption for this is that there is some form of correlation between density and velocity, and, if one parameter (velocity) changes, the other parameter (density) will change proportionally.

Therefore, the effectiveness of seismic studies depends critically on how well we know seismic velocity in the ground. Modern methods of velocity analysis in conventional reflection technology predominantly make use of the curvature of the reflection travel time curve. This curvature decreases rapidly with reflection time, so that the deeper we go in the crust the less sensitive and less accurate velocity analysis becomes. Consequently, in conventional reflection technology, seismic velocities are poorly constrained in the deep part of the crust.

Conversely, refraction/wide-angle reflection seismic technology utilises observations at much larger offsets than those in conventional reflection studies. As a result, it can provide much more accurate estimates of seismic velocity in the deep part of the crust.

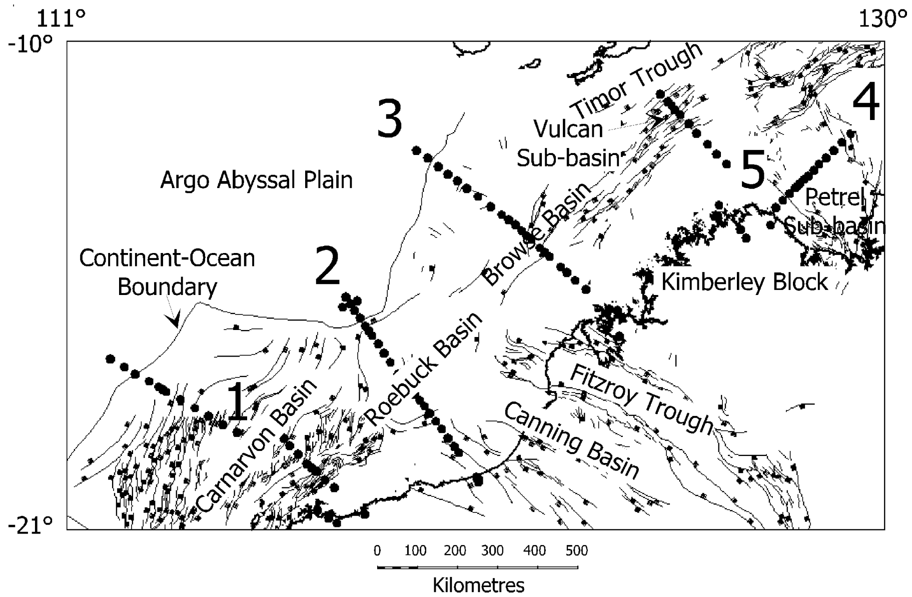

Fig. 9. Locations of the profiles in the AGSO OBS experiment, and major structural features, North West Shelf. Dots show the locations of the OBS stations. The lines are numbered: 1, Carnarvon; 2, Canning; 3, Browse; 4, Petrel; 5, Vulcan.

AGSO's OBS experiment

To realise this advantage, AGSO recorded high-quality refraction and wide-angle reflection seismic data to maximum offsets of 300 km on OBSs along five profiles on Australia's North West Shelf in 1995 (cf. AUSGEO News 49, for December 1998, 8–9). All OBS transects (Fig. 9) coincided with previously acquired deep-crustal reflection profiles.

The experiment revealed that crustal reflectivity imaged by conventional reflection data does not correlate universally with crustal velocity distribution derived from the refraction/wide-angle reflection seismic data.

Petrel line

For this line, a conventional travel-time-based interpretation of the OBS data (Goncharov et al. 1998: Exploration Geophysics, 29, 384–390) was supplemented by depth migration of the recorded wave field. Our migration technique (Pylypenko 1982: in: A.S. Alekseyev, Editor, 'Application of numerical methods in studies of the lithosphere' [in Russian], Novosibirsk, Siberian Branch of the Academy of Sciences USSR, 144–154), based on both the kinematic and dynamic characteristics of the wave field recorded at large offsets, presented refraction/wide-angle seismic data in the same style as the conventional reflection data.

Such processing provided images of several refracting boundaries for the Petrel line. The 6.0-km/s refractor (B in Fig. 10) correlates poorly with the reflectivity of the crust imaged by the conventional reflection data in the centre of the line. It deviates markedly from the high-amplitude reflective band (RB), and cuts through the structure imaged by the reflection data. According to the reflectivity pattern, the RB event may represent the crystalline basement.

The 6.0-km/s refractor in the after-stack image (Fig. 10a) comprises prominent events evident in both original data and pre-stack depth-migrated images for several OBSs. The coherent stacking of several individually migrated datasets producing the image of this refractor confirms the integrity of our velocity model. Ray-tracing through this velocity model produces computed travel times which correlate well with those recorded in the experiment. Therefore, both travel-time-based interpretation and depth migration of the same dataset in this part of the section are consistent.

Consequently, the origin of the events marked RB in the conventional reflection dataset (Fig. 10b) and some other events above that level cannot be explained by changes in bulk-velocity distribution.

Vulcan line

The velocity model for the Vulcan line (Fig. 11a) has boundaries and isovelocity lines incongruent with the structure identified in the conventional reflection section (Fig. 11b). The top of the lower-crustal velocity-model layer 7 is near the prominent reflections at 6 s TWT, but the OBS data show no significant velocity increase (only ~200m/s) at this level. Even more incongruous, subhorizontal velocity-model layer boundaries and isovelocity lines cut across reflection boundaries beneath the Cartier Trough. Away from the trough, bulk velocity at the depth level of the near-top-Permian reflections (~2s TWT) is ~4 km/s. Closer to the centre of the trough, where the same reflections are recorded at ~5 s TWT, velocity increases to ~5.5 km/s (Fig. 11).

Prominent Moho refractions (not shown) in the wide-angle OBS data imply a velocity increase from 6.9 to 8.1 km/s. Yet the vertical reflectivity associated with the Moho is weak (Fig. 11b).

Carnarvon line

A travel-time-based interpretation of the data for this line gives a velocity model with six major layers (Fig. 12a).

Before the OBS experiment, we based a preliminary geological interpretation of the coincident reflection line primarily on the reflectivity pattern, and on the limited velocity information from expanding-spread profiles (ESP) 150–250 km southwest of the line (Mutter et al. 1989: Geology, 17, 8–15). Accordingly, we identified the upper, middle, and lower crust, the top of underplating, and the Moho (Fig. 12c). The upper crust, apparently block-faulted, has subparallel to parallel reflectors showing mainly horizontal layering. The middle crust is characterised by discontinuous, undulatory, high-amplitude reflectors. The lower crust is transparent. Underplating was deduced from reflectivity pattern, not from velocity estimates. The top of the underplated layer was taken to coincide with a band of low-frequency, very high-amplitude reflectors 13–17 km deep (one of the most prominent features in Fig. 12c). From the ESP results, we estimated the P-wave velocity below these prominent reflectors to be ≥7 km/s. High-amplitude discontinuous events or a weak band of reflectors ~14 km deep, primarily in the northwest part of the line (beneath oceanic crust), represent the Moho.

This interpretation shows some conformity with the new OBS-derived velocity model — for example, the interpreted base of the middle crust is close to the boundary between layers with velocities

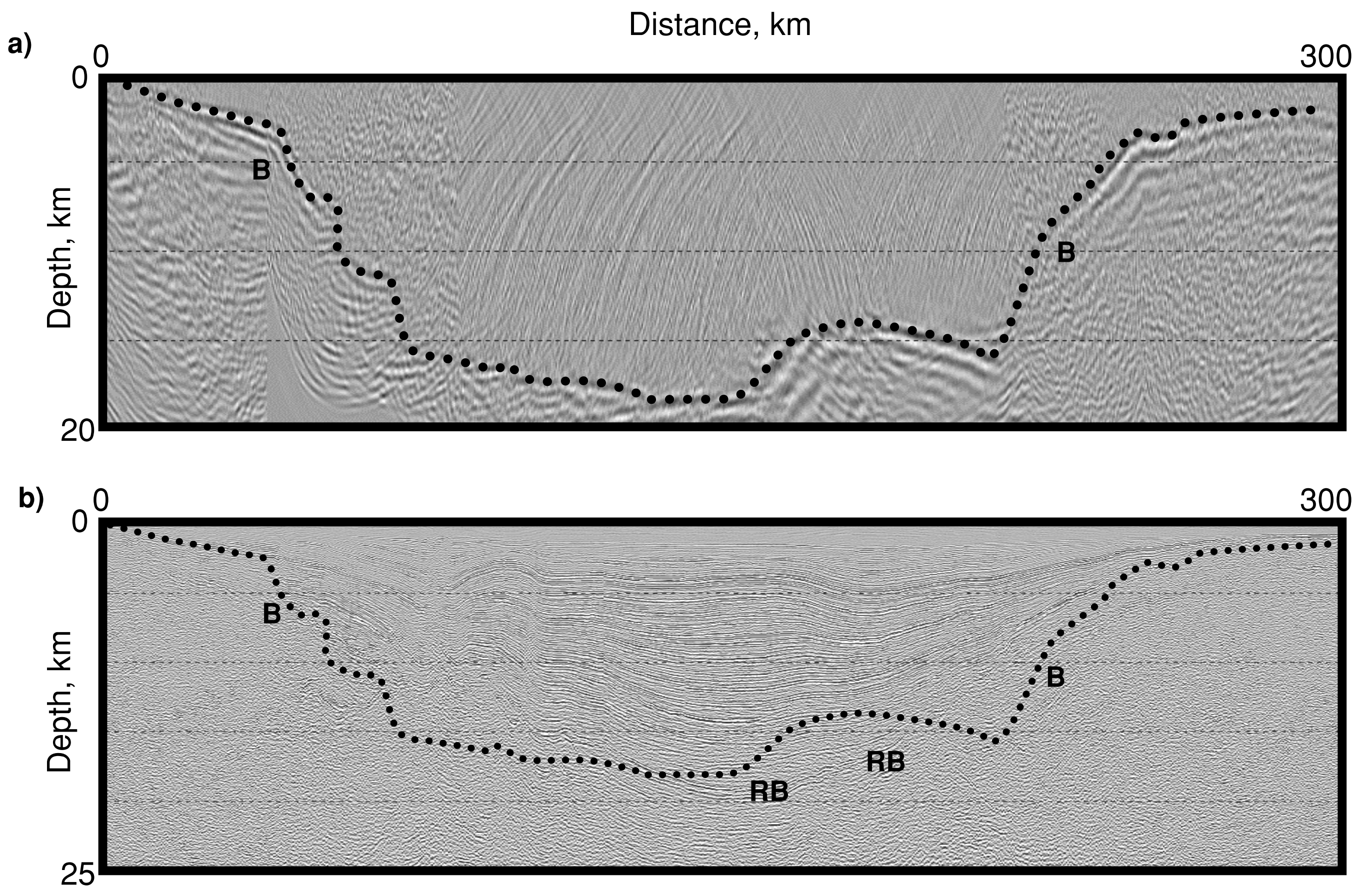

Fig. 10. (a) After-stack image of the 6.0-km/s refractor (dotted line marked B; crystalline basement?) obtained as a result of depth migration of the OBS data along the Petrel line. (b) Migrated and depth-converted conventional reflection section with the 6.0-km/s refractor superimposed on it. RB (reflection basement) index marks the bottom of continuous reflectivity in the section.

of 4.3–5.0 and 5.7–6.4 km/s (Fig. 12a, b). Even so, some remarkable incongruities between the interpretation and the velocity model are apparent (Fig. 12b, c).

Firstly, the prominent reflectivity 13–17 km deep in the conventional reflection data does not correspond to any significant velocity increase imaged by refraction/wide-angle techniques. The velocity below that level estimated from the OBS data is in the range 5.7–6.4 km/s, considerably lower than that indicated by the ESP data.

Secondly, the local velocity increase in the lens-shaped lower crustal body 15–23 km deep (Fig. 12a) produces no noticeable response in the conventional reflection section (Fig. 12b, c).

Finally, the Moho occurs at an average depth of ~18 km, in contrast to 14 km in the preliminary interpretation. This implies a considerably thicker oceanic crust beneath the Gascoyne Abyssal Plain in the outer part of the Carnarvon transect.

Consequences for the petrological interpretation

Inaccurate velocity estimates will lead to unrealistic estimates of the petrology of rocks at depth. The Carnarvon line example can be used to quantify this observation.

In our preliminary geological interpretation, we correlated the top of underplating in the Carnarvon line (Fig. 12c) with the top of a mafic layer intruded into the lower crust as a result of partial upper-mantle melting. We can test the validity of this correlation by using the petrophysical modelling technique of Sobolev & Babeyko (1994: Surveys in Geophysics, 15, 515–544; Goncharov et al. 1997: AGSO Research Newsletter 26, 13–16) to interpret the OBS-derived velocity model in terms of bulk rock geochemistry.

A comparison of the representative velocity–depth function in the southeast part of the Carnarvon line (Fig. 13b) with the results of petrophysical modelling (Fig. 13a) shows that velocities 5.7–6.4 km/s in the lower crust cannot correspond to mafic rocks, even under high heat-flow conditions. Though a rock will record its lowest possible velocity under a high-temperature regime, our modelling (even assuming such conditions) shows that velocities 5.7–6.4 km/s are restricted to rocks with granite-type bulk compositions (Fig. 13a). Mafic rocks (gabbro-type bulk composition) have velocities mainly in the range 7.1–7.8 km/s (Fig. 13a). The velocities of rocks with low-garnet–high-plagioclase gabbroic compositions in the lower crust rarely approach 6.4–7.1 km/s. Therefore, even the layer with velocities of 6.4–7.1 km/s in the northwest part of the Carnarvon line (Figs. 12a and 13b) is unlikely to represent purely mafic rock. Rather, these velocities correspond mainly to granite-to-diorite-type bulk compositions and their mixtures (Fig. 13a).

Our preliminary interpretation, therefore, does not satisfy the velocity information derived from the OBS experiment in the northern Carnarvon Basin. Even so, the lens-shaped body distinguished by the OBS data in the lower crust (Fig. 12a) has a velocity (~7.2 km/s) consistent with a gabbroic composition (Fig. 13a). Therefore, underplating may be a feature of the northern Carnarvon Basin — but ~90 km farther northwest and ~5 km deeper than we originally interpreted.

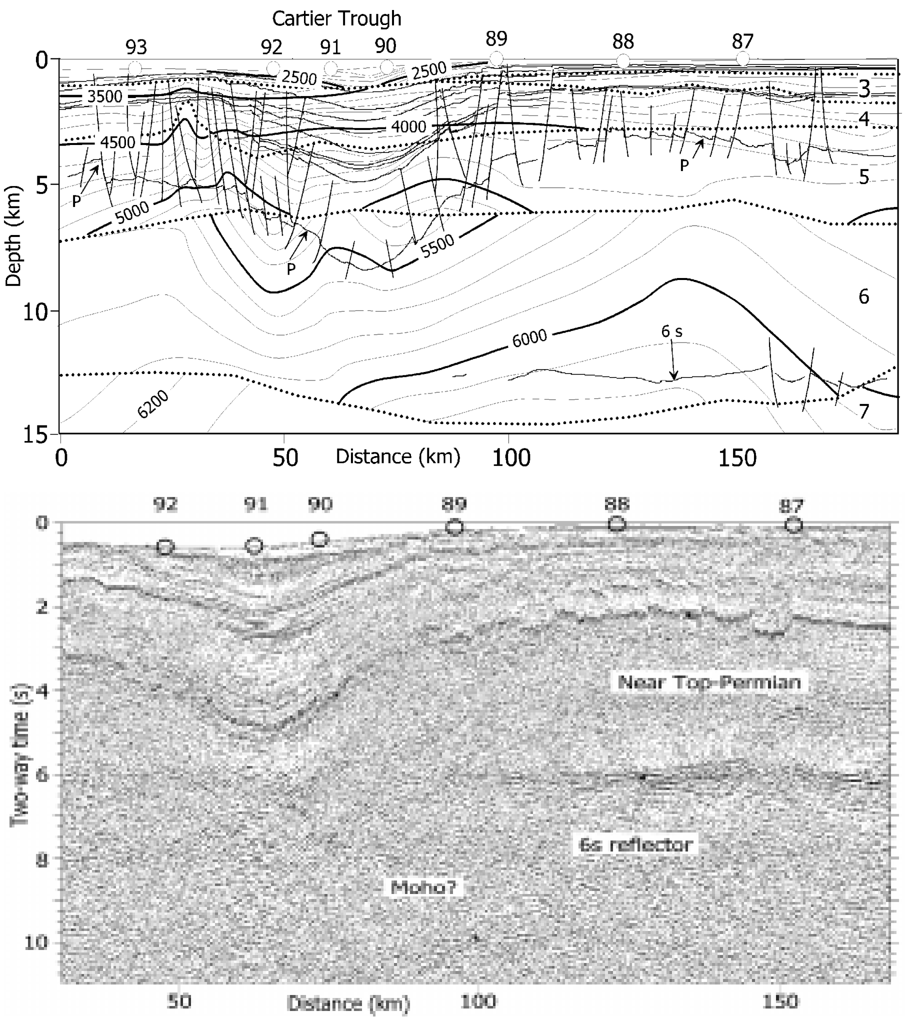

Fig. 11. (a, top) Part of the OBS-derived seismic velocity model showing isovelocity lines at 100-m/s intervals and (dotted) boundaries between layers (numbered at right). (b, bottom) Conventional reflection section along the coincident AGSO line 98/03. Circles numbered 87 to 93 are OBS locations. Thin lines in (a) are prominent horizons from the reflection section presented in (b): '6s' — high-amplitude reflector at 6 s TWT; P — near-top-Permian carbonates.

Speculations on the origin of discrepancies between reflectivity and bulk-velocity changes

According to Berzon (1976: 'Seismic prospecting in finely stratified media' [in Russian], Nauka Press, Moscow), simple sharp boundaries with step-like velocity increases produce prominent seismic responses at large offsets. The same applies to transitional layers whose velocities gradually increase with depth. Near-vertical reflections in both cases may be 10–100 times weaker than the wide-angle ones. Conversely, assemblages of thin (on a seismic-wave-length scale) layers with sharp velocity contrasts at their boundaries are more likely to produce high-amplitude near-vertical reflections and only weak responses at large offsets.

Accordingly, we suggest that the high-amplitude reflective band 13–17-km deep along the Carnarvon line (Fig. 12b) represents thin interlayering of high- and low-velocity material (e.g., sheet intrusives; mylonites associated with fault zones; etc.). Despite considerable velocity contrasts at the boundaries of individual thin layers within this depth interval, bulk velocities above and below this layer are similar. Otherwise, a prominent response at large offsets would have been expected in our dataset.

The same thin layering mechanism may explain the origins of the reflectivity at ~15–20-km depth along the Petrel line (Fig. 10b), and the 6-s reflector on the Vulcan line (Fig. 11b).

Why the finely stratified assemblages do not coincide with boundaries where bulk-velocity changes significantly (e.g., the 6.0-km/s refactor along the Petrel line) remains unclear. It is also not clear why the Moho in the Carnarvon and Vulcan sections is more likely to be a sharp and simple velocity boundary or a transitional layer rather than a finely stratified interval; a marked velocity contrast at this boundary coincides with only weak near-vertical reflections.

Beneath the Cartier Trough, where isovelocity lines are incompatible with the structure imaged by the conventional reflection data (Fig. 11), the progressive velocity increase with depth can probably be attributed to compaction due to increasing geostatic pressure. This smooth trend would be superimposed on the original fine stratification, which in turn probably would control the reflectivity pattern, whereas bulk-velocity changes would be determined by compaction-related factors.

In summary, reflective boundaries and bulk-velocity boundaries in the crust are commonly controlled by different factors whose causes require further research. Whereas conventional reflection technol-

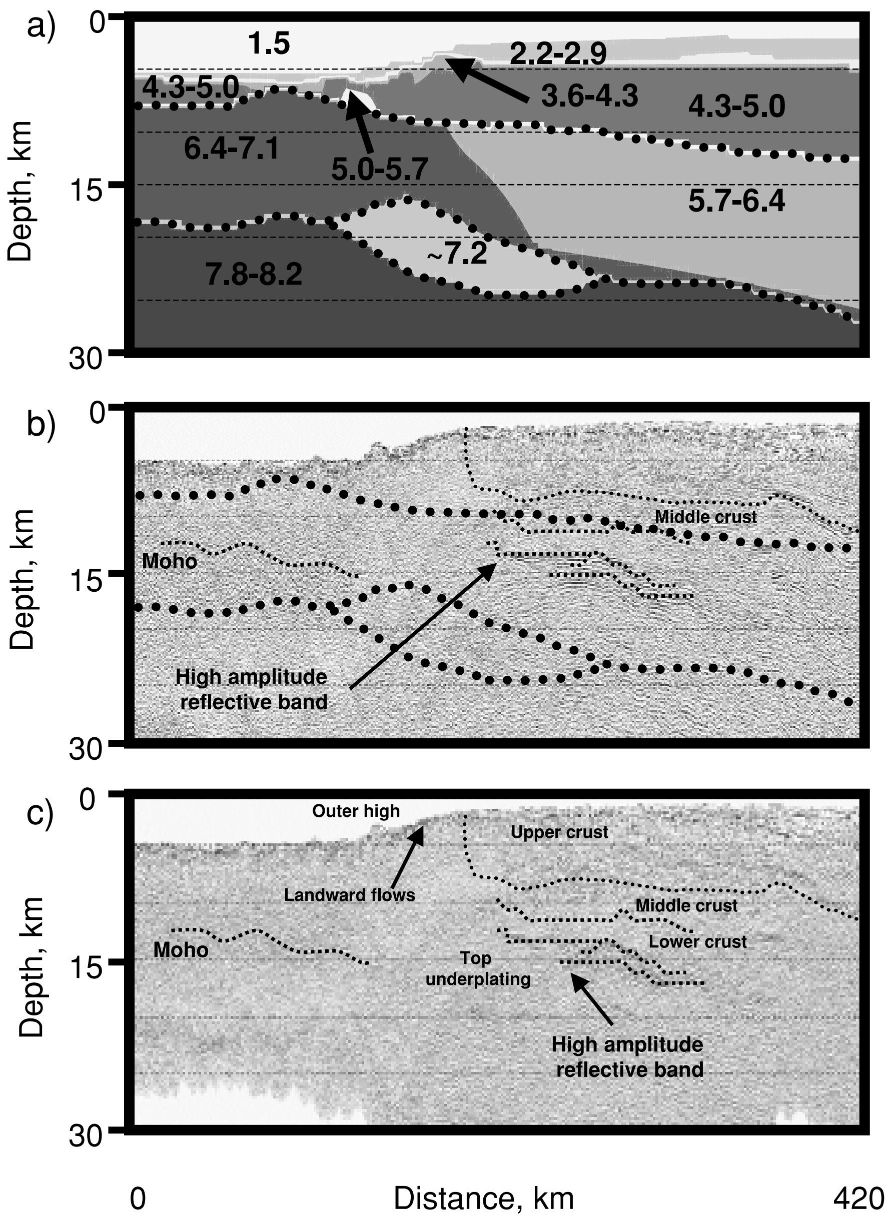

Fig. 12. (a) Seismic velocity model for the Carnarvon line from the OBS data. (b) and (c) Reflection section along the coincident reflection line depth-converted with OBS-derived velocities (b), and with CDP-derived velocities (c). Large dots in (a) mark some velocity boundaries discussed in the text, and small dots in (c) show some elements of interpretation discussed in the text. Both sets of dots superimposed on top of the reflection section in (b).

ogy tends to highlight fine seismic stratification of the crust, refraction/wide-angle reflection technology images better bulk-velocity changes in the crust. Only a combination of both techniques offers clues to a consistent geological interpretation of seismic data.

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[1] Petroleum & Marine Division, Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601; tel. +61 2 6249 9595 (AG), +61 2 6249 9278 (PP); fax +61 6 249 9980; e-mail alexey.goncharov @agso.gov.au, peter.petkovic@agso.gov.au.

[2] Minerals Division, Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601; tel. +61 2 6249 9725; fax +61 6 249 9972; e-mail tanya.fomin @agso.gov.au.

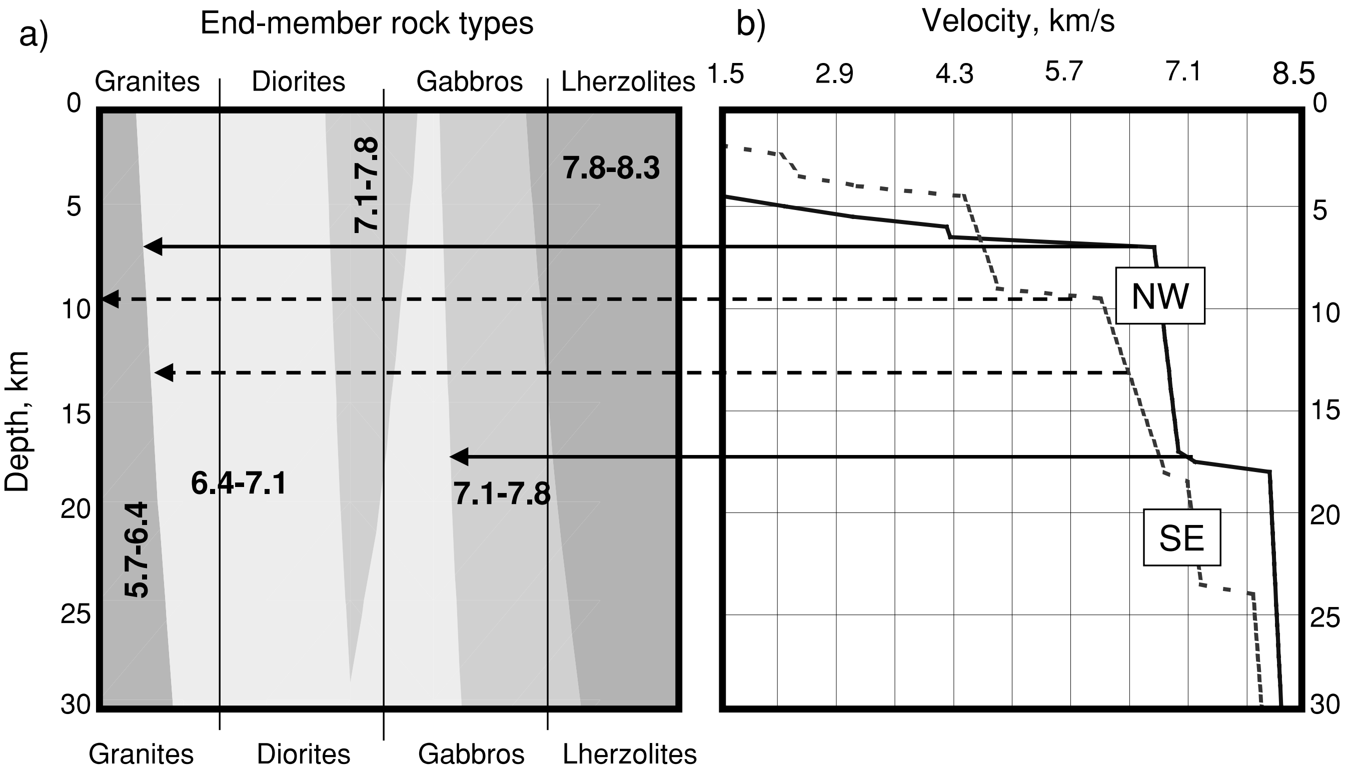

Fig. 13. (a) P-wave velocity in various rock types as function of depth computed for high heat flow, and (b) representative 1-D velocity models in the northwest and southeast parts of the Carnarvon line. The bulk geochemical composition within each rock type is constant, and the mineralogical compositions are allowed to vary to account for equilibration at the pressures and temperatures likely to have existed when the rock was formed.