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Quarterly Notes

Geological Survey of New South Wales

December 2008 **No 129**

Deep structure beneath the Murray Basin from teleseismic tomography

ABSTRACT

Results from Part 2 of the South East Australia Linkage teleseismic experiment are presented for the first time, and enhance understanding of deep Earth structure beneath southwestern New South Wales. A total of 187 distant earthquakes recorded by 31 short-period seismometer stations were used to constrain three-dimensional variations in P-wavespeed in the upper mantle using teleseismic tomography. The new data were also combined with pre-existing data from adjacent arrays to build a high-resolution model of the upper mantle in southeastern Australia. The resulting images reveal that the upper mantle consists of several distinct domains of fast and slow P-wavespeed that provide unprecedented insight into compositional and temperature variations related to lithosphere of different origin, and more recent processes such as Cenozoic volcanism. One of the main results from this study is the presence of a pronounced west to east transition from higher to lower Vp near the eastern edge of the Stawell Zone. One possible explanation for this feature is that Precambrian continental lithosphere extends beneath the western subprovince of the Lachlan Orogen, which has important implications for the tectonic evolution of the Tasmanides, and the location of the boundary between the Lachlan and Delamerian orogens. However, the absence of good constraint on crustal structure, and possible overprinting of Palaeozoic velocity anomalies by such recent events as magmatic underplating which accompanied rifting and subsequent opening of the Bass and Otway basins and the Tasman Sea, means that further data are required. Future work in southeastern Australia will use receiver functions and ambient noise data that have the potential to resolve structures within the crust at high resolution, and naturally complement the teleseismic data, which only constrain the upper mantle.

Keywords: teleseismic, seismic, seismometers, tomography, Stawell Zone, Delamerian Orogen, Tasman Orogen, Tasmanides, Lachlan Orogen, SKIPPY, SEAL2, Bendigo Zone, Tabberabbera Zone, Hay–Booligal Zone.

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Papers in* Quarterly Notes *are subject to external review. External reviewer for this issue was Russell Korsch. His assistance is appreciated.

Quarterly Notes *is published to give wide circulation to results of studies in the Geological Survey of New South Wales. Papers are also welcome that arise from team studies with external researchers.*
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ISSN 0155-3410

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Production co-ordination and general editing :	*Simone Meakin Geneve Cox*
Geological editor:	*Richard Facer*
Geospatial information:	*Cheryl Hormann Phillip Carter*
Layout:	*Carey Martin*

Cover photograph:
Typical short-period seismic station installation. This is station s2c2, located on Figure 2. (Photographer: Nick Rawlinson)

Editorial note:
No *Quarterly Note* was published in either July or October 2008.

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INTRODUCTION

The Tasman Orogen or 'Tasmanides' (Foster & Gray 2000; Glen 2005) covers the eastern one-third of the present day Australian continent and mainly represents the accretion of material onto the eastern margin of Precambrian Australia, part of the Pacific margin of eastern Gondwana, from the Middle Cambrian through to the onset of the breakup of Gondwana and Pangea in the Triassic. The Delamerian, Lachlan, New England, Thomson and North Queensland orogens (Glen 2005) represent separate components of this collage. In southeastern Australia (Figure 1), the Delamerian Orogen, which extends southward from the mainland into Tasmania, formed as a result of subduction along the proto-Pacific margin (Betts et al. 2002). The underlying basement consists of Proterozoic lithosphere, which is thought to partially extend beneath the Lachlan Orogen to the east (Rawlinson et al. 2006).

The evolution of the Lachlan Orogen began in the Late Cambrian, and was largely complete by the Early Carboniferous. This is a highly complex region of Australia, the formation of which may have involved either multiple coeval subduction zones (Foster & Gray 2000) or orogen-parallel strike-slip tectonics (e.g. Willman et al. 2002; Glen 2005; Meffre et al. 2007). A solid consensus on this issue remains elusive, with a variety of possible substrates still under consideration, from purely oceanic to mixed oceanic and continental (Glen 2005). Correspondingly, tectonic models of the region vary between a predominantly accretionary oceanic system (Foster & Gray 2000; Fergusson 2003; Spaggiari et al. 2004) and a largely intracratonic setting (VandenBerg 1999; Taylor & Cayley 2000; Willman et al. 2002). It has also been suggested that fragments rifted from the Precambrian craton (Glen 2005) or 'continental ribbons' underlie parts of the Lachlan Orogen within a basement dominated by oceanic crust (Foster & Gray 2000; Betts et al. 2002).

Previous passive imaging studies of the Australian lithosphere have concentrated on elucidating broad variations in upper mantle shear wavespeed derived from continent-scale surface-wave tomography. The Australia-wide SKIPPY project (1993–1998) of the Research School of Earth Sciences, Australian National University, used a rolling array of broadband seismometers to occupy a total of 65 sites with a nominal station spacing of 400 km. Surface-wave data from SKIPPY and subsequent deployments have allowed three-dimensional images of shear wavespeed (and azimuthal anisotropy) to be constructed for the entire continent at a horizontal resolution of 200–250 km (Zielhuis & van der Hilst 1996; Simons et al. 2002; Debayle & Kennett 2003; Fishwick et al. 2005). One clear observation that can be made from all of these studies is that high shear wavespeeds exist beneath Precambrian western Australia, which contrast with the low wavespeeds beneath Phanerozoic eastern Australia.

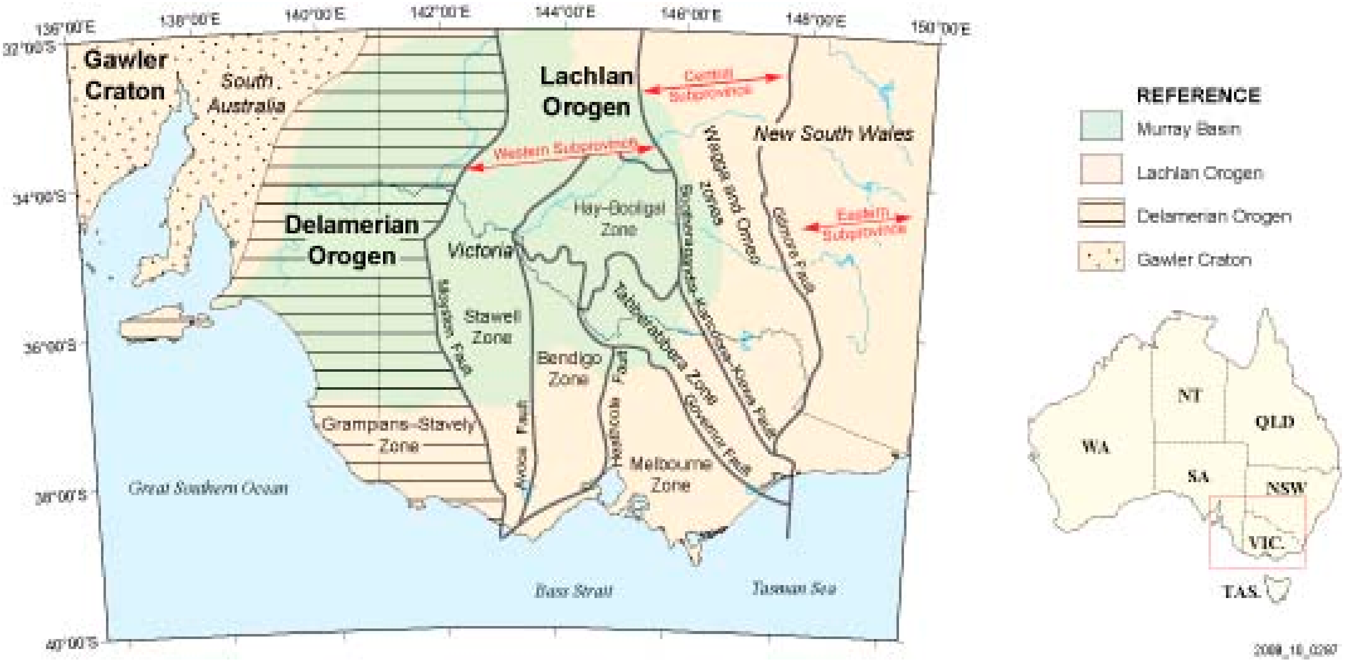

Figure 1. Schematic map of the southern Tasman Orogen in eastern Australia showing structural zones interpreted in this study. The Murray Basin and other Cenozoic deposits obscure much of the underlying basement.

Over the last decade the emphasis has moved from continental-scale imaging to higher density, more localised seismic arrays deployed to target regions of particular geological interest using teleseismic body-wave tomography. These studies more directly complement the reflection and wide-angle refraction surveys that have been carried out in various parts of the continent, to illuminate the structure of the crust in great detail.

THIS STUDY

In a collaborative agreement with the Australian National University through the Research School of Earth Sciences (RSES), and the NSW Department of Primary Industries through the NSW Government's *New Frontiers* initiative, the South East Australia Linkage Part 2 (SEAL2) teleseismic experiment was undertaken in the southwestern part of New South Wales. In this paper preliminary tomographic results from the SEAL2 experiment are presented for the first time. SEAL2 involved the deployment of 31 short-period (eigenfrequency of 1 Hz) stations, and 5 broadband stations across the Murray Basin in southwestern New South Wales (Figure 2) between February and November 2007. A typical short-period station installation is shown in the cover photograph. The SEAL2 array spans the transition from the Delamerian Orogen to the western subprovince of the Lachlan Orogen in New South Wales, which corresponds to the northern extension of the gold prospective Bendigo Zone, from western Victoria into the southwest of New South Wales.

Questions that can be addressed by this study include four critical challenges to tectonic understanding of southeastern Australia.

(1) Does Precambrian lithosphere extend eastwards beneath the western part of the Lachlan Orogen in New South Wales and Victoria?

(2) Can the lithospheric boundary between the Delamerian and Lachlan orogens be defined, and what surface structure does it correspond to?

(3) Can the mantle lithosphere that correlates with the Selwyn Block of Cayley et al. (2002) be detected?

(4) Are there wavespeed variations in the lithosphere which correspond to various crustal elements (e.g. Tabberabbera Zone, Hay–Booligal Zone) of the Lachlan Orogen that have been inferred from surface geology and potential field studies?

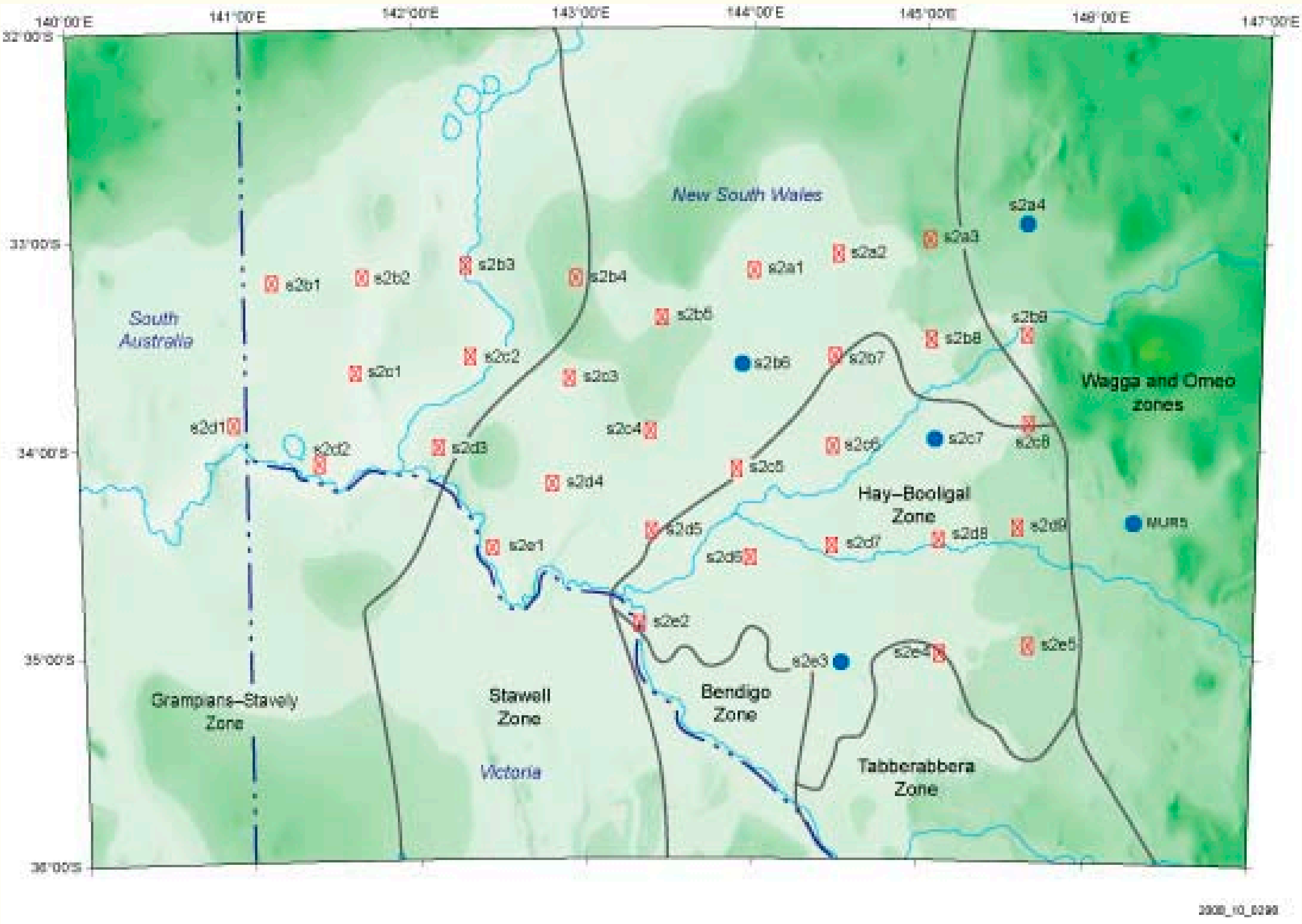

Figure 2. Location and annotation of all seismic stations that make up the SEAL2 array. Short-period stations are denoted by red dots and broadband stations are denoted by blue dots. Shading represents surface elevation extracted from SRTM data.

DATA AND METHOD

A total of 187 distant earthquake records from the SEAL2 array have been used for the extraction of relative-arrival time residual maps. The location of New South Wales relative to surrounding seismogenic zones means that most of the detected earthquakes originate from convergent plate boundaries to the north and east of the array (Figure 3), with relatively few occurring to the south and west, where the margins of the Australian plate are in divergent settings. The use of three-component sensors means that both P- and S-wave arrival time information has the potential to be extracted. However, in this study, only the P-wave arrival times are considered, as there would be considerable work to identify and process the noisier S-wave arrivals. In addition, only data from the 31 short-period stations are used. The five broadband stations are still in operation, and the processing that is required prior to event-based extraction is incomplete.

First-arriving P-wavetrains from three distant earthquakes recorded by the SEAL2 array are shown in Figure 4. All traces have been subjected to preliminary alignment using travel-time predictions from the *ak*135 global reference model (Kennett et al. 1995). Extraction of relative arrival-time residual information is achieved using an adaptive stacking technique developed by Rawlinson and Kennett (2004), which exploits the coherency of the arriving waveform across the array clearly evident in Figure 4. The basic assumption that underlies teleseismic tomography is that differences in the arrival time of a phase recorded by different stations, once moveout due to variations in source-receiver offset has been accounted for using a spherically symmetric Earth model, can be largely attributed to lateral heterogeneity beneath the seismic array. Thus, in Figure 4, the remaining misalignment between the wavetrains recorded at different stations is due to the presence of arrival-time residuals (usually of the order of hundreds of milliseconds) which are a manifestation of lateral wavespeed variations beneath the stations.

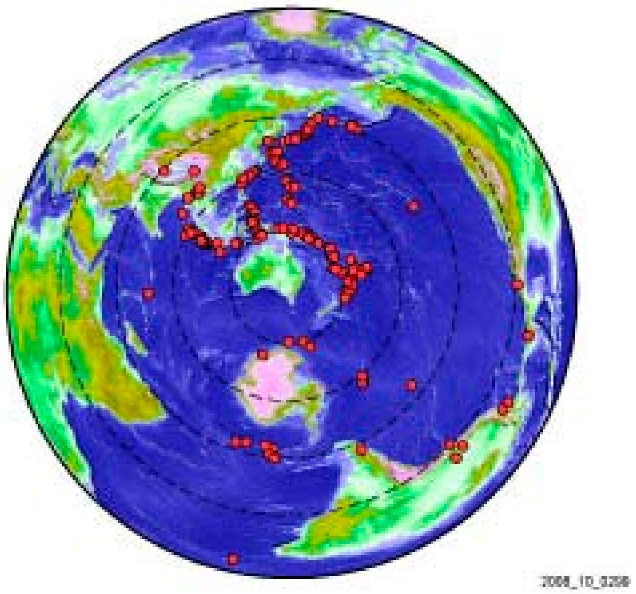

Figure 3. Distribution of the 187 teleseismic events (red dots) used in the tomographic inversion for three-dimensional seismic structure beneath the Murray Basin. Note that some events are obscured by others. Dashed circles represent 30° increments in great circle distance from the centre of the SEAL2 array. Shading represents surface elevation extracted from SRTM data.

From the 187 earthquakes used in this study, a total of 195 coherent phases were targeted for adaptive stacking. For the most part, these were direct P, but also included are PcP, ScP, PKiKP and SKiKP phases. The availability of other phases with different incident angles has a beneficial effect on the tomographic imaging. In total, 5325 relative arrival-time residuals were extracted.

Teleseismic tomography is used to map the patterns of relative arrival-time residuals as three-dimensional perturbations in P-wavespeed (Vp) from a depth-dependent reference model. One of the principal assumptions of this technique is that relative arrival-time residual patterns are largely unaffected by lateral variations in structure outside a local model volume defined beneath the array. Here, a new tomographic software package called FMTT (Fast Marching Teleseismic Tomography) is used to perform the teleseismic tomography. This package combines an advanced wavefront tracking technique with an efficient gradient-based inversion method to enable robust iterative non-linear inversion of large travel-time datasets that potentially constrain thousands of velocity parameters (Rawlinson & Urvoy 2006).

TOMOGRAPHIC SOLUTION MODEL

FMTT is used to invert the 5325 relative arrival-time residuals extracted from the SEAL2 dataset for variations in P-wavespeed beneath the Murray Basin in the southeast of New South Wales. A total of 51 324 velocity nodes spaced approximately 20 km apart in latitude, longitude and depth are used to define the model. The laterally invariant reference or starting model is based on one-dimensional velocity verses depth curves obtained from a refraction study of the Lachlan Orogen (Collins 1991). However, since these curves only extend into the uppermost mantle, *ak*135 velocity values are used to define velocities below approximately 50 km depth. The final solution model reduces the data variance from 0.0454 s^2 to 0.0096 s^2, a reduction of 79%. This corresponds to an RMS reduction from 213 ms to 98 ms. The estimated standard deviation of the data noise is 82 ms, which means that the solution model fits the data to an acceptable level. The remaining misfit can be attributed to unresolved variations in crustal structure, which can be short-wavelength and high-amplitude; deep mantle structure beneath the local model volume; and anisotropy.

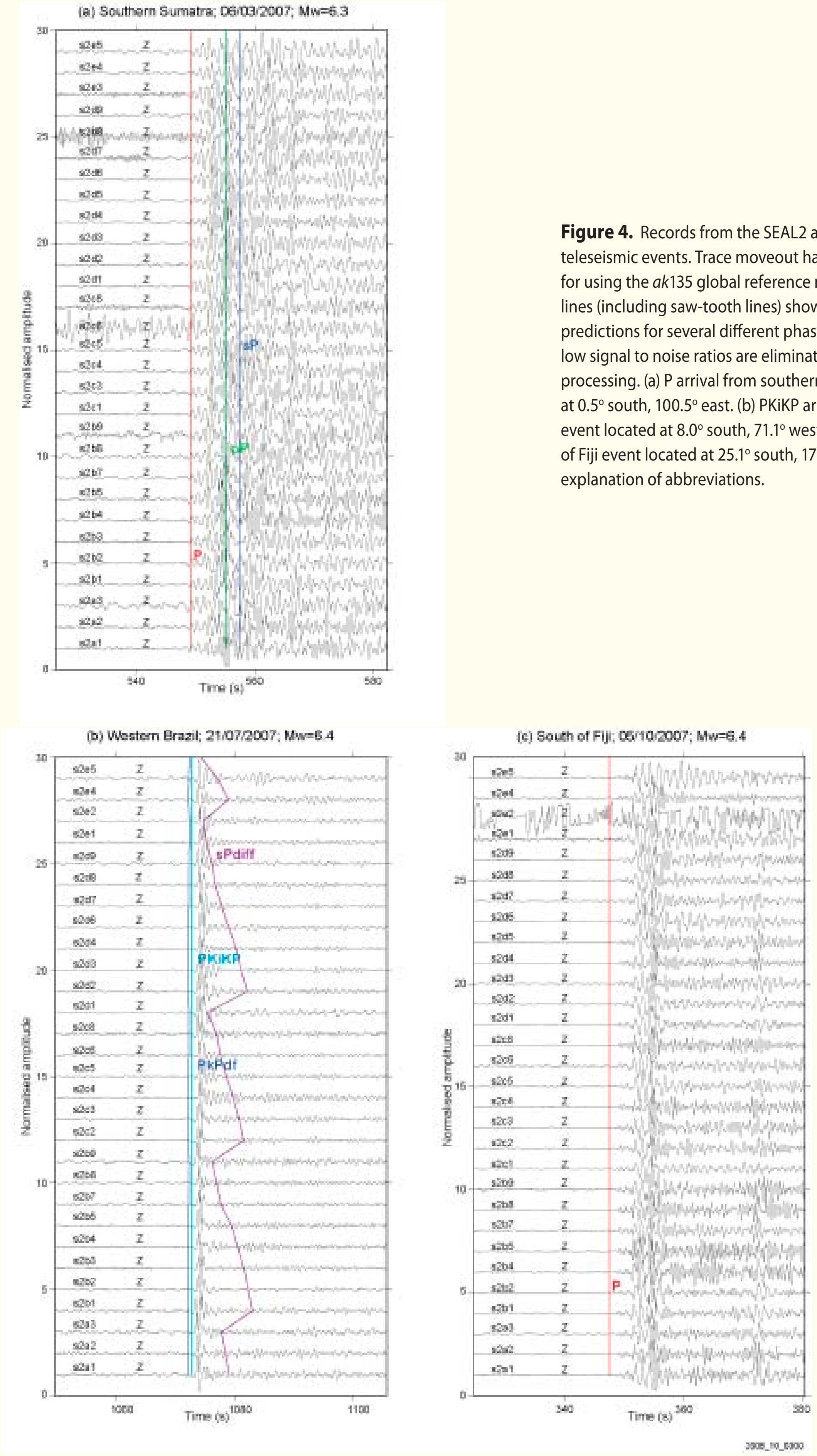

Figure 4. Records from the SEAL2 array for three different teleseismic events. Trace moveout has been corrected for using the *ak*135 global reference model. Thick vertical lines (including saw-tooth lines) show *ak*135 arrival time predictions for several different phases. Traces exhibiting low signal to noise ratios are eliminated from subsequent processing. (a) P arrival from southern Sumatra event located at 0.5° south, 100.5° east. (b) PKiKP arrival from western Brazil event located at 8.0° south, 71.1° west. (c) P arrival from south of Fiji event located at 25.1° south, 179.4° east. See glossary for explanation of abbreviations.

A series of horizontal slices through the P-wavespeed solution model are shown in Figure 5. The pattern of anomalies reveals a low-velocity zone near the southern end of the model at 50 km and 100 km depth, which contrasts with the higher velocities that broadly characterise the northern section of the model. At greater depth (150 km to 200 km), a west to

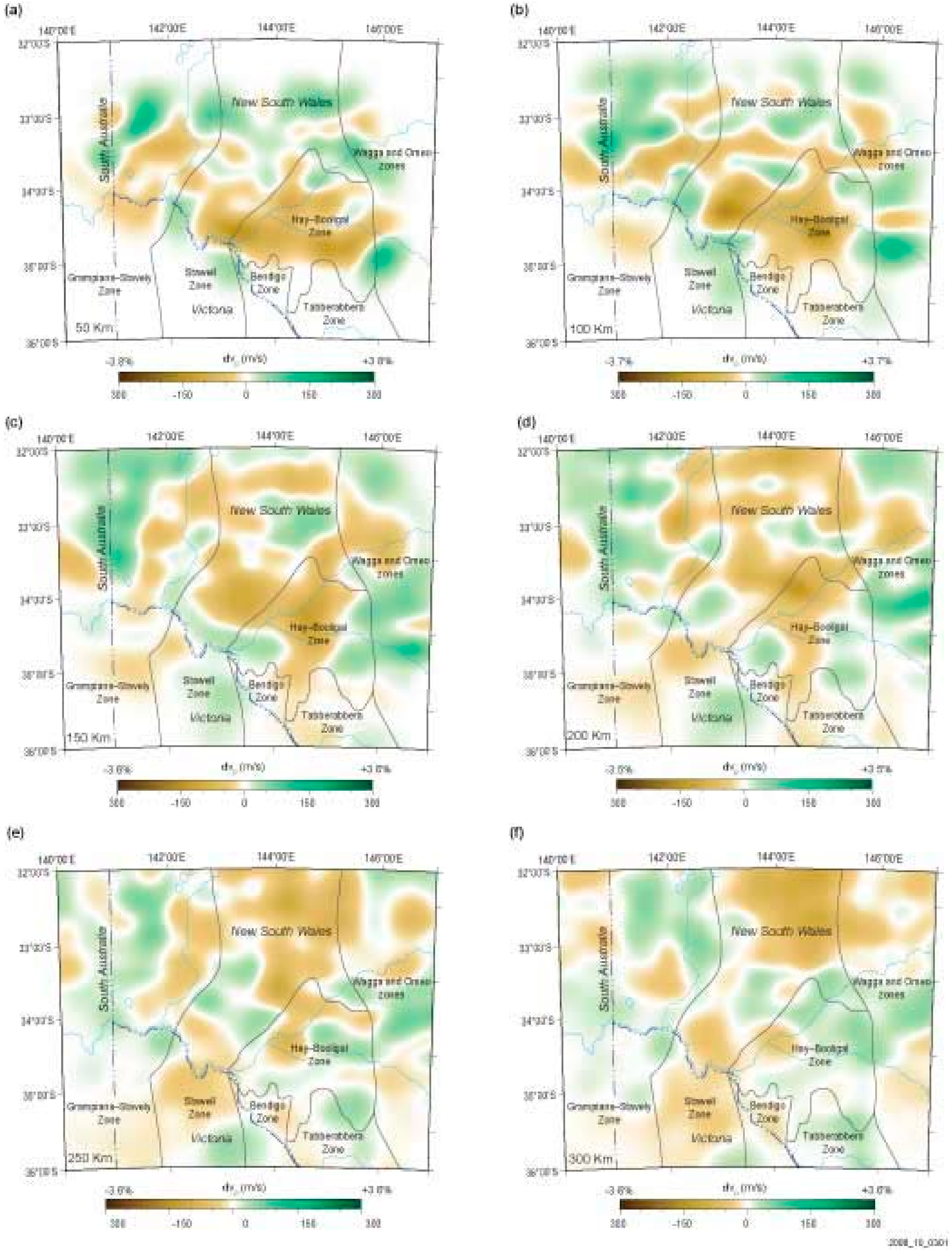

Figure 5. Horizontal sections at depth intervals from (a) 50 km to (f) 300 km through the three-dimensional solution model obtained by inversion of SEAL2 relative arrival time residual data. P-wavespeed variations from a reference one-dimensional model are represented using colour contouring (brown shows low velocities; green shows high velocities). Variation in wavespeed of P-waves (Vp) is also expressed as % of average wavespeed (-% = slower Vp; +% = faster Vp).

east fast–slow–fast trend emerges in the longer wavelength features. Regions of the model that are devoid of path coverage will not deviate from their initial values during the inversion process, and will therefore have zero perturbation. Smearing effects due to ray-path clustering also results in artefacts appearing in the model. The ability of the teleseismic data to accurately recover structure is assessed using a checkerboard resolution test, in which a synthetic model is reconstructed using the same path coverage as the observational dataset. Figure 6 shows the result of this test at two depth slices. The alternating pattern of fast and slow anomalies is generally clearly recovered, although resolution decreases with depth in the southern half of the model due to limited teleseismic events from the south (Figure 3).

REGIONAL SYNTHESIS

In the last decade, a dense rolling array of short-period seismometers has been used to achieve a cumulative coverage of over 400 sites throughout southeastern Australia via ten separate deployments, of which SEAL2 is just one (Figure 7). On a regional scale, this represents one of the largest continuing programs of passive seismic deployments in the world, and has the long term goal of achieving almost complete coverage of the entire continent. The huge volumes of seismic data collected so far can be used for teleseismic tomography, ambient noise tomography, receiver function analysis and array studies of deep mantle and core structure. One of the main aims of the project is to combine all of the teleseismic data in a unified inversion for the high resolution

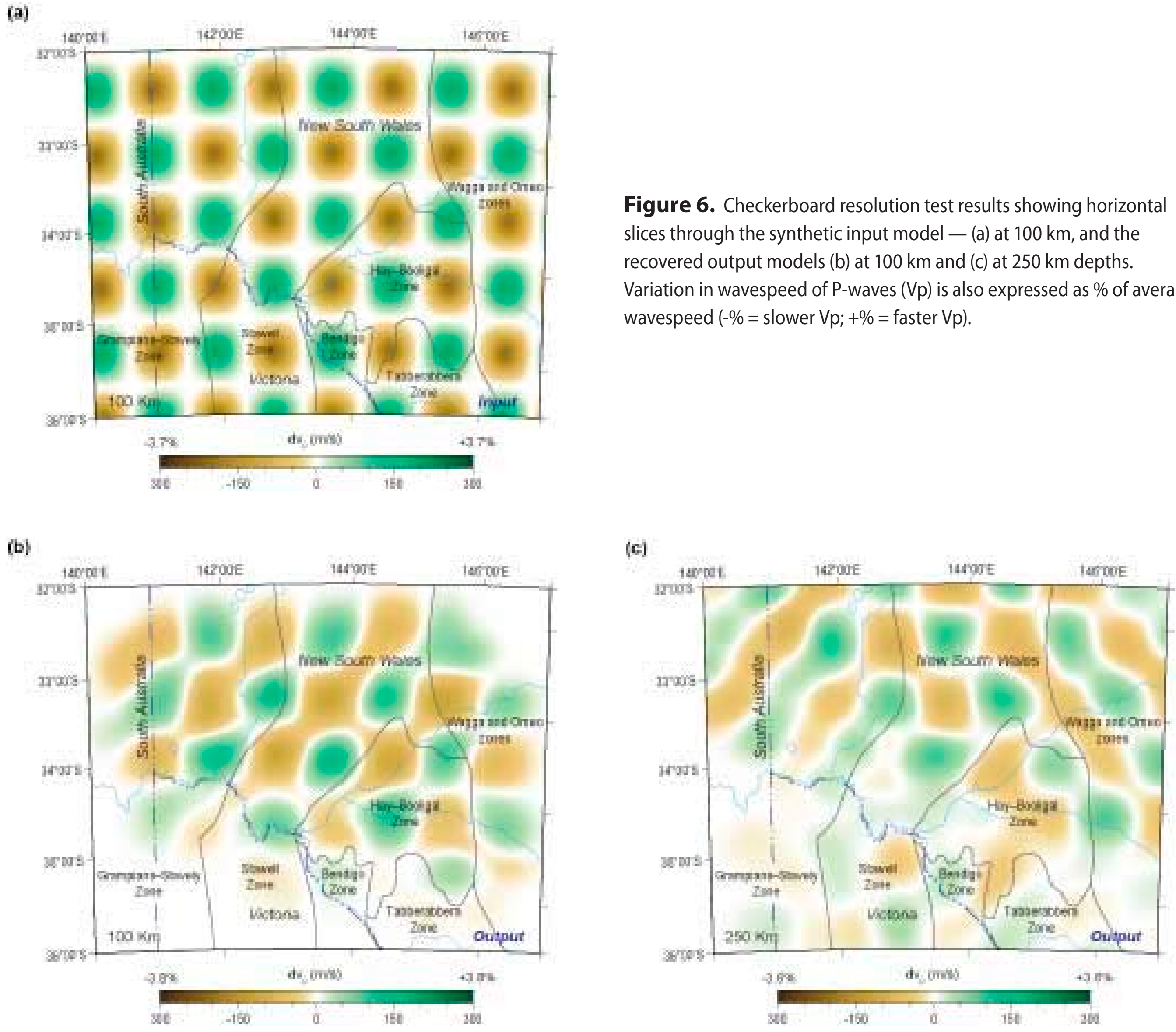

Figure 6. Checkerboard resolution test results showing horizontal slices through the synthetic input model — (a) at 100 km, and the recovered output models (b) at 100 km and (c) at 250 km depths. Variation in wavespeed of P-waves (Vp) is also expressed as % of average wavespeed (-% = slower Vp; +% = faster Vp).

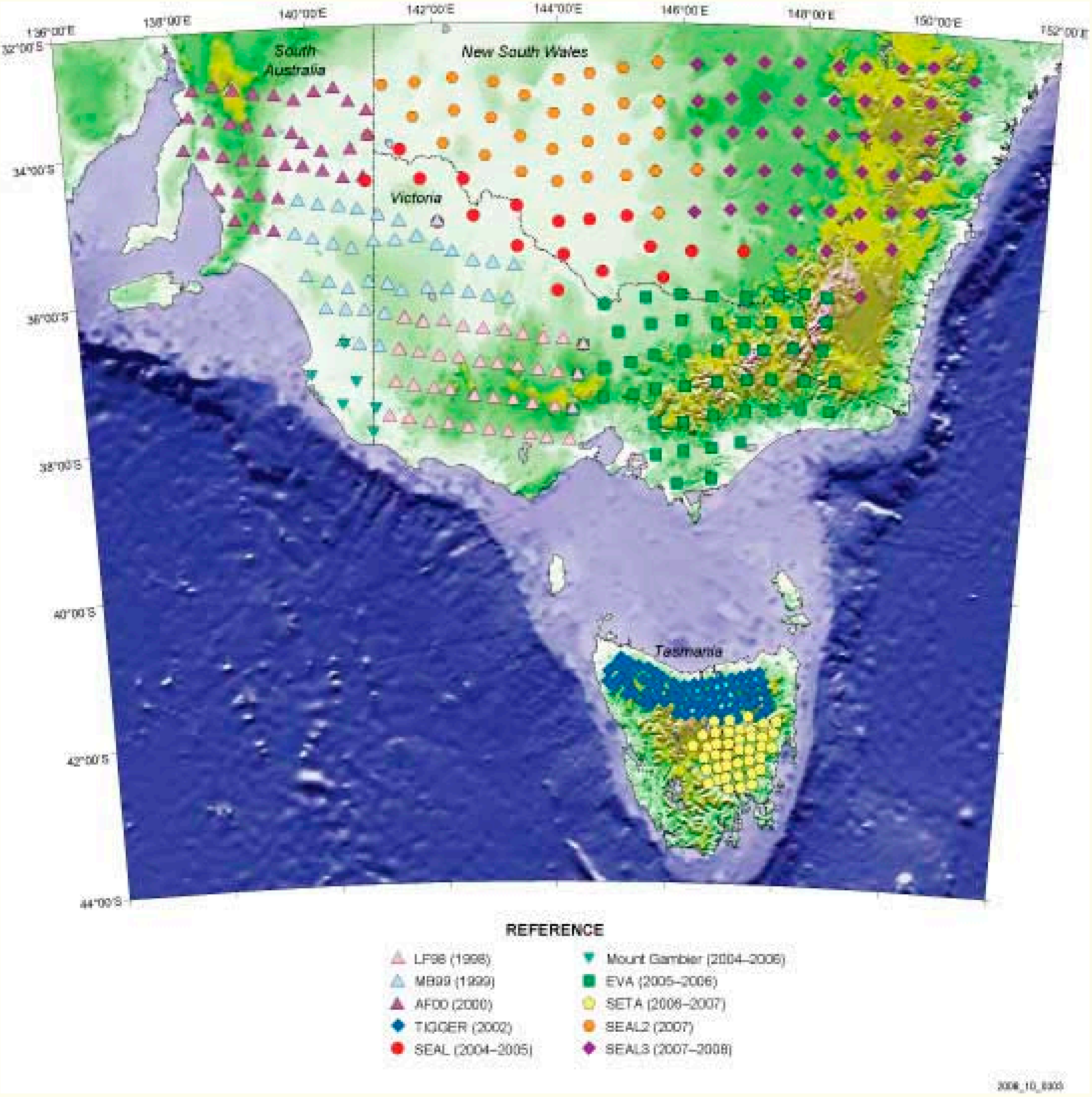

Figure 7. Map showing the locations of all high-density passive seismic arrays deployed in southeastern Australia from 1998 to 2008 on a colour backdrop of terrain based on SRTM data.

upper mantle structure beneath southeastern Australia. To date, data from LF98, MB99, EVA, SEAL and SEAL2 have been picked, and can therefore be inverted using FMTT. Figure 8 shows two horizontal cross-sections at depth slices of 150 km and 200 km, through the preliminary three-dimensional model obtained by inverting arrival-time residual data from all five mainland arrays that have been processed to date of writing. Similar grid spacings and inversion parameters to the SEAL2 results shown earlier were used in this case.

An important consideration in all seismic tomography studies is how to relate variations in seismic properties to the underlying geology. In this case, the seismic property is P-wavespeed, which reflects the ability of the rocks in the upper mantle to propagate compressional waves. Seismic P-wave perturbations (i.e. departures from a spherically symmetrical Earth model) in the upper mantle are largely a function of variations in temperature, composition, the presence of melt, solid-phase transformations and anisotropy. However, it is generally thought that in most cases temperature and composition are the two main factors (Sobolev et al. 1996). According to Cammarano et al. (2003), a 100ºC increase in temperature at 200 km depth can produce a negative P-wave anomaly of up to nearly 1%. Faul and Jackson (2005) used laboratory measurements of shear wavespeed in melt-free polycrystalline aggregates of olivine to suggest that variations in wavespeed observed in the continental shear wave model of Fishwick et al. (2005) can be explained by physically reasonable temperature anomalies. Thus, the older lithosphere beneath Precambrian western Australia may simply be thicker and cooler than the younger and thinner Palaeozoic lithosphere that underlies much of eastern Australia.

The effects of composition are more contentious, with maximum estimates for wavespeed perturbations as a result of realistic variations in mantle composition ranging between 1% and 5% (Sobolev et al. 1996; Griffin et al. 1998; Cammarano et al. 2003). A P-wave velocity model alone does not contain sufficient information to discriminate between contributions from temperature and composition, which means that caution is required when attempting to identify the underlying causes for the presence of a velocity anomaly.

The depth slices shown in Figure 8 are clearly resolved by the data, and correspond to the lower mantle lithosphere. Three distinct wavespeed domains can be readily identified. A zone of lower Vp underlies central Victoria and extends northward into New South Wales, and is bounded to the east and west by regions of elevated Vp. Those two relatively fast Vp domains underlie: western Victoria, corresponding to the Grampians–Stavely and Glenelg zones, with an easterly extension corresponding to the northern two-thirds of the Stawell Zone; and the southern part of the Melbourne Zone, with a possible bridge northwards into the northern part of the Tabberabbera Zone and adjacent Omeo Zone to the east.

One of the clearest features in Figure 8 is the east to west change from slower to faster velocities from the Bendigo Zone to the Stawell Zone. It is tempting to interpret this as a change from Phanerozoic mantle lithosphere of oceanic origin to Proterozoic mantle lithosphere of continental origin. Expected changes in both composition and temperature between these two types of material make this a plausible argument. In addition, this approximate boundary has also been observed, albeit at lower resolution, using surface-wave tomography (Simons et al. 2002), which appears to clearly distinguish between cratonic western Australia and the younger orogens that characterise eastern Australia. However, it must remembered that recent overprinting effects, such as the hotspot-related Newer Volcanic Province in Victoria and magmatic processes related to the opening of the Bass and Otway basins and the Tasman Sea, may well have contributed significantly (via increased temperatures) to reduced wavespeeds observed in central and southern Victoria.

In interpreting the results there does not appear to be a clear relationship between the apparent wavespeed domain boundaries projected to the surface and the surface traces of structural zones (Figure 8) deduced from seismic reflection and magnetic imaging. For example, the western boundary of the central domain of reduced wavespeed projects up to near the trace of the Avoca Fault. However, recent deep seismic imaging suggests that this is a west-dipping fault, with shallow dip, that terminates at a depth of ~22 km beneath the surface trace of the Winjallok Fault in the Stawell Zone. The reflection seismic data also suggest that the Moyston Fault, further to the west, can be traced as a pair of east-dipping faults to the base of the crust (~40 km) (Korsch et al. 2008). At that depth the eastern strand projects up to beneath the Avoca Fault. Given the general lack of understanding as to how structure in the crust may relate to structure in the underlying mantle, the lack of clear correlations is perhaps not surprising.

Given the possibility of rifted Proterozoic crustal fragments occurring as local basement to the Lachlan Orogen (Glen et al. 1992; Cayley et al. 2002; Betts et al. 2002; Gray & Foster 2004; Glen 2005), it is quite likely that they broke off and were transported together with their underlying continental lithosphere. If so, then the northeastern and less distinctive southeastern domains of elevated wavespeed (Figure 8) may reflect the presence of Proterozoic crustal fragments. An alternative explanation for such anomalies is that they represent imbricated lithosphere resulting from east–west convergent subduction accretion (Foster &

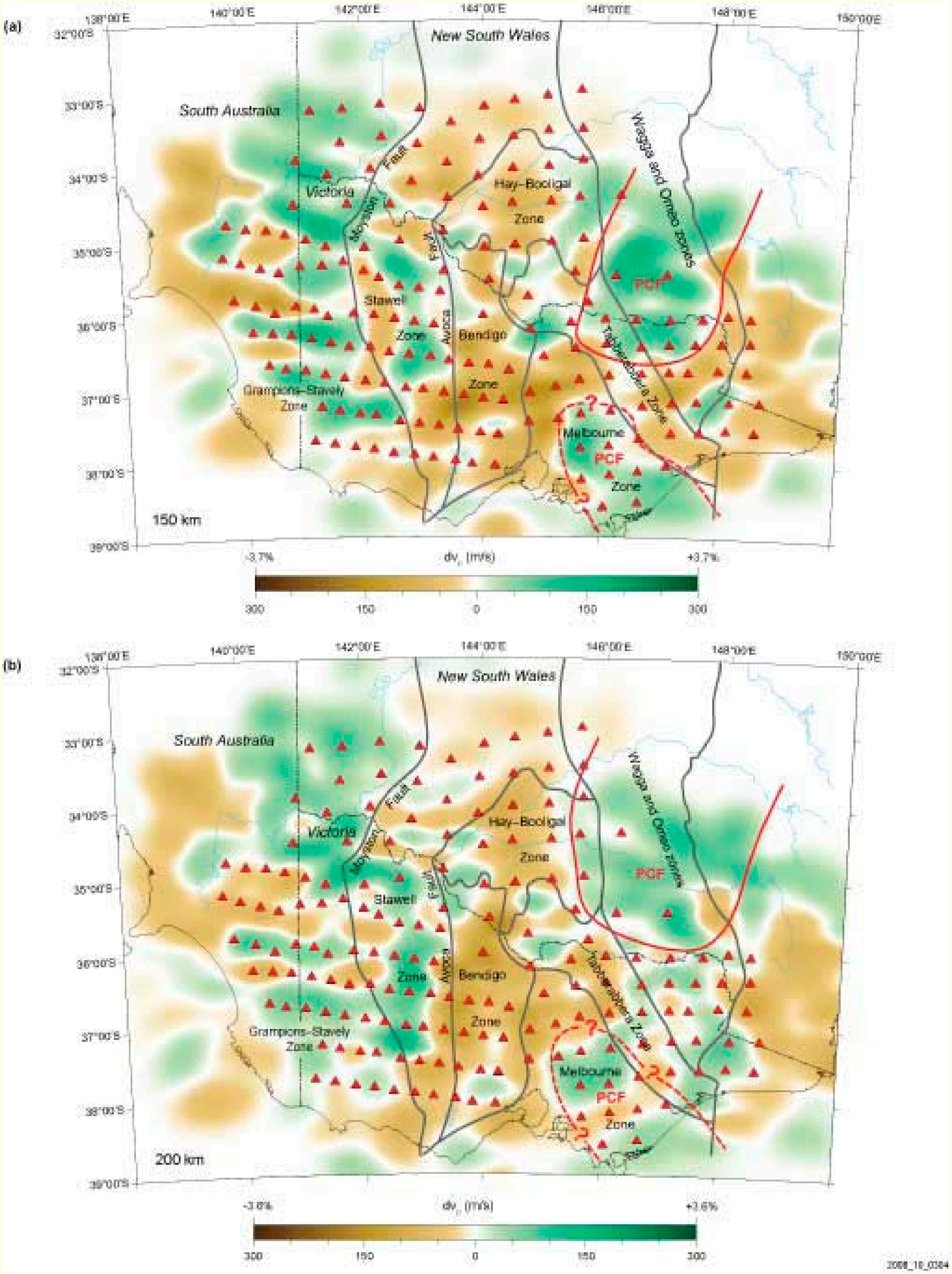

Figure 8. Two horizontal slices through the combined solution model shown with features of interest highlighted. (a) Depth slice at 150 km. (b) Depth slice at 200 km. PCF = Proterozoic Crustal Fragment. The black structural boundaries are from Glen 2005 and Hallett et al. 2005. Variation in wavespeed of P-waves (Vp) is also expressed as % of average wavespeed (-% = slower Vp; +% = faster Vp).

Gray 2000). However, if this is the case, the anomalies would have a greater north–south extent. An argument against a Proterozoic crustal fragment origin for fast Vp comes from the Selwyn Block of central Victoria, a Precambrian crustal substrate in the Lachlan Orogen (Cayley et al. 2002), which encompasses domains of both fast and slow Vp. Similarly, the possible Precambrian block beneath the Hay–Booligal Zone (Glen & Musgrave in prep.) corresponds to a slow Vp domain in Figure 8.

FUTURE WORK

From the above discussion it is apparent that there is a need to resolve the mantle velocity domains in more detail, and be able to extend the analysis towards the surface so that it overlaps with the seismic reflection profiling. This will be possible because of the large volumes of passive seismic data collected to date by the arrays shown in Figure 7; so far only a relatively small proportion of useful information has been extracted. Almost exclusively, this has been in the form of teleseismic P-wave arrival time residuals. Other data that could be used include receiver functions (only for three-component stations), ambient noise, and teleseismic S-wave arrival times. Receiver functions and ambient noise data have the potential to resolve structures within the crust at high resolution, and naturally complement the teleseismic data (which only constrains the upper mantle). Thus, by combining these multiple data types, it should be possible to image both the crust and lithospheric mantle at high resolution. That would provide valuable insight into the geology and tectonic evolution of the region. The use of S-wave information should provide important additional constraints on the physical and petrological properties of the mantle.

The potential of ambient noise tomography, which exploits diffuse seismicity generated in the Earth largely by oceanic and atmospheric disturbances, is immense. Compared to traditional tomography based on deterministic sources, such as explosions or earthquakes, it has the advantage that data coverage is dictated purely by the array geometry. In Australia, ambient noise tomography has recently been carried out using records from the continent-wide deployments of broadband stations undertaken by the Research School of Earth Sciences over the last decade and a half. The resultant images (Rawlinson 2008) clearly discriminate between hard rock areas and regions of thick sedimentary cover or high heat flow. Application of this technique to ambient noise data from the arrays shown in Figure 7 will allow the top 5 km to 15 km of the crust to be imaged at a horizontal resolution of 40 km or better. Clearly, this would provide important constraints on the broad-scale geology of prospective regions, such as the Ordovician Macquarie Arc, which hosts world class deposits of copper and gold such as Cadia.

ACKNOWLEDGEMENTS

The SEAL2 research described above was undertaken as a collaborative agreement with the Australian National University and the NSW Department of Primary Industries through the *New Frontiers* initiative of the NSW Government.

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GLOSSARY

***ak*135**	Name of a standard global reference velocity model, derived from earthquake data.
Broad band stations	Records both teleseismic body waves and surface waves over a much wider range of frequencies (frequency of 0.025 s or less (40 s period)) than short-period stations. They are physically larger and more cumbersome to deploy than short-period stations.
EVA	Earthquake Vulnerability Analysis
FMTT	Fast Marching Teleseismic Tomography
LF98	Lachlan Fold Belt seismic survey 1998
MB99	Murray Basin seismic survey 1999
PcP	P-wave reflection from the core-mantle boundary
PKiKP	P-wave reflected from the inner core boundary
PKPdf	As for PKIKP, but P-wave transmits through the inner core
P-wave	A seismic body (primary) wave in which particle motion is in the direction of propagation
RMS	Root Mean Square
ScP	Same as PcP, but the incident wave is an S-wave, which gets converted to P upon reflection
SEAL	South East Australia Linkage
Short-period stations	Records the high frequency component of the teleseismic body wave at the corner frequency (or natural period) of 1Hz. They are compact for efficient deployment in the field.
SKiKP	Reflection from the inner core boundary. Wave begins as an S-wave in the mantle, becomes compressional in the outer core (which is liquid) and returns to the surface as a P-wave in the mantle.
SKIPPY	Name of a project of the Research School of Earth Sciences, ANU
sP	S-wave from earthquake at depth, converted to P-wave at surface
sPdiff	As for sP, but P-wave segment diffracts along the core-mantle boundary
SRTM	Shuttle Radar Topography Mission
S-wave	A seismic body (secondary) wave in which the particle motion is perpendicular to the direction of propagation.

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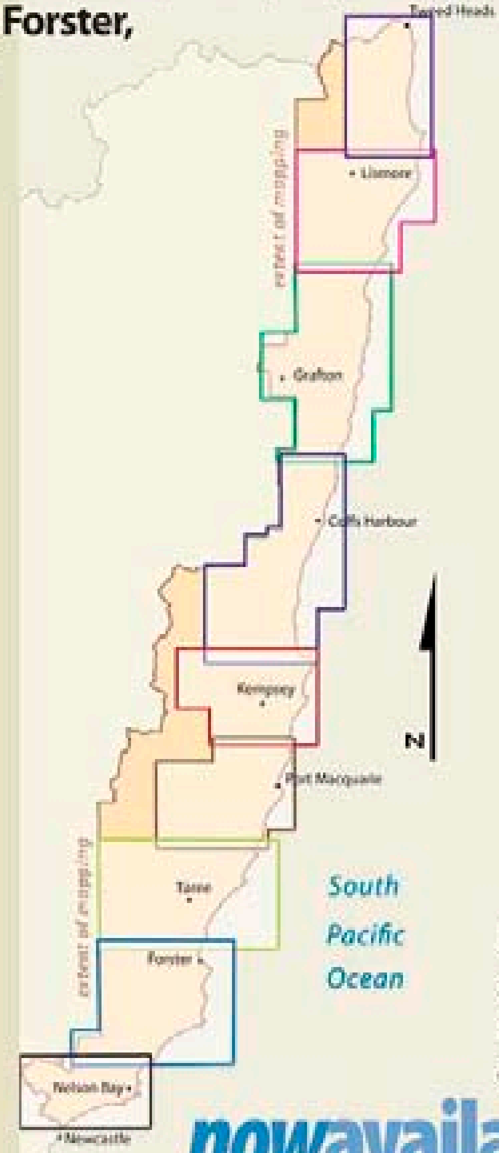
NSW coastal Quaternary geology

Nine hard copy maps covering the Tweed Heads, Lismore, Grafton, Coffs Harbour, Kempsey, Port Macquarie, Taree, Forster, and Nelson Bay areas.

In 2005, the Geological Survey of NSW released high-resolution (1:25000 or better) digital mapping data of the coastal Quaternary deposits of New South Wales (excluding the Greater Sydney region) as part of its contribution to the Comprehensive Coastal Assessment. A series of 1:100000 and 1:25000 hard copy map products has now been produced from the digital data for the nine areas of the North Coast. The maps are double-sided and show on one side a 1:100000 overview of the area's Quaternary geology. On the reverse side there are two to four maps of key areas of the region at 1:25000. A well illustrated set of explanatory notes has now also been published to accompany the maps. The map data represents a vast improvement on hitherto available geological mapping in the coastal lowland areas of New South Wales, due to its greater degree of differentiation of depositional units, and a unique methodology that has enabled the simultaneous mapping of surface and shallow sub-surface sedimentary deposits.

The Quaternary geology was combined with existing 1:250000 bedrock mapping, and the GIS-based map product was complemented by linked databases, such as the locations of past mineral sands mining, mining and quarrying activity, field sampling data and sediment characteristics. Information contained in the mapping can assist with land-use planning and natural resource management issues, for example, through conversion to predictive maps of geological hazards, land-use capability, or location of extractive resources. A series of four hard copy maps at 1:100000 and 1:25000 for the South Coast region is expected to be available in 2009.



Quaternary geological mapping depicts the spatial distribution of both surface landforms and subsurface sedimentary materials, i.e. morphostratigraphic units. The maps produced are of higher resolution than most conventional geology maps. An innovative multi-layered data structure permits the simultaneous mapping of surface and up to two subsurface units at a given location.

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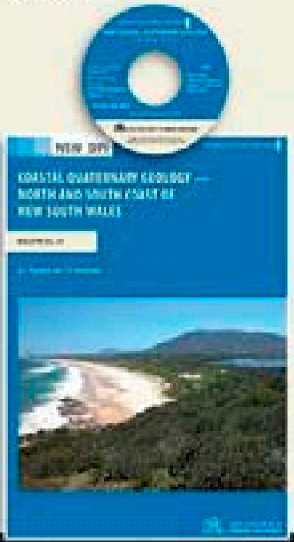

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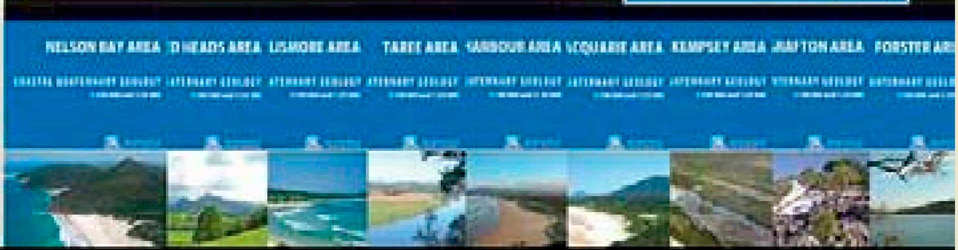

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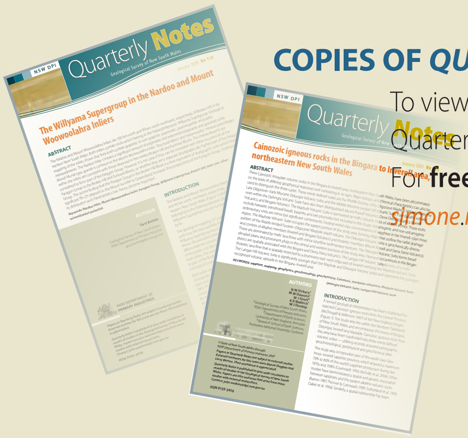

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