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SEISMIC ANALYSIS OF IGNEOUS SYSTEMS IN SEDIMENTARY BASINS AND THEIR IMPACTS ON HYDROCARBON PROSPECTIVITY: EXAMPLES FROM THE SOUTHERN AUSTRALIAN MARGIN

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ABSTRACT

The increasing availability of 3D seismic data from sedimentary basins at volcanic and non-volcanic continental margins has provided fundamental new insights into both the storage and transport of magma in the continental crust. As global hydrocarbon exploration increasingly focuses on passive margin basins with evidence for past intrusive and extrusive igneous activity, constraining the distribution, timing and pathways of magmatism in these basins is essential to reduce exploration risk. Producing and prospective Australian passive margin basins where igneous systems have been identified include the Bight, Otway, Bass, Gippsland and Sorell basins of the southern margin. This paper reviews both the impacts of volcanic activity on sedimentary basin hydrocarbon prospectivity (e.g. advective heating, reservoir compartmentalisation and diagenesis), and the styles, distribution and timing of late Cretaceous–Recent extrusive and intrusive igneous activity along basins of the southern Australian margin, providing illustrative examples based on 2D and 3D seismic reflection data.

KEYWORDS

Australia, sedimentary basins, volcanics, intrusives, seismic reflection, petroleum systems.

INTRODUCTION

The past few decades have witnessed a progressive shift of focus in the quest for new conventional hydrocarbon resources, away from the onshore and shallow-water regions that dominated production throughout the 20th century, and towards the submerged and often deep-water (>500 m below sea level) continental margins that fringe the deep ocean basins (White et al, 2003). Although exploration of all hydrocarbon basins is subject to problems (Doré et al, 2002), exploration of continental margins poses major risks due to the significant geological uncertainties that stem from sparse data coverage and their poorly understood formation and evolution. An important geological risk associated with exploration in almost all continental margins is the presence of igneous rocks. Volcanic activity is a key outcome of lithospheric stretching processes (Planke et al, 2000), and thus all extensional sedimentary basins located along continental margins witness some degree of intrusive and extrusive activity during their life spans. This includes basins that are located along margins considered to be 'cold', or 'non-volcanic' (White et al, 2003).

Hydrocarbon exploration has traditionally overlooked or avoided basins containing igneous rocks (Schutter, 2003; Rohrman, 2007). This is mainly because of the difficulties associated with seismic imaging of sedimentary sequences beneath basalt covers, and the detrimental short-term and long-term impacts on petroleum systems, including reservoir degradation and compartmentalisation (Schutter, 2003; Planke et al, 2005; Rohrman, 2007). The depletion of reserves in traditional hydrocarbon provinces, however—coupled with improvements in seismic acquisition and processing methods in basins containing problematic high-impedance layers (e.g. basalts)—has led to increasing exploration activity, with some notable successes in basins containing igneous rocks. These include the Faroe-Shetland, Vøring and Møre basins of the northwest European Atlantic margins (Smallwood and Maresh, 2002; Archer et al, 2005; Planke et al, 2005; Rohrman, 2007), and the Browse Basin of the Australian North West Shelf (Symonds et al, 1998).

One of the chief factors that has empowered explorers working in volcanic basins has been the increasing availability and quality of 2D and 3D seismic data (Cartwright and Huuse, 2005) and the development of new interpretative tools and workflows for characterising both extrusive and intrusive igneous rocks and related phenomena (e.g. Bell and Butcher, 2002; Davies et al, 2002; Thomson and Hutton, 2004; Planke et al, 2005; Hansen and Cartwright, 2006; Thomson and Schofield, 2008). Though significant challenges in understanding volcanic systems in sedimentary basins remain, the recent advances in seismic imaging and interpretation have considerably aided explorers in delineation and assessment of prospects (Rohrman, 2007). They have also provided invaluable insights into long-standing controversies regarding the storage and transport of magma through the upper crust (Cartwright and Hansen, 2006; Thomson and Schofield, 2008).

To date, most investigations into igneous systems at continental margins have understandably focused on volcanic rifted margins, where continental breakup was accompanied by abundant subaerial volcanism and intra-crustal intrusive activity. Such margins include the northwest European Atlantic margin (Bell and Butcher, 2002; Davies et al, 2002; Thomson and Hutton, 2004; Planke et al, 2005; Hansen and Cartwright, 2006; Thomson and Schofield, 2008), and to a lesser extent the North West Shelf of Australia, which has been described as a transitional-type volcanic margin (Symonds et al, 1998; Rey et al, 2008). Volcanic and intrusive rocks also occur along many 'non-volcanic' margins, however, where thick and extensive basaltic lava sequences and their attendant imaging problems are absent. One such margin is the southern Australian margin, which contains a scattered record of late Cretaceous–contemporary igneous activity (Schofield and Totterdell, 2008). Both extrusive and intrusive rocks have been recognised on offshore

seismic data from producing and prospective sedimentary basins, including the Bight, Otway, Torquay, Sorell, Bass and Gippsland basins (Fig. 1), though there are many outstanding questions regarding the age, distribution and origins of this magmatic activity (Schofield and Totterdell, 2008). This paper reviews some of the recent methodological advances of seismic imaging and interpretation of igneous systems in sedimentary basins, and assesses the implications of igneous activity for petroleum systems in prospective basins. Critically, however, it also provides the first margin-wide synthesis of the distribution of extrusive and intrusive igneous rocks along the offshore southern margin.

SEISMIC IMAGING OF IGNEOUS ROCKS IN SEDIMENTARY BASINS

The first studies to describe offshore igneous rocks at submerged rifted continental margins used regional-scale 2D seismic reflection and refraction profiles (e.g. Hinz, 1981; White et al, 1987). These investigations led to two key observations regarding the styles of igneous activity accompanying continental breakup:

1. the occurrence of prominent wedges of seaward dipping reflectors (SDR) near the continent-ocean transition, which have been confirmed by drilling to consist of stacks of subaerially emplaced flood basalts (White and McKenzie, 1989; Planke et al, 2000), and;
2. high P-wave velocity (V_p > 7 km s^{-1}) bodies in the lower crust, originally interpreted as magmatic underplated material (White et al, 1987), but now recognised to comprise suites of basic sills that cross-cut the fabric of the extended continental crust (White et al, 2008).

These criteria have been successfully employed to map the regional-scale distribution of igneous rocks at several continental margins (White and McKenzie, 1989), though major challenges remain in defining the distribution of igneous systems at basin-scales and below, particularly at margins that contain thick basalt sequences (Archer et al, 2005).

Sub-basalt imaging is problematic because of the high impedance, and the internal physical heterogeneities of layered basaltic sequences tend to generate strong multiple reflections and lead to scattering of the seismic signal (Rohrman, 2007). This issue is less relevant to basins at non-volcanic margins such as the southern Australian margin, where thick sequences of layered basaltic lava flows are rare, although the occurrence of intrusive sills and dykes in these settings can equally degrade seismic quality in deeper sections. Other problems with basalts, and indeed other igneous rocks, may arise if they have been subject to significant weathering and subsequent burial, resulting in lower impedance values that may make it difficult to distinguish them from clastic rocks (Rohrman and Lisk, 2010).

In basins where thick, layered flood basalt sequences are absent, extrusive and intrusive rocks can be identified relatively easily with seismic reflection data, due to the differing rock properties between the igneous rocks and the host basinal sedimentary sequences (Fig. 2). Basic lava flows (e.g. basalts) and sills (e.g. dolerites) have seismic velocities commonly >5 km s^{-1} and densities of ~2,750–3,000 kg m^{-3}, which contrast markedly with those of typical host sedimentary rocks such as shales and sandstones (<3 km s^{-1} and <2,500 kg m^{-3}) (Planke et al, 2000; Bell and Butcher, 2002). The unusually high densities and velocities combine to give acoustic impedance contrasts commonly >40%, resulting in considerably higher amplitude seismic reflection events compared to sedimentary bodies of identical thickness, which tend to have typical impedance contrasts of ~10% (Thomson, 2005). Other rock property contrasts between basic sills and sedimentary host rocks can be identified using wireline logging tools. For example, basic sills tend to show reduced responses on gamma ray logs (~35–45 API lower than adjacent sediments) and variable electrical resistivity (~1,000–2,000 ohm m), although substantially higher

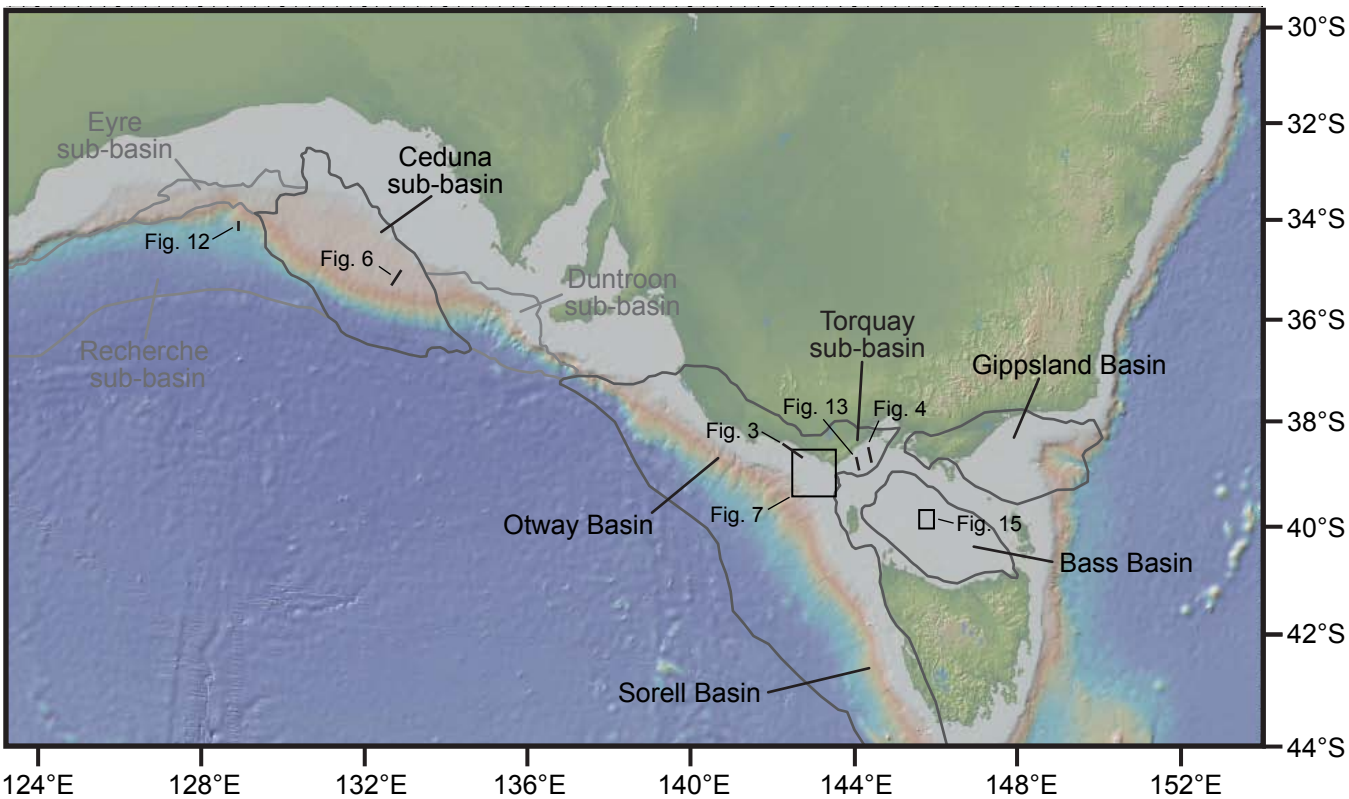

Figure 1. Location map showing basins along the southern Australian margin where igneous rocks have been identified from seismic data or intersected during drilling. Basins outlined in black are discussed in detail throughout this paper.

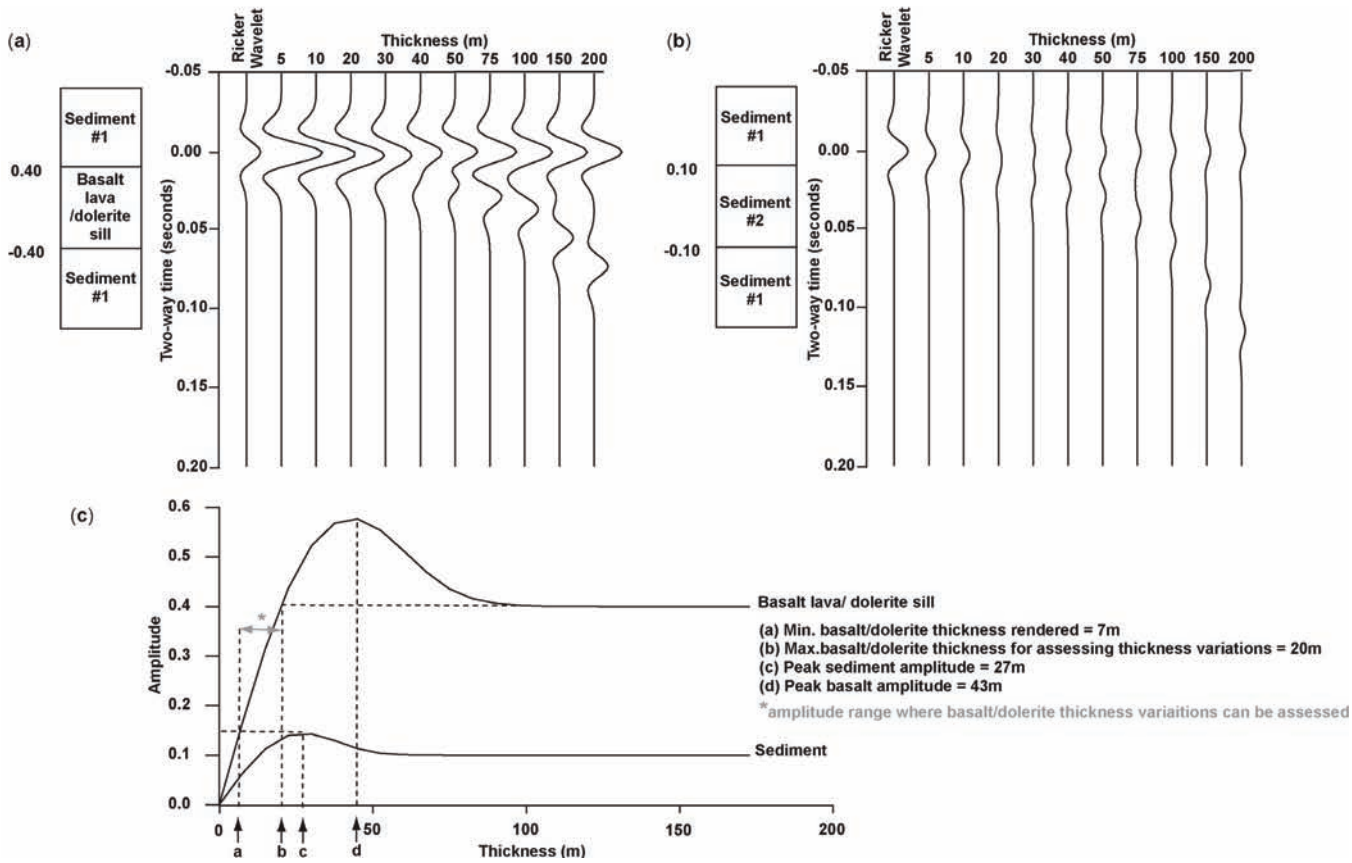

Figure 2. (a) The seismic response of a basalt of varying thickness (velocity = 5.5 km s^{-1}, acoustic impedance contrast = 40%, Ricker wavelet frequency = 25 Hz). The left side shows the schematic lithological succession and the acoustic impedance contrasts at the lithological boundaries. The seismic (Ricker) wavelet and the seismic response for various basalt thicknesses are shown on the right. (b) The seismic response of a sediment of varying thickness (velocity = 3.5 kms^{-1}, acoustic impedance contrast = 10%, Ricker wavelet frequency = 25 Hz). The left side shows the schematic lithological succession and the acoustic impedance contrasts at the lithological boundaries. The seismic (Ricker) wavelet and the seismic response for various Sediment #2 thicknesses are shown on the right. (c) Maximum amplitude versus thickness plot for both the basalt and sediment based on (a) and (b). In both cases, the peak amplitude corresponds to optimum seismic tuning thickness of the layer (basalt = 43 m, sediment = 27 m). The optimum seismic tuning thickness of the sediment layer has an amplitude of 0.15, which corresponds to a basalt thickness of 7 m. Consequently, making all the sediment transparent (i.e. making amplitudes ≤0.15 transparent) would result in all basalts with a thickness >7 m being rendered. Furthermore, basalt thickness variations in the 7–20 m range can be assessed. Modified after Thomson (2005).

than that of the host sedimentary rocks (Bell and Butcher, 2002; Smallwood and Maresh, 2002).

The high impedance contrasts that occur at the interfaces between igneous bodies and surrounding sediments mean that igneous intrusions and extrusive lava sequences imaged in sedimentary basins typically form the highest amplitude events in a seismic survey after the seabed event. Seismic modelling indicates that igneous bodies with thickness of about 30–40 m show the highest amplitude on seismic sections, due to constructive interference (tuning) at typical seismic frequencies, of the seismic events caused by the top and base of the sill or lava flow (Bell and Butcher, 2002; Smallwood and Maresh, 2002). In sills of greater thickness it may be possible to identify the top and base of the event, though it can be difficult to interpret whether an observed seismic event results from one sill or a package of stacked sills (Bell and Butcher, 2002), with the low energy penetration through sills meaning the quality of seismic reflection data can often be very poor below the uppermost sill reflector (Smallwood and Maresh, 2002). Furthermore, because standard seismic reflection acquisition geometries and standard processing methods are not designed to image vertical or very steep structures, vertical intrusions (i.e. dykes) may not be imaged and it may be difficult to image steeply inclined limbs of sills (Smallwood and Maresh, 2002). Figures 3 and 4 provide some examples of intrusive and extrusive igneous bodies imaged on 2D seismic profiles from the Otway Basin and Torquay sub-basin that are generally easily distinguishable from surrounding sedimentary rocks using conventional amplitude and envelope attributes.

INTERPRETING IGNEOUS ROCKS IN SEDIMENTARY BASINS USING SEISMIC DATA

Interpretative techniques

As in many other areas of earth science, the proliferation of 3D seismic surveys that cover large areas (typically >1,000 km^2) and high lateral resolution (typically 20–200 m depending on target depth) has provided researchers working in sedimentary basins with valuable datasets that have allowed a wide range of extrusive and intrusive products to be identified (Cartwright and Huuse, 2005). Approaches to the analysis of igneous rocks using 3D seismic datasets have generally followed two approaches: mapping of events using specific criteria for identification of extrusive and intrusive bodies, and 3D volume visualisation, which uses opacity rendering or geobody extraction.

Conventional mapping using 3D seismic datasets enables excellent control on the morphology of igneous intrusions and extrusive flows, and confident separation between separate intrusions and adjacent high-amplitude stratal reflections, which can be difficult to discriminate using volume visualisation techniques (Hansen and Cartwright, 2006). Mapping of igneous bodies as horizons also enables creation of amplitude or other attribute maps that can reveal valuable information on the morphological characteristics of extrusive or intrusive features (Smallwood and Maresh, 2002; Hansen et al, 2004; Miles and Cartwright, 2010). Some workers have adapted concepts from seismic stratigraphy when attempting to identify and in-

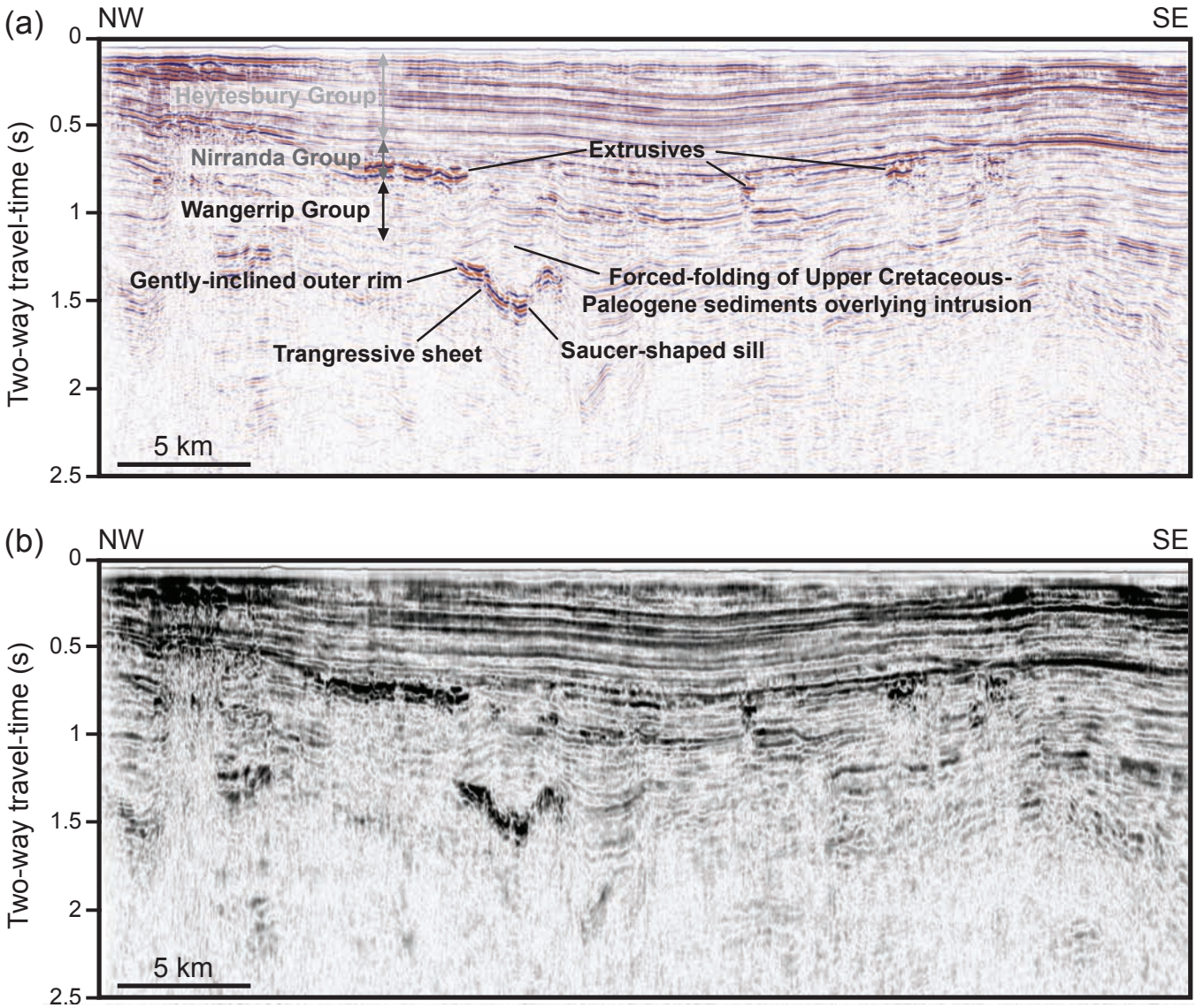

Figure 3. (a) Amplitude display of seismic reflection profile OH91-112 from the central Otway Basin (Portland Trough to the west, Port Campbell Embayment to the east), illustrating a variety of intrusive and extrusive igneous features of Palaeogene age observable in Upper Cretaceous–Palaeogene sedimentary units, including a large saucer-shaped sill (diameter ~4 km, amplitude ~0.25 s twtt), which has caused forced-folding of overlying sedimentary units. Note how igneous rocks tend to form the highest amplitude events below the seabed. (b) Envelope display of seismic reflection profile OH91-112. Igneous rocks are particularly conspicuous and can easily be discriminated from surrounding sedimentary rocks.

terpret volcanic sequences in sedimentary basins. Planke et al (2000) introduced the method of seismic volcanostratigraphy to aid interpretation of extrusive sequences at continental margins, assigning seismic facies units to different volcanic deposits based on their bounding and internal seismic reflection characteristics, and wherever possible coupled to synthetic seismograms based on available drilling data. By applying this approach on a regional-scale to the northwest European Atlantic margin and the Australian North West Shelf, Planke et al (2000) have been able to define distinct extrusive provinces reflecting different tectonomagmatic and depositional settings. Seismic stratigraphic methods can also be applied to identify and discriminate between different styles of igneous intrusions in sedimentary basins. In a study of intrusive complexes in the Møre and Vøring basins along the Norwegian Atlantic margin, Planke et al (2005) were able to identify nine types of sills (mostly layer parallel or saucer-shaped) on the basis of distinct seismic characteristics.

An additional approach to analysing intrusive and extrusive complexes in sedimentary basins using 3D seismic data is that of seismic volume visualisation, and in particular opacity rendering (Bell and Butcher, 2002; Smallwood and Maresh, 2002; Thomson and Hutton, 2004; Planke et al, 2005). This method uses the conversion of 3D seismic data into a voxel volume, in which each voxel retains the information from the original portion of the seismic volume that it occupies, with an additional user-defined variable that controls its opacity (Thomson and Hutton, 2004). The user can vary the opacity of individual voxels as a function of their seismic amplitude; consequently, it is relatively easy to make the surrounding sedimentary country rocks transparent while preserving igneous rocks with high seismic amplitudes as opaque features (Thomson and Hutton, 2004). This approach has mainly been applied to the study of sill complexes (e.g. Bell and Butcher, 2002; Smallwood and Maresh, 2002; Thomson and Hutton, 2004; Thomson and Schofield, 2008), and has proven particularly successful in enabling lobate structures that are indicative of magmatic flow directions to be identified (Schofield et al, in press). The method of opacity rendering has one distinct advantage, in that the images produced are a function of manipulation of the raw amplitude data. To an extent, this removes interpretational bias that a user may introduce during normal conventional seismic picking techniques.

Studies of extrusive systems using opacity rendering have been less common, with the notable exception of Thomson

(2005) who applied this technique to 3D seismic data containing a buried basaltic succession from the North Rockall Trough, UK Atlantic Margin. Thomson (2005) was able to visualise a complex volcanic terrain comprising lava flows originating from discrete volcanic centers, linear and radial fissures, inflation ridges and a large hyaloclastic delta system. Figure 5 presents an example of the application of opacity rendering to 3D seismic data acquired over the Yolla gas field in the Bass Basin, in which it has been possible to visualise a large Miocene-age volcanic complex that overlies the reservoir units.

New insights into igneous process from 3D seismic data—sill morphology and emplacement

While it is beyond the scope of this paper to provide a comprehensive examination of the large body of literature on seismic analysis of igneous systems in sedimentary basins that has accumulated during the past decade, the remainder of this section reviews two key outcomes from this work: the new insights that have been obtained into sill morphologies and emplacement mechanisms and their role in the transport of magma through the crust, and the widespread recognition of hydrothermal vents in basins affected by igneous activity.

Investigations of intrusive complexes using 2D and 3D seismic surveys from sedimentary basins along the northwest European Atlantic margin (e.g. Bell and Butcher, 2002; Smallwood and Maresh, 2002; Trude et al, 2003; Hansen et al, 2004; Thomson and Hutton, 2004; Planke et al, 2005; Cartwright and Hansen, 2006; Thomson and Schofield, 2008) have consistently reported the predominance of concave-upwards, 'saucer-shaped' sills with radially or bilaterally symmetrical forms that possess flat or gently concave inner saucers connected to flat outer rims by steeply inclined, transgressive sheets. Although the concave-upwards morphology of doleritic sills has long been recognised from classic field examples (e.g. from the Karoo Basin [Du Toit, 1920] and Tasmania [Leaman, 1975]), factors such as erosion and incomplete exposure meant that the true, three-dimensional geometries of sills could only be completely revealed with the advent of 3D seismic datasets. Hansen et al (2004) and Thomson and Schofield (2008) present detailed studies of the three-dimensional geometries of buried sills along the northwest European Atlantic margin, and their relationships to pre-existing structures and lithological heterogeneities in sedimentary basins.

While recent investigations of intrusive complexes using 3D seismic data have provided crucial data that confirm field-based models of sill geometries, their findings have also challenged long-standing models of sill growth and emplacement, and have shed new light on the roles that sills play in the transport of magma through the crust. Classic mechanisms for sill intrusion include the compensation model of Bradley (1965) and the gravitational flow model of Francis (1982). The former model suggests that sills, fed by ascending dykes, intrude at depths where the magma pressure equals lithostatic pressure (the 'compensation level'), resulting in sills that form a mirror image of the overlying topography. The latter model proposes that sills begin to grow when ascending dykes overshoot the compensation level, and since the magma is denser than the surrounding country rocks it will flow laterally downwards and accumulate in the basin floor—exploiting bedding where possible but regularly transgressing. Eventually the forces attempting to re-establish hydrostatic equilibrium will drive magma upwards from the basin floor, resulting in a concave-upwards, saucer-shaped intrusion. Both these models envisage that sills are initially fed by dykes, and that both upwards and downwards flow of magma is possible.

Studies of sills using both horizon mapping and opacity rendering have shown it is possible to resolve small-scale surface features that provide valuable kinematic indicators for the propagation of sills (Cartwright and Huuse, 2005). Recognition of features such as flow ridges (Trude, 2004) and lobate branch-

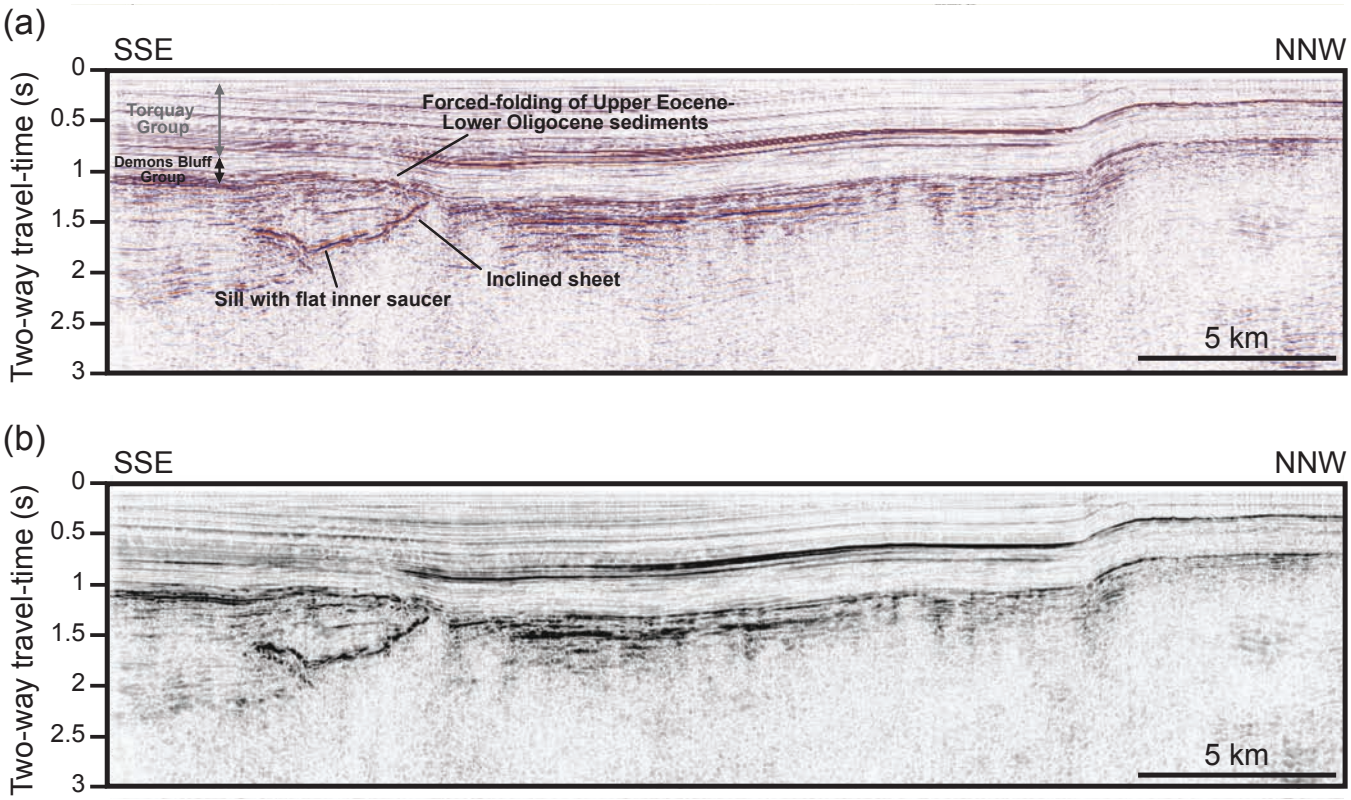

Figure 4. (a) Amplitude display of seismic reflection profile OS90A-43 from the Torquay sub-basin. A large, asymmetrical saucer-shaped sill (diameter ~4.5 km, amplitude ~0.5 s twtt) is clearly observable towards the SSE end of the profile. This intrusion has caused forced-folding of the overlying Demons Bluff Group and the basal Torquay Group sediments (Upper Eocene–Lower Oligocene age), enabling the age of this sill to be inferred. (b) Envelope display of seismic reflection profile OS90A-43.

ing patterns (Thomson and Hutton, 2004) on the surfaces of sills have been used to infer that magma is transported in sills through systems of tubes that consistently indicate upwards and outwards flow directions (Thomson and Schofield, 2008). Furthermore, detailed studies of major sill complexes, such as that of Cartwright and Hansen (2006) who mapped two major intrusive complexes in the Møre and Vøring basins, have described networks of interconnected saucer-shaped or inclined sheet-like sills, linked by junctions that occur systematically at the lowest parts of the overlying sills. These observations confirm shallower sills in intrusive complexes are fed by deeper sills, and that sill complexes can act as through going magmatic plumbing systems capable of transporting melts over vertical distances of >10 km from mid-lower crustal levels to near-surface depths without the need for intervening feeder dykes (Cartwright and Hansen, 2006).

The consistent evidence for upward and outward growth of sills away from feeder zones (which may be either dykes or other sills) that occur at the lowest point of the intrusion, is incompatible with the compensation and gravitational flow models of sill growth that predict downwards flow of magma. The former of these models proposes that sill geometries should mirror the overlying topography (Bradley, 1965), though studies that have been able to identify both sills and the topographic surface at the time of intrusion have often revealed no mirroring of the syn-intrusion topography (Thomson and Hutton, 2004). Recent investigations in the Faroe-Shetland and northeast Rockall basins along the northwest European Atlantis margin, however, have documented the occurrence of forced folds with structural relief >100 m that formed at the seabed when shallow (<1 km) saucer-shaped sills with large diameter-depth ratios (>1.5) 'jacked-up' the overlying sediments (Trude et al, 2003; Hansen and Cartwright, 2006). It has been suggested that some of the forced folds recognised in the northeast Rockall Basin in fact represent small volcanic centres (Thomson, 2007a), though forced folds that overlie sills and are not associated with extrusive systems are observed in many other offshore basins, including the Otway, Torquay and Bight basins (Fig. 6). These structures offer an indirect mechanism for assessing the timing of shallow-level intrusions, if the ages of onlapping strata can be dated (Trude et al, 2003), while forced folds above sills with four-way dip closures have been proposed as potential hydrocarbon traps (Hansen and Cartwright, 2006).

New insights into igneous process from 3D seismic data—hydrothermal vents

Seismic investigations of sill complexes have also led to the increasing recognition of hydrothermal vent systems that appear to be related to sill emplacement. Mound-like hydrothermal vents were first inferred to be related to underlying sills by studies using sparse 2D seismic data (Joppen and White, 1990), although detailed mapping of these mounds was only possible with the advent of 3D seismic data (Davies et al, 2002; Svensen et al, 2004; Planke et al, 2005; Hansen, 2006). Davies et al (2002) and Bell and Butcher (2002) first mapped these mounds with 3D seismic data in the Faroe-Shetland Basin, identifying their layered internal geometry and conical external form, and interpreting them as volcanic or volcaniclastic in origin. Subsequent workers have suggested hydrothermal

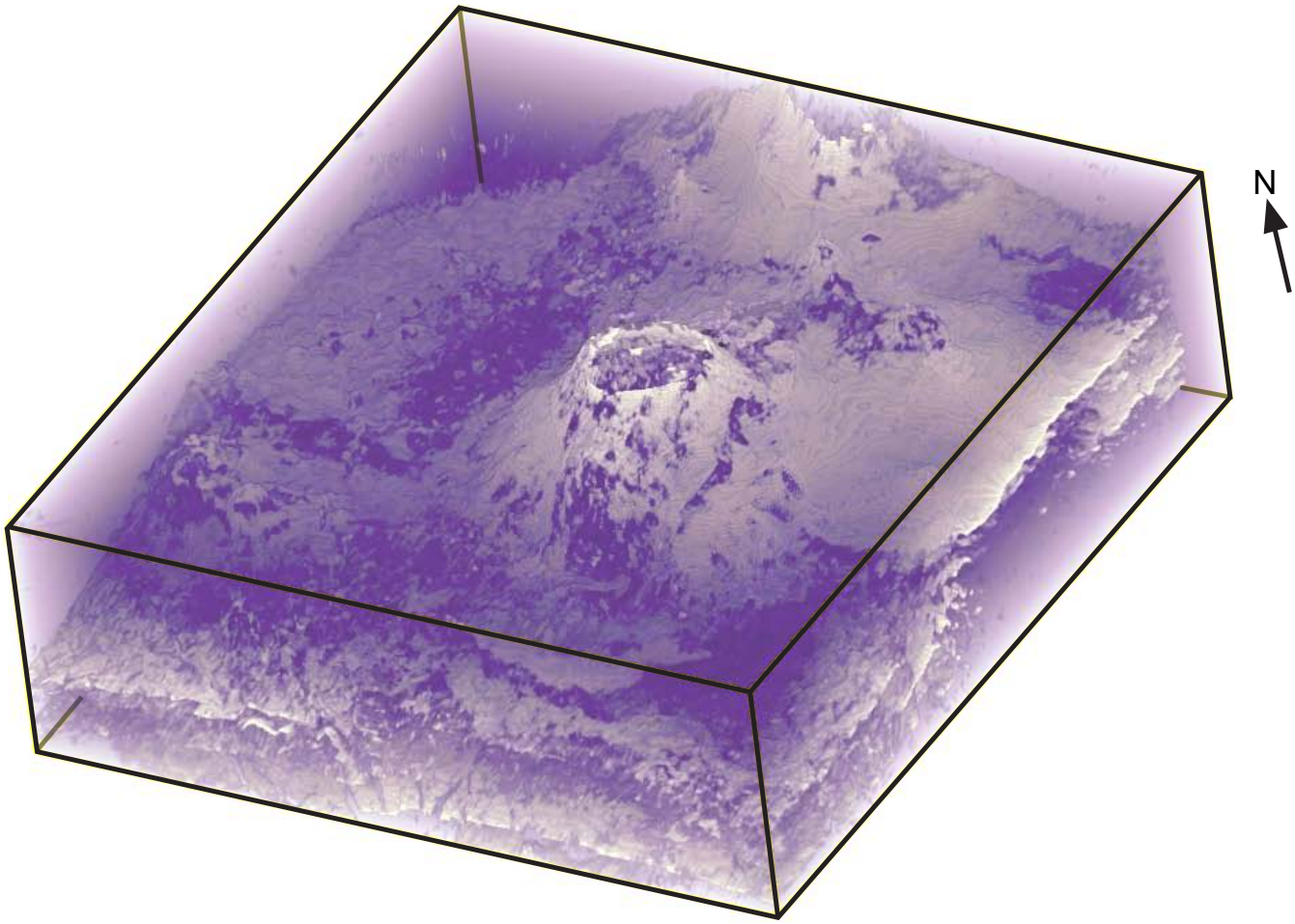

Figure 5. Visualisation of an extrusive igneous complex in the Bass Basin using opacity rendering applied to the Yolla 3D seismic survey (extent of this survey shown in Fig. 15). Opacity rendering has been applied to a subset of a bricked seismic volume between 0.9 and 1.3 s twtt. Two large volcanic vents are clearly visible, one located in the centre of the cube and another along the northeastern edge, while the top and base volcanic layers are apparent along the southwestern edge of the cube.

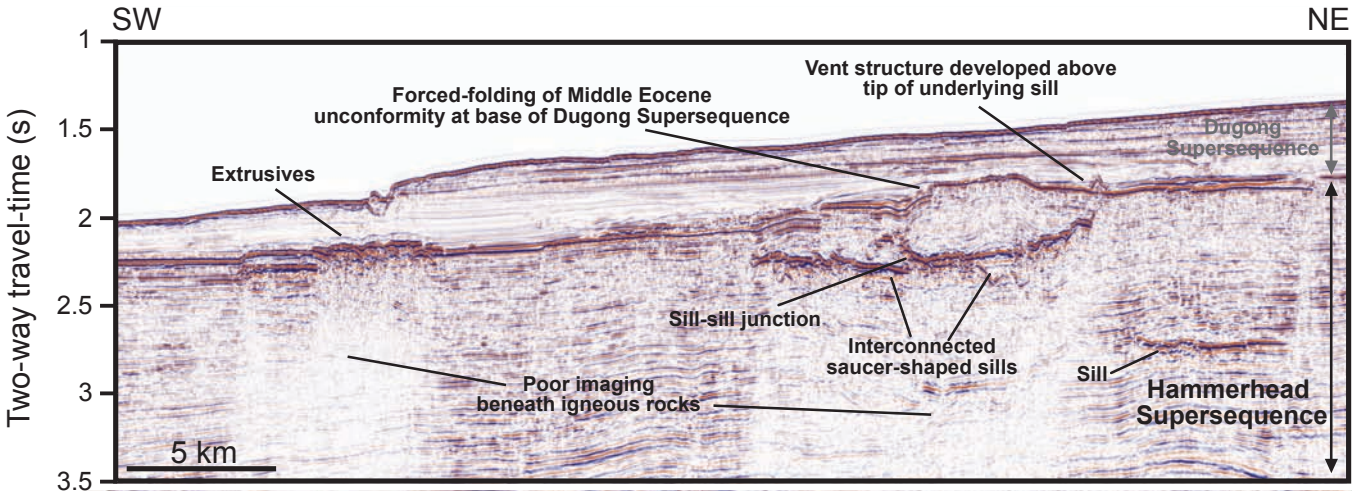

Figure 6. Amplitude display of seismic reflection profile 60 from the Flinders 2D survey, Ceduna sub-basin (modified after Schofield and Totterdell, 2008). A variety of extrusive and intrusive igneous features are apparent, including a series of interconnected, transgressive saucer-shaped sills with an associated small vent, and (fissure-fed?) extrusives towards the southwest end of the profile. Note poor quality of seismic imaging beneath igneous rocks.

vents can also be formed by the remobilisation of sediments overlying the sills by the rapid upwards movement of hydrothermal fluids that are focused at the tips of the underlying sills (Fig. 6) (Svensen et al, 2004). Hansen (2006) compiled data on the geometric characteristics of hydrothermal vents observed in various basins along the northwest European Atlantic margin, noting their commonly crater, dome or eye-shaped morphologies, with diameters ranging from 0.5–3.5 km and heights varying between 50–640 m, but mostly less than 300 m. Based on regional seismic mapping, Planke et al (2005) have estimated that at least 2,000–3,000 hydrothermal vent complexes are present in the Vøring and Møre basins alone. Since these vents form on the palaeo-surface at the time of sill intrusion, they can be used to estimate the timing of sill emplacement using seismic-stratigraphic techniques (Hansen, 2006). Hydrothermal vents are relevant to hydrocarbon exploration because the boiling and transport of host-rock pore fluids may lead to diagenetic alteration of reservoir units (Planke et al, 2005), and can potentially result in breaching of sealing sequences (Cartwright et al, 2007). Hydrothermal vents occurring in basins along the southern Australian margin have not yet been described in detail, though the authors have observed candidate features on seismic data from the Bight, Otway, Bass and Sorell basins (Fig. 6).

3D SEISMIC ANALYSIS OF AN EARLY CENOZOIC IGNEOUS COMPLEX IN THE OTWAY BASIN

In this section, a case study from the eastern Otway Basin is presented in which some of the previously described seismic interpretation methods are applied to analyse an early Cenozoic igneous complex. This represents the first systematic assessment of an igneous system in this basin using 3D seismic data to the authors' knowledge.

The described igneous system is located in the northern part of the Investigator 3D survey, about 10–15 km to the east of the Conan–1 well (Fig. 7). The Investigator 3D survey was acquired in 2000, covering 986.4 km^2 with a bin spacing of 12.5 m, and the quality of the data is good. A broadly ~north–south-trending arbitrary amplitude profile through the survey that ties the Geographe–1 and Thylacine–2 wells reveals a set of high-amplitude reflectors between ~0.75–0.9 s twtt near the northern end of the line (Fig. 8). A higher-resolution amplitude profile from the northern part of the survey reveals this set of reflectors to comprise a hybrid geometry, with a saucer-shaped northeastern reflection event that transgresses the local stratigraphy, which is apparently linked to a southwest-dipping, high-amplitude event that has an irregular appearance, but is broadly parallel to the local structural dip (Fig. 9). Amplitude time slices through these events indicate the saucer-shaped body (which is most likely a sill) has a diameter of ~3 km, and that the broadly linear southwest-dipping reflection event has a maximum width of ~3 km and length of ~5 km (Fig. 9). Based on seismic mapping of regional intra-Maastrichtian (i.e. top Sherbrook Group) and intra-Lutetian (i.e. top Wangerrip Group) unconformities in the eastern Otway Basin, it appears the lowest point of the sill occurs just above the intra-Maastrichtian unconformity, and that the layer-parallel event is situated beneath the intra-Lutetian unconformity, indicating these high-amplitude events reside in the early Palaeogene Wangerrip Group. There is clear downlap of steeper-dipping reflections that are characteristic of the progradational deltaic-marine Wangerrip Group, onto the high-amplitude layer-parallel event. These progradational reflections are also clearly visible on amplitude time slices (Fig. 9).

Detailed horizon-mapping of the saucer-shaped sill reveals it comprises a number of distinct flow lobes that are clearly apparent on both time and amplitude maps. These flow lobes radiate away from the deepest part of the sill, and a series of arbitrary lines show the sill has a step-like, segmented geometry caused by the branching of lobes as they flow upwards and outwards (Fig. 10). The lobate, branching morphology of this saucer-shaped sill is consistent with features observed in comparable intrusions that occur in basins along the northwest European Atlantic margin (Thomson and Hutton, 2004; Hansen and Cartwright, 2006; Thomson and Schofield, 2008; Schofield et al, in review), and are thought to be characteristic of sills that intruded at shallow subsurface depths (<400 m) (Miles and Cartwright, 2010). It is not possible to determine what fed this sill, but an earlier structural analysis of the Investigator 3D dataset identified a large north–south-trending strike-slip fault and numerous southwest-dipping normal faults nearby this intrusion (Palmowski et al, 2004), and it is possible that one of these structures facilitated the transport of magma from deeper levels in the basin.

Figure 11 contains a number of opacity-rendered views of the Otway Basin igneous complex. These confirm the radially-symmetrical, saucer-shaped geometry of the sill, which comprises the northeastern part of the igneous complex. They also reveal the morphological characteristics of the southwestern component of the complex, which appears to be an irregular sheet-like body with a large length:width ratio, comprising multiple generations of branching lobate segments. It is possible this component of the igneous complex represents a layer-parallel sill

that was intruded between bedding surfaces at a shallow depth. Miles and Cartwright (2010) have described similar discordant sheet-like, high-amplitude reflections from the Vigra sill complex in the Møre Basin, offshore Norway, which they interpret to be shallowly intruded sills; however, the example from the Otway Basin lacks the axial seismic amplitude anomalies observed by Miles and Cartwright (2010) that are thought to represent the magma tubes that fed the Vigra sills. An alternative interpretation of the data from the Otway Basin—favoured by the authors—is that the southwestern component of the complex is an extrusive lava flow. It is possible the saucer-shaped sill was intruded at a very shallow depth (possibly ~100–200 m subsurface at its lowest point), and that as it grew upwards and outwards, the steeply inclined lobes along the southern margin of the sill managed to intersect the palaeo-surface, causing the magma to erupt at the surface and flow for ~6 km down the southwest-dipping palaeo-slope of the basin. This interpretation, if correct, would imply a Palaeocene–mid Eocene age for this igneous complex.

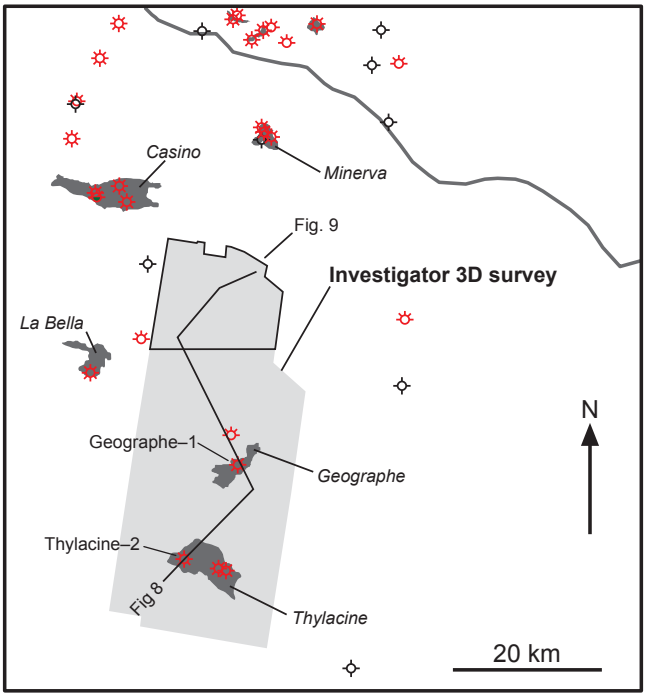

Figure 7. Location of Investigator 3D seismic survey, eastern Otway Basin, with adjoining and neighbouring gas fields indicated.

THE IGNEOUS RECORD OF THE OFFSHORE SOUTHERN AUSTRALIAN MARGIN

The Cretaceous–Cenozoic igneous record of southeastern Australia and Tasmania has been intensely studied (e.g. Johnson, 1989; Sutherland, 1991, 2003; Price et al, 2003), but there has been very little work on the offshore record of igneous activity, despite the fact that intrusive and extrusive rocks of various ages can be found in all basins along the margin (e.g. O'Halloran and Johnstone, 2001; Teasdale et al, 2003; Schofield and Totterdell, 2008).

The southern Australian margin has been classified as a non-volcanic margin (Sayers et al, 2001) due to the relatively small amount of igneous activity that accompanied Cretaceous–early Cenozoic separation from Antarctica (Norvick and Smith, 2001). This is in comparison to the voluminous extrusive and intrusive activity that accompanied the formation of archetypal 'volcanic' margins, such as the conjugate North Atlantic margins (i.e. offshore northwest Britain and Norway, and Greenland) during the early Palaeogene, and the conjugate South Atlantic margins (witnessed by the Paraná basalts of Brazil and the Etendeka basalts of Namibia and Angola) during the early Cretaceous (White and McKenzie, 1989). Some rift-related volcanism of late Jurassic and early Cretaceous ages, associated with Casterton and Eumeralla Formations of the Otway Group has been recognised in the Otway Basin (Duddy, 2003). Late Cretaceous intrusive and extrusive activity associated with rifting has also been described from the northeastern

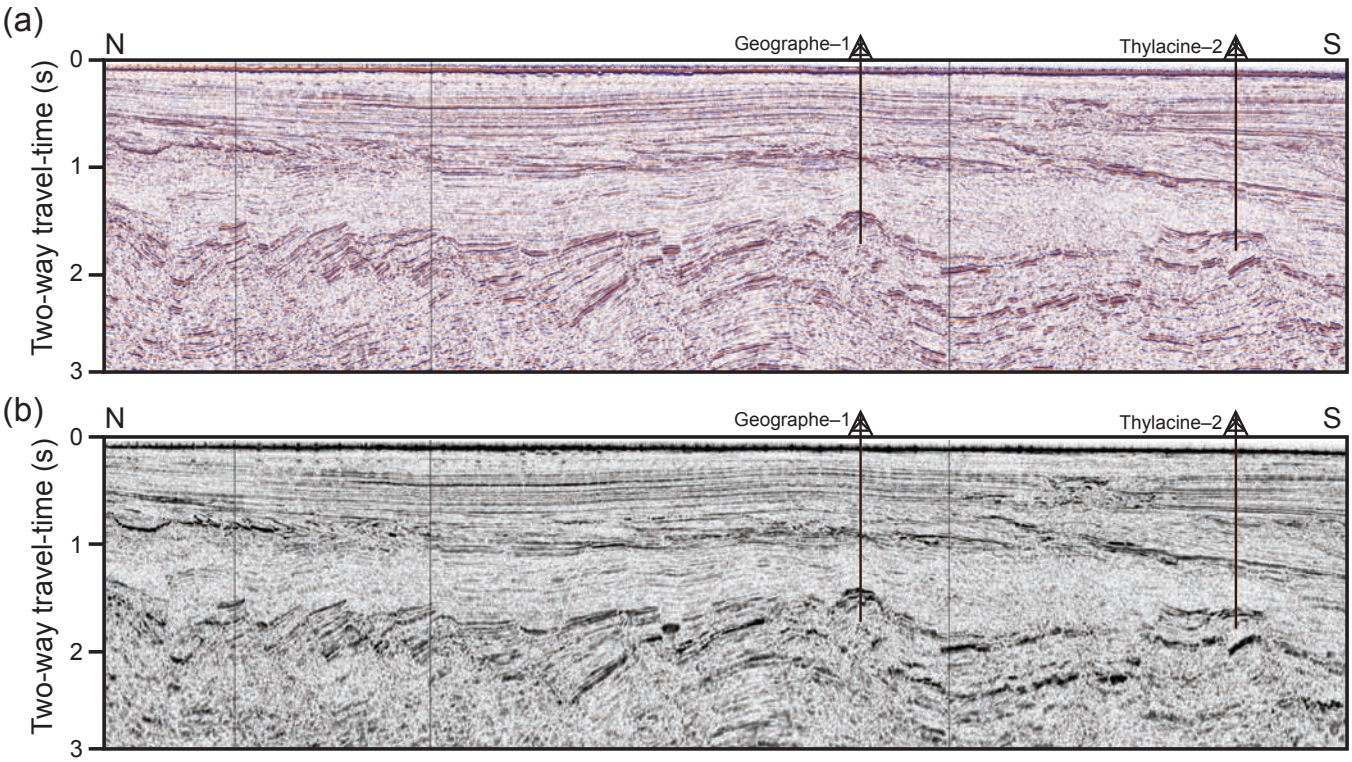

Figure 8. (a) Amplitude and (b) envelope displays of arbitrary seismic reflection profile through the Investigator 3D survey. Profile intersects the Geographe–1 and Thylacine–2 wells. Note prominent high-amplitude reflectors at northern end of profile. See text for further discussion.

Gippsland Basin (O'Halloran and Johnstone, 2001). The extensive record of Cretaceous–Cenozoic, dominantly basic igneous activity in southeastern Australia, is most commonly attributed to southward-migrating, plume-related magmatism (Johnson et al, 1989; Sutherland, 1991, 2003); however, the presence of an extensive magmatic complex in the offshore Bight Basin of presumed mid-Eocene age that appears to correlate with contemporaneous volcanic activity in Victoria, suggests the record of Cretaceous–Cenozoic igneous activity along the southern margin may not be solely attributable to southward migrating plume activity (Schofield and Totterdell, 2008).

Bight Basin

The Bight Basin is a large, mainly offshore basin that contains five main depocentres: the Ceduna, Duntroon, Eyre,

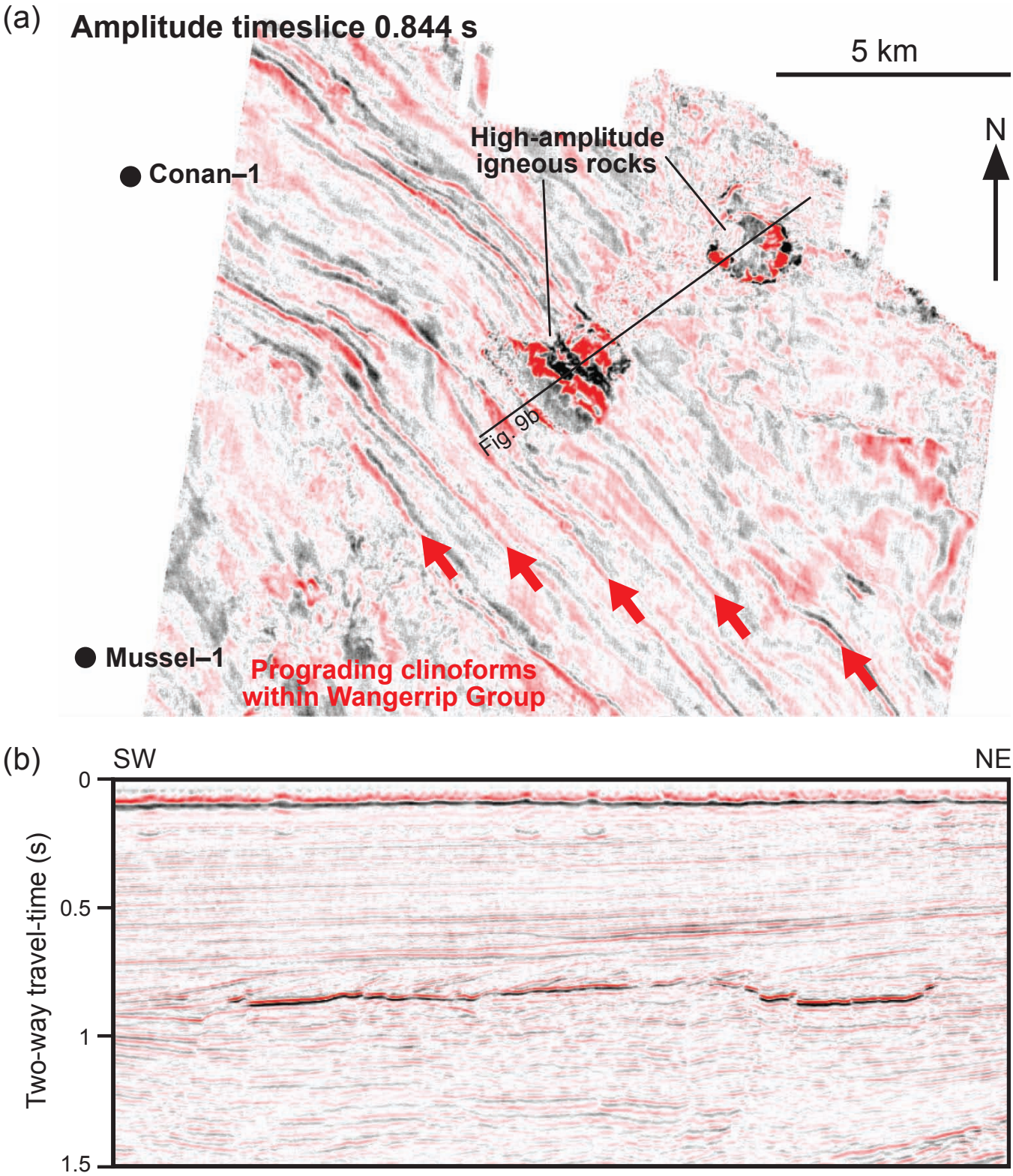

Figure 9. (a) Amplitude slice (0.844 s twtt) through the northern part of the Investigator 3D survey. Two high-amplitude igneous bodies clearly stand out from the surrounding sedimentary rocks. Strong ~NW–SE-trending fabric in the seismic data is caused by southwesterly prograding clinoforms in the early Palaeogene Wangerrip Group. (b) Arbitrary seismic amplitude profile (uninterpreted) illustrating nature of the high-amplitude igneous rocks and their relationship with surrounding sedimentary layers. See text for further discussion.

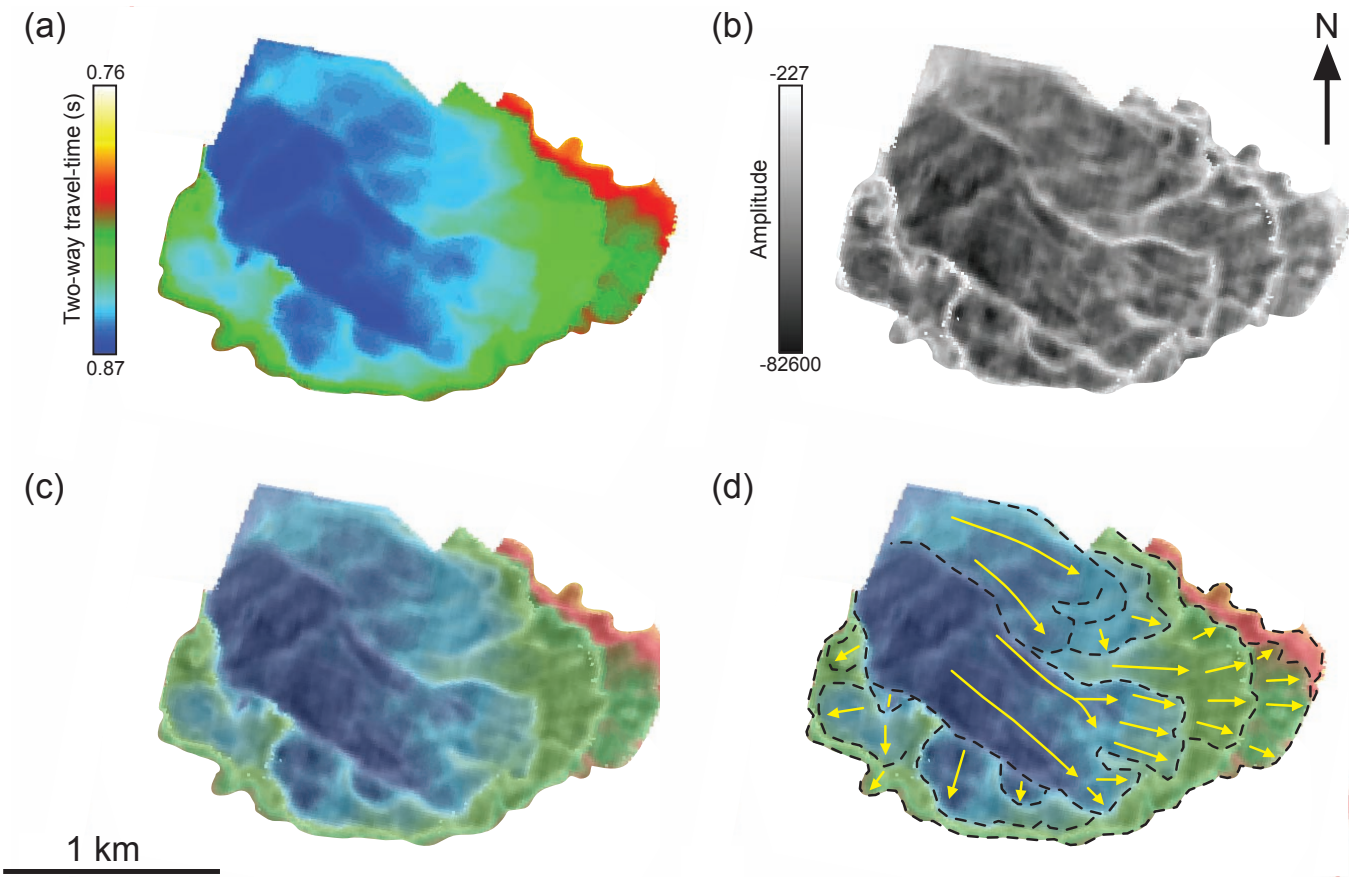

Figure 10. Detailed analysis and interpretation of lobate, saucer-shaped sill that comprises the northeastern component of the igneous complex imaged by the Investigator 3D survey. (a) Time-structure map based on picking the top-sill reflector. Lobate nature of the sill is clearly apparent. (b) Amplitude map of the top sill surface, enabling better definition of individual lobes. (c) Amplitude attribute superimposed on the time-structure map. (d) Interpretation of (c). A number of distinct flow units are identified (yellow arrows indicate flow direction), implying that sill grew by upwards and outwards flow to the southeast and southwest, with the feeder presumably located to the northwest of the sill. The feeder cannot be identified, but it is possible the sill was fed by a dyke that exploited one of the nearby NW–SE-trending normal faults that have been identified in the Investigator 3D survey by Palmowski et al (2004). A shallow-emplacement depth is proposed for this sill, with the southwestern flow units potentially intersecting the palaeo-land surface and supplying the magma for the extrusive lava flow that comprises the southwestern component of this igneous complex. See text for additional discussion.

Bremer and Recherché sub-basins (Fig. 1). The presence of igneous rocks of presumed late Cretaceous–early Cenozoic age in the Bight Basin was indicated by early seismic investigations of the basin (Fraser and Tilbury, 1979) and confirmed by dredging (Davies et al, 1989). Schofield and Totterdell (2008) have recently conducted a detailed study of the distribution and nature of igneous activity in the basin based on mapping of the high-resolution and closely spaced (~4–8 km) Flinders 2D seismic survey. Their work has defined a ~northwest–southeast-oriented igneous field, broadly parallel to the margins of the basin, that covers an area of ~50,000 km^2 with the greatest density of volcanoes and intrusions occurring in a roughly circular area (diameter ~130 km) in the central Ceduna sub-basin. In this region, Schofield and Totterdell (2008) have documented multiple sills, broad, conical volcanic edifices with basal widths of between <2 to 11 km, and lava flow aprons that occur independently of volcanic cones and are attributed to fissure-style eruptions. Many of the volcanoes and extrusive flows appear to have been fed by large sill complexes, which most commonly occur in sheet-like or tabular forms, and less common saucer-shaped forms (Schofield and Totterdell, 2008). Schofield and Totterdell (2008) reported that in the central Ceduna sub-basin, sills and dykes are typically intruded at various levels in the late Santonian-Maastrichtian Hammerhead Supersequence, implying a post-Maastrichtian age for these intrusions. The Hammerhead Supersequence encompasses the Potoroo Formation, which contains fluvio–deltaic sandstones that exhibit excellent reservoir potential and were the target of the Potoroo–1 and Gnarlyknots–1 wells (Tapley et al, 2005).

There are no available isotopic constraints on the ages of the igneous rocks in the central Ceduna sub-basin, but Schofield and Totterdell (2008) have estimated the timing of extrusive and intrusive activity based on seismic mapping and relative dating techniques. They noted that volcanic build-ups tend to have their basal contact on the late early–Eocene unconformity that marks the base of the Dugong Supersequence, signifying a mid-Eocene age for the extrusive activity (Somerville, 2001). This estimate is supported by seismic data that show early Dugong sediments onlapping forced folds that are underlain by sills. As noted by Schofield and Totterdell (2008), this timing is broadly coincident with a series of important reconfigurations of the Indo-Australian plate boundaries that occurred during the mid-Eocene, including the cessation of spreading along the Wharton Basin Ridge in the Indian Ocean and in the Tasman Sea, and the onset of accelerated seafloor spreading in the southern Ocean, which began at ~43 Ma (Veevers, 2000; Teasdale et al, 2003; Li et al, 2004; Holford et al, 2011).

The densest concentration of extrusive and intrusive igneous complexes in the Bight Basin is in the central Ceduna sub-basin, but igneous rocks have also been observed on seismic data to the east in the Duntroon sub-basin (Totterdell and Bradshaw, 2004). Sills and volcanic complexes are also observed in the western parts of the Ceduna sub-basin, where their distribution appears to be more diffuse in comparison to the main igneous province in the centre of the sub-basin (Schofield and Totterdell, 2008); however, new seismic data that image deepwater

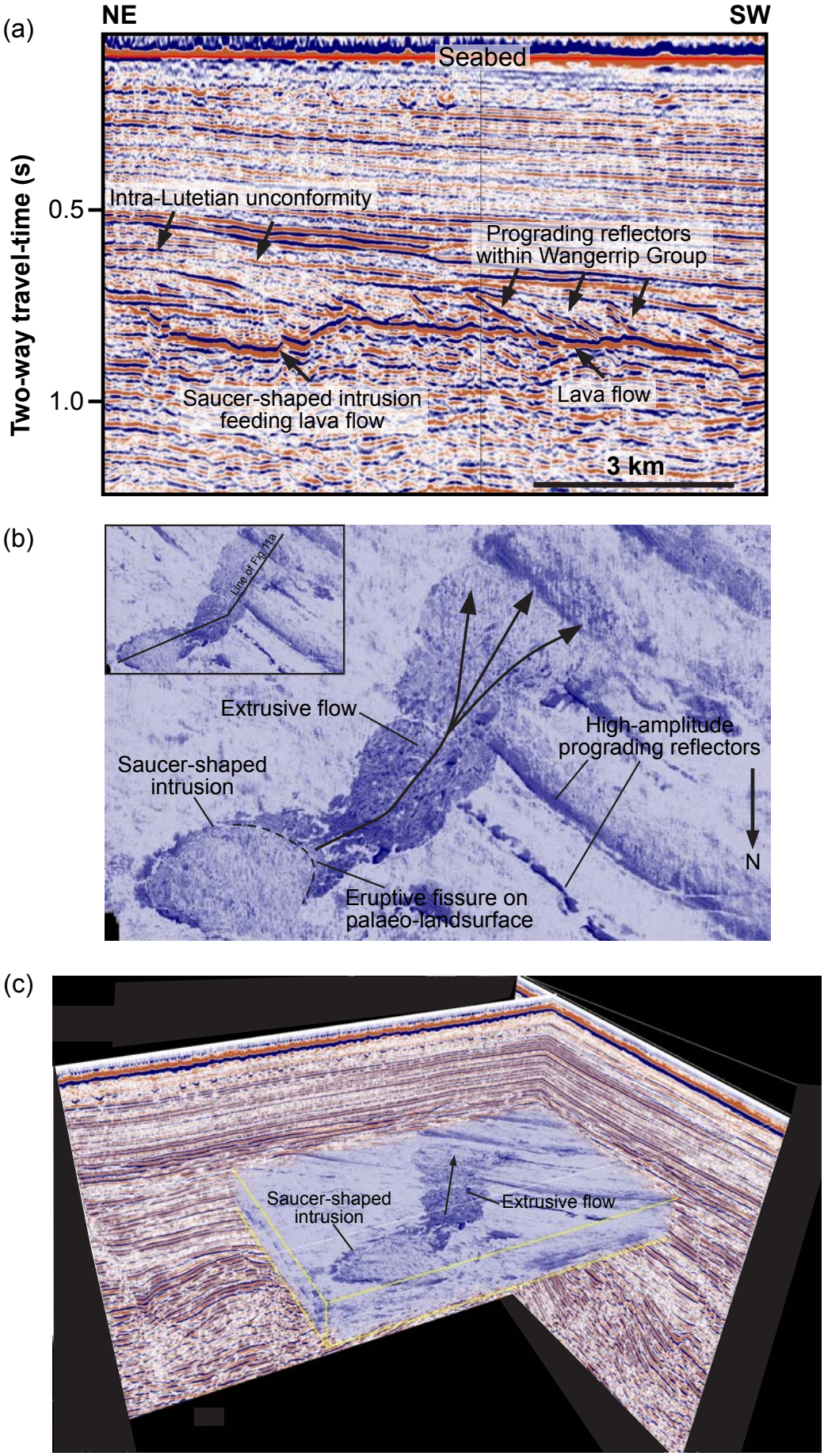

Figure 11. (a) Arbitrary 2D seismic reflection profile (location shown in [b]), with interpretation of the igneous complex as an early–Palaeogene-age saucer-shaped sill, emplaced at a shallow depth that erupted at the palaeo-land surface through a fissure and supplied the magma for an extrusive lava flow. (b) 3D opacity-rendered view of igneous complex with interpretation. See text for explanation. (c) 3D opacity-rendered perspective view of igneous complex, with conventional seismic profiles displayed on the southern and eastern walls.

parts of the western Bight Basin (the Recherché sub-basin) reveal evidence for extensive intrusive and extrusive activity, including stacked and interconnected saucer-shaped sill complexes, some of which are associated with forced-folding of late Cretaceous and early Cenozoic sediments (Fig. 12). Interestingly, some of the sills appear to have exploited large thrust-faults that accommodated compression in the deepwater fold-thrust belt at the toe of the late Cretaceous Ceduna delta system. MacDonald et al (2010) have identified a number of potential plays in this deepwater fold thrust-belt, including hangingwall anticline traps associated with imbricate thrust faults, and large-scale detachment folds that offer two-way and four-way dip closure.

Otway Basin

The Cenozoic volcanic record of the onshore Otway Basin has been intensely studied (e.g. Price et al, 2003, and references therein), but to date there has been little effort to constrain the distribution and timing of offshore igneous activity. Igneous rocks in the onshore Otway Basin are mostly extrusive in origin and mafic in character, and include rocks from both the Older and Newer Volcanic Provinces. A significant volcanic component in Lower Cretaceous Otway Group sediments is recognised (Duddy, 2003) and volcanic activity during the Cenozoic was near continuous, with the Older and Newer Volcanics representing volumetric peaks at around 57–42 Ma and 5–0 Ma, respectively (Price et al, 2003). Basaltic lava flows and shallow intrusives belonging to the Older Volcanic Province have been encountered in the Otway Basin sedimentary succession by boreholes drilled in the Colac and Portland areas. Three dates obtained for samples from the two boreholes in Colac area gave ages of ~37 Ma, while an age of ~58 Ma was obtained from the Portland borehole (Price et al, 2003). The Newer Volcanic Province occupies an area of ~15,000 km^2, mostly in the Victorian and South Australian Otway Basin, and contains a variety of volcanic features including lava flows, cinder cones, shield volcanoes and maars (Joyce, 1988). The most recent eruptive activity onshore Australia occurred in the Gambier volcanic province in the South Australian Otway Basin, with ^{14}C ages and palaeomagnetic data suggesting the Mount Gambier and Schank volcanics erupted less than 5 Kyr ago (Demidjuk et al, 2007). The high quantities of CO_2 in some gas fields in the Penola Trough (e.g. Caroline–1, 98%; Ladbroke Grove–1, 54%) are thought to reflect charge by subsurface gas-prone feeder dykes intruded during this most recent phase of magmatic activity (McKirdy and Chivas, 1992; Lovibond et al, 1995). Several CO_2 accumulations in the Port Campbell Embayment including the commercial Boggy Creek field are also thought to have been charged by degassing of magmas in the past few Myr (Watson et al, 2003).

Our preliminary analyses using mostly 2D seismic reflection data from the offshore Otway Basin indicate igneous rocks occur diffusely throughout the basin, with the greatest concentration found in a ~northwest–southeast-trending region that extends some ~160 km along the inner offshore basin between Portland and Cape Otway. In this area a number of small sills, lava aprons, and features that may be hydrothermal vents have been identified (Fig. 3). Many of the extrusive features that have been identified occur in the latest Maastrichtian to Middle Eocene Wangerrip Group or near the top Wangerrip Group, intra-Lutetian age unconformity, which can be mapped throughout the offshore basin. Most of the sills that have been identified, including the example mapped using the Investigator 3D survey, are intruded into Wangerrip Group, while some larger sills that intrude the Upper Cretaceous Sherbrook Group succession appear to have caused forced folding of overlying Wangerrip Group sediments. Igneous features at similar stratigraphic levels have been observed in the Minerva 3D survey (Schneider et al, 2004). These initial observations indicate a probable early–mid Eocene age for these offshore igneous rocks. This timing is broadly consistent with a period of activity reported by Price et al (2003) occurring between ~45–37 Ma and extending from the Bellarine Peninsula in the eastern Otway Basin to the Mornington Peninsula and Phillip Island at the western margin of the Gippsland Basin.

It is noted that basaltic boulders have been recovered from the summits of several offshore bathymetric highs located ~15 to 30 km to the southwest of Cape Otway (Gill and Segnit, 1986), and broadly along strike from the Otway Ranges. Although no radiometric dates are available for these samples, petrological and geochemical observations apparently demonstrate affinities with the basalts from the onshore Newer Volcanic Province, and an Upper Pliocene age has been proposed for these boulders (Gill and Segnit, 1986).

Torquay sub-basin

The Torquay sub-basin forms part of the eastern Otway Basin, but the stratigraphy above the regional mid-Cretaceous unconformity shares a closer affinity with the Bass Basin to the southeast (Messent et al, 1999). Some small occurrences of lavas and volcanic plugs occur in the sedimentary succession of the sub-basin at coastal sections in the Eastern View and

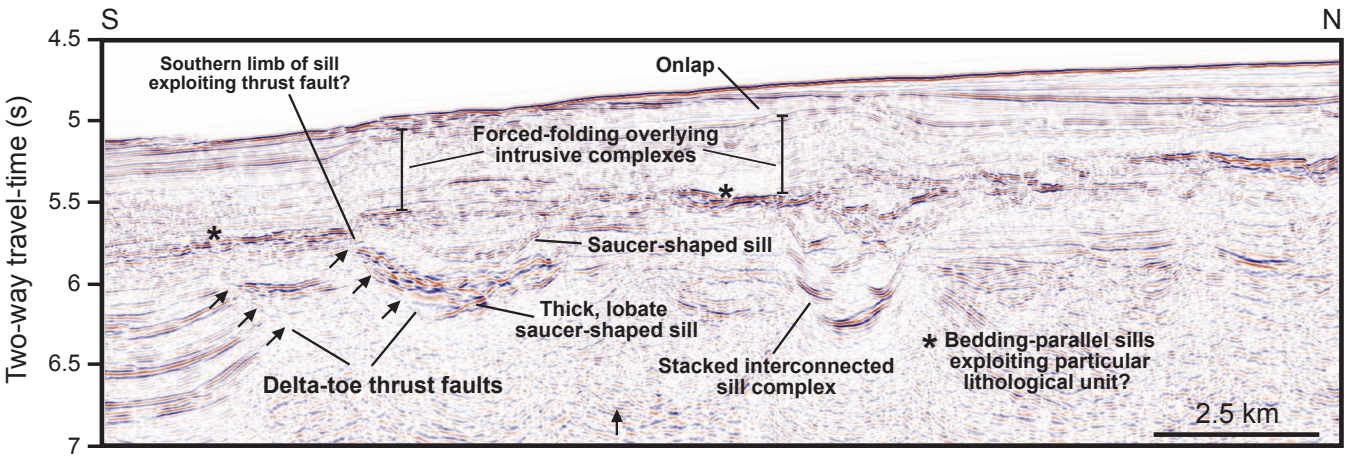

Figure 12. Sub-section of BightSPAN line 100, a 2D seismic reflection profile from the Recherché sub-basin, deepwater Bight Basin. Data reveal complex, interconnected sill complexes that have exploited pre-existing thrust faults and caused significant forced-folding of overlying sedimentary layers. See text for further discussion. Data published with permission of ION Geophysical.

Airey's Inlet areas (Price et al, 2003). The latter area contains the remnants of a shallow marine basaltic volcanic complex (Cas et al, 1993). Recent $^{40}Ar/^{39}Ar$ dating of basalts from this locality have yielded ages of 28.7 and 28.8 Ma (McLaren et al, 2009), indicating a mid-Oligocene timing of igneous activity.

Both intrusive and extrusive rocks are observable on 2D seismic profiles from the offshore basin. Some of the intrusive sills are clearly saucer-shaped and quite large (up to 5 km in diameter), and in places sills have caused forced folding of overlying sediments, implying shallow emplacement depths (Fig. 4). The timing of this offshore igneous activity is constrained by sediments that onlap both forced folds underlain by sills, and intrusive and extrusive rocks themselves, which implies an early Oligocene age for this igneous activity (Messent et al, 1999), and is consistent with onshore data (McLaren et al, 2009).

One of the largest intrusions in the sub-basin occurs in Lower Cretaceous Eumeralla Group sediments near the Wild Dog–1 well, one of three unsuccessful wells that have been drilled to date (Trupp et al, 1994). This intrusion comprises a low-amplitude, concave upwards saucer-shaped sill that becomes a dyke as it intersects and exploits the large northwest-dipping fault that bounds the Wild Dog prospect (Fig. 13). Apatite fission-track analysis (AFTA) and vitrinite reflectance (VR) data from the Wild Dog–1 well provide possible evidence for a transient hot fluid flow event accompanying this intrusive activity (Fig. 14).

VR data from the Middle Eocene Boonah Formation and the deeper latest Palaeocene–Early Eocene Eastern View Group indicate palaeotemperatures >25°C higher than those recorded by VR data from the overlying Anglesea Siltstone and younger stratigraphic units. This implies a marked break in palaeotemperatures below the contact between the Boonah Formation and Anglesea Siltstone (Fig. 14). Extrapolation of this 'mid-Cenozoic' palaeotemperature profile from the Boonah Formation and Eastern View Group to the underlying Eumeralla Formation implies this unit should record mid-Cenozoic temperatures of >110°C, but an AFTA sample from near the base of the well indicates the maximum Cenozoic (62–0 Ma) palaeotemperature witnessed by the drilled section is ~95°C. Furthermore, the Cenozoic palaeotemperatures from this AFTA sample are broadly consistent with a linear palaeotemperature profile fitted to the shallower VR data from the Anglesea Siltstone and younger units (Fig. 14).

These data point to a palaeotemperature anomaly in the Boonah Formation and Eastern View Group that cannot be explained by deeper burial. One possible explanation is that the elevated VR-derived palaeotemperatures record a heating event caused by the flow of hot fluids that either derived or were mobilised by the nearby intrusion. Both the Boonah Formation and Eastern

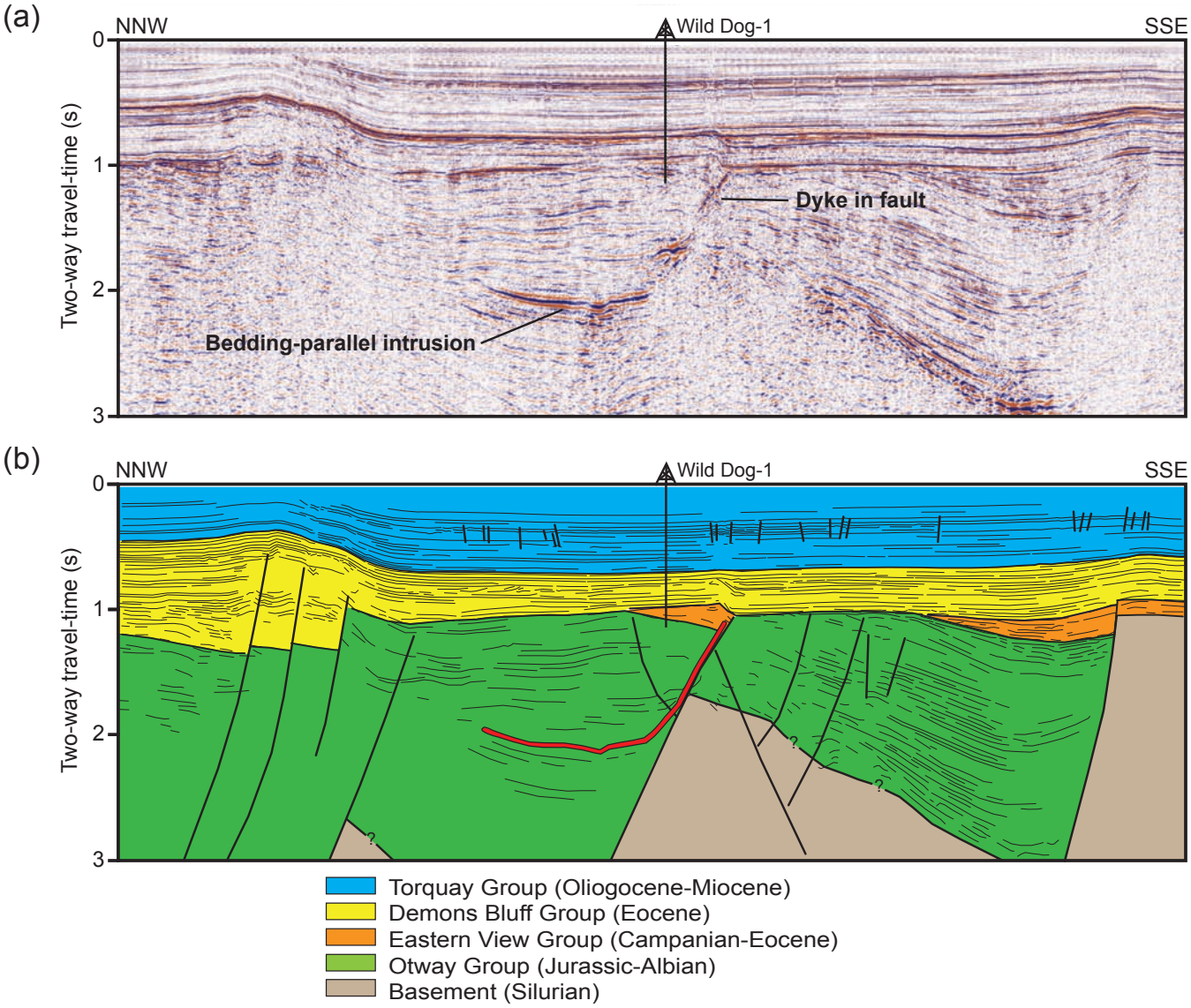

Figure 13. (a) Amplitude display of seismic reflection profile OS90A-13 from the Torquay sub-basin. Note large bedding-parallel sill at ~2 s twtt beneath the Wild Dog–1 well. Towards the SSE the sill begins to transgress stratigraphy and exploits a large ~NNW-dipping normal fault, becoming a dyke. (b) Interpreted seismic reflection profile. See text for further discussion.

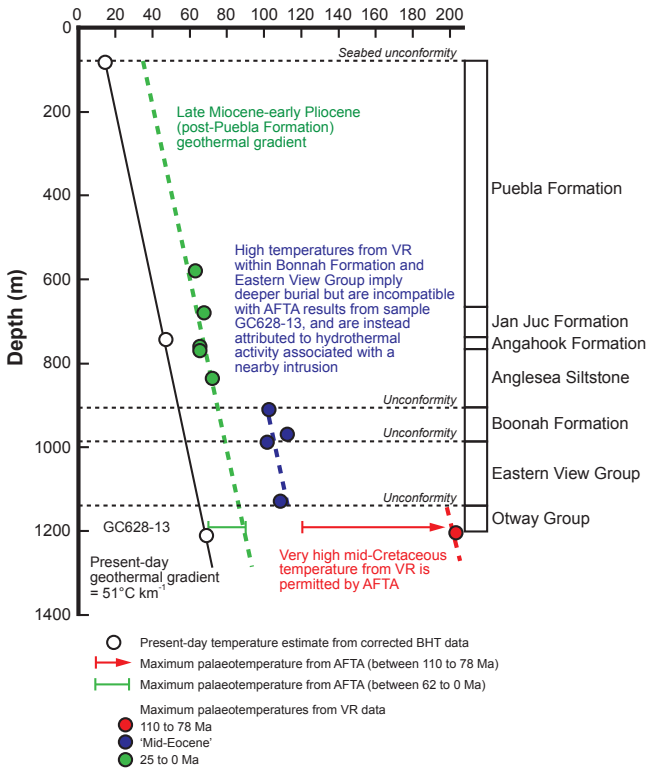

Figure 14. Palaeotemperatures derived from AFTA and VR data in the Wild Dog–1 well plotted against depth and the estimated present-day geothermal gradient. Integration of AFTA and VR results provides evidence for a transient hot fluid flow event restricted to the Boonah Formation and Eastern View Group. This heating event is attributed to the development of a hydrothermal circulation system initiated following intrusion of the sill and dyke shown in Fig. 13. Note the late Miocene–early Pliocene geothermal gradient, which is sub-parallel to the present-day gradient, indicates some degree of post-Puebla Formation uplift and erosion.

View Group contain candidate reservoir horizons, with excellent porosity and permeability (Trupp et al, 1994). Average log porosities for the Boonah Formation and Eastern View Group reservoirs intersected by Wild Dog–1 were calculated at 32.1% and 29.8%, respectively (Messent et al, 1999). The Anglesea Siltstone provides the seal to underlying sands in Boonah Formation, and sidewall samples from Wild Dog–1 indicate this unit can have a sealing capacity for an oil or gas column of several hundred metres (Trupp et al, 1994). It is plausible that the Anglesea Siltstone acted as an impermeable barrier that focused the circulation of heated fluids in Boonah Formation and Eastern View Group reservoirs. The temperature and duration of this hot fluid event seems to have been sufficient to account for the elevated VR values from the Boonah Group and Eastern View Group, but does not appear to have induced any significant quartz cementation in reservoir horizons. The observation that the 'mid-Eocene' palaeogeothermal gradient appears to be similar in value to the post-Puebla Formation and present-day geothermal gradients indicates the 'mid-Eocene' fluid flow event may have been sufficiently long-lived for temperatures in the Boonah Formation and Eastern View Group to have reached steady-state (c.f. Ziagos and Blackwell, 1986). Both fluid inclusion and AFTA data from the Boonah Formation and Eastern View Group would be desirable to evaluate the notion of hot fluid flow triggered by Oligocene intrusive activity in the Torquay sub-basin.

Bass Basin

There is widespread evidence for multiple phases of igneous activity in the offshore Bass Basin, with many wells penetrating intrusive and extrusive rocks of Cretaceous–Miocene age (Cummings and Blevin, 2003), and the largest petroleum discovery in the basin (Yolla) is situated in close proximity to a major volcanic centre. Igneous rocks are particularly abundant in the southern and western parts of the basin, and are commonly associated with major faults and accommodation zones (Cummings and Blevin, 2003).

The oldest encountered volcanic rocks in the basin are early Cretaceous volcaniclastic sands intersected by the Durroon–1 well that bear close lithological similarities to the Otway and Strzekecki groups of the Otway and Gippsland basins, respectively (Cummings and Blevin, 2003). The Durroon–1 well also intersected a >100 m thick succession of highly altered amygdaloidal olivine basalt interbedded with clastic sediments of probable Aptian age (Cummings and Blevin, 2003). Mid-Cretaceous volcanics, in the form of flows, mounds and cones, can be observed on seismic data across much of the southeastern Bass Basin (the Durroon sub-basin), and their close association with major normal faults implies rifting was the causal factor behind this igneous activity (Cummings and Blevin, 2003).

A subsequent period of volcanism occurred during deposition of the latest Maastrichtian–Palaeocene Tilana Sequence in central and northeastern parts of the Bass Basin, with extrusive rocks intersected at Aroo–1, Bass–1, Chat–1, Tilana–1, Yolla–1 and Yolla–2 and sills intersected at Cormorant–1 (Cummings and Blevin, 2003). The intrusions mask the original stratal geometries in the Tilana Sequence on seismic data, resulting in chaotic, high-amplitude and low-frequency reflections throughout the succession (Blevin et al, 2005). The extrusive rocks include fine-grained amygdaloidal basaltic flows interbedded with clastic units, and reservoir facies quartzose sandstones, which were originally interpreted as purely volcanic but appear to have been altered and cemented by volcanic fluids and basaltic material subsequent to their deposition (Blevin et al, 2005).

The most recent and extensive period of volcanism occurred during the Oligocene to Miocene, with volcanic mounds, vents, lava flows and intrusive sills and dykes widespread throughout the central and northeastern Bass Basin (Smit, 1988; Gunn et al, 1997; Cummings and Blevin, 2003; Cummings et al, 2004). Large volcanic mounds of Miocene age occur near the Bass–1, Yolla–1 and Cormorant–1 wells (Fig. 15). Seismic analysis of these features suggests they likely represent scoria cones and maar volcanoes, analogous to onshore extrusive complexes in the Otway Basin such as Mt Eccles and Tower Hill (Faustman, 1995). Olivine basalt flows and highly weathered pyroclastics have been intersected by wells, indicating a combination of magmatic and phreatomagmatic volcanism, with the marine setting of the basin during the late Cenozoic likely resulting in explosive volcanism (Faustman, 1995). In a study of the large Oligocene–Miocene volcanic complex overlying the Yolla gas field, Faustman (1995) reported significant variability in seismic velocities, attributed to facies changes (from basalt, to scoria, to tuff) in the volcano. This facies variation poses challenges for accurate depth conversion and interpretation of reservoir horizons in the Palaeocene–Eocene Eastern Coal Measures underlying the volcanics. This is because the seismically-fast basaltic material and seismically-slow pyroclastics result in velocity pull ups and push downs, respectively (Faustman, 1995).

A number of wells have encountered mafic intrusives of Miocene age that likely fed the shallower volcanics in Eocene units. Seismic data indicate both intrusive and extrusive activity were coincident with strike-slip fault reactivation and inversion during the Miocene (Fig. 15; Cummings et al, 2004). In particular, north–south-trending faults appear to have acted as feeder conduits for overlying volcanoes, facilitating both transport of magma through the basin and dyke emplacement (Lennon et al, 1999).

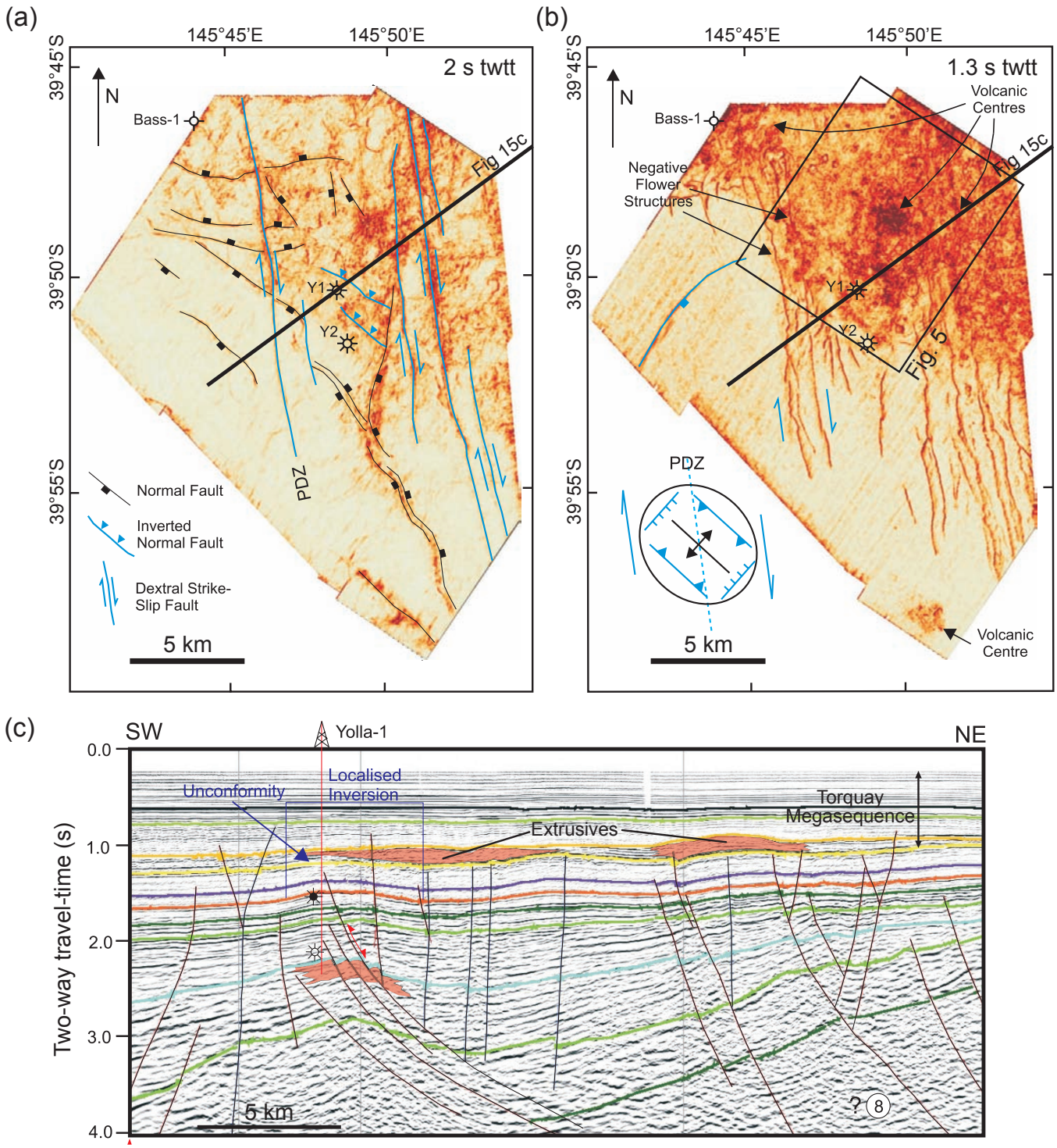

Figure 15. Coherency time slices at (a) 2 s twtt and (b) 1.3 s twtt from the Yolla 3D seismic survey, Bass Basin. Black structures are Cretaceous–Eocene normal faults, blue structures are related to Oligocene–Miocene strike-slip deformation and inversion. The latter phase of deformation overlaps temporally with a significant period of intrusive and extrusive activity in the Bass Basin, and the distribution of many igneous features (such as those apparent in the northern part of the Yolla 3D survey) is likely structurally controlled. The central volcanic complex observable on the 1.3 and 2 s twtt time slices is that shown in the 3D opacity render in Fig. 5. Y1 and Y2 refer to the Yolla–1 and Yolla–2 wells. (c) Interpreted 2D seismic reflection profile illustrating high-level extrusive complexes of Oligocene–Miocene age in the late Cenozoic Torquay Megasequence. Modified after Cummings et al (2004).

Sorell Basin

The Sorell Basin, located offshore western Tasmania, is the least explored of the southern margin basins to the east of the Bight Basin, with only three wells drilled to date (Clam–1, Cape Sorell–1, and Jarver–1). The basin consists of a series of ~north–northwest-trending transtensional depocentres that formed during the separation of Australia and Antarctica between the Cretaceous–early Oligocene (Boreham et al, 2002; O'Brien et al, 2004). Sediment thicknesses are thought to vary significantly between depocentres, with ?early Cretaceous–Recent sediments thought to reach more than 6.5 km in the Strahan sub-basin into which the Cape Sorell–1 was drilled (Boreham et al, 2002). This well encountered oil shows in late Cretaceous sediments (Boreham et al, 2002), and O'Brien et al (2004) have inferred the presence of an active Cretaceous source system in deep syn-rift sediments on the basis of gas chimneys that are preferentially distributed along ~north to northwest-trending fault systems and focused up-dip from areas where source rocks are thought to be thermally mature. Mounded features that

show close spatial associations with faults have been observed on seismic data but are not thought to be volcanic in origin, and have been interpreted as bioherms of late Oligocene–early Miocene age (Boreham et al, 2002). Although seismic coverage across the basin is sparse, volcanics have been observed in the King Island sub-basin (into which the Clam–1 well was drilled). These have been interpreted to be sills or extrusive flows that formed coevally with Maastrichtian–Palaeocene strike-slip faulting along the west Tasmanian margin (Hill et al, 1997). There are also extensive Late Cenozoic volcanics in this area, which are likely associated with the extensive basalt fields that occur onshore northwest Tasmania, and have been dated at between 38–9 Ma (Sutherland, 1989). Volcanic features interpreted as late Cenozoic basaltic flows have also been described from seismic profiles off the central and southern west coast of Tasmania (Hill et al, 1997).

Gippsland Basin

Intrusive and extrusive igneous rocks have been intersected by numerous wells in the Gippsland Basin, with the majority of these wells (>80%) located along the northern and southern fault systems that bound the basin (Birch, 1987; McPhail, 2000). The distribution of wells that intersected igneous material corresponds closely with the areal distribution of igneous rocks as determined by seismic mapping, with the highest concentration of igneous rocks covering an area of ~300 km^2 in the northeastern Gippsland Basin (Birch, 1987). A secondary volcanic province covering an area of ~200 km^2 has been identified from seismic in the southeastern part of the basin, in an area to the south of the Kingfish Field that is largely untested by drilling (Birch, 1987). Igneous rocks have also been intersected by numerous wells in the Bream Field in the Gippsland Basin Central Deep, and by the Perch–1 and Dolphin–1 wells in the southwestern part of the basin.

Absolute age constraints for igneous rocks in the offshore Gippsland Basin are unavailable, as the rocks are commonly highly weathered or altered (McPhail, 2000), but stratigraphic relationships with bounding sediments indicate the majority of the igneous rocks in the northern part of the basin are late Cretaceous (Campanian) in age (Birch, 1987). Igneous rocks of equivalent age do not crop out in the onshore Gippsland Basin (O'Halloran and Johnstone, 2001), although Barker at al (1998) have described a suite of basalt dykes from the onshore western Gippsland Basin that intrude the Upper Jurassic–Lower Cretaceous Strzelecki Group and are of presumed mid-Cretaceous age. The youngest igneous rocks that have been intersected in the offshore basin are mid Eocene intrusives that are encountered at the top of the Latrobe Group sediments in the Bream Field (McPhail, 2000).

The igneous rocks in the northeastern Gippsland Basin have been the most intensely studied, following the discovery of an extensive gas accumulation below 98 m of highly altered basaltic lava flows at Kipper–1 (Birch, 1987). These Campanian volcanics provide the top seal to a 328 m gross gas column, which is both the largest in the basin and the first discovery in the Golden Beach Group (Sloan et al, 1992; Woollands and Wong, 2001), and provides a rare and noteworthy example of a conventional hydrocarbon accumulation that is partially sealed by igneous rocks (Schutter, 2003). Other notable occurrences of igneous rocks in the Gippsland Basin include: Remora–1, where oil is trapped beneath 61 m of volcanics; Tuna–4, where both oil and gas occurs below <30 m of igneous rock; and Omeo–1, Emperor–1, Sunfish–1 and the Wirrah Field where oil and gas are trapped below layers of igneous rocks between 10 and 20 m thick (Birch, 1987). Although these volcanics have invariably been subject to significant chlorite alteration, this does not appear to have impacted their sealing qualities (McPhail, 2000). The Eocene basaltic rocks encountered at the Bream Field are thought to be intrusive in origin, and are less weathered and altered than the late Cretaceous igneous rocks from the northern Gippsland Basin, consistent with their younger age (McPhail, 2000).

O'Halloran and Johnstone (2001) completed a detailed study of the distribution, extent and character of the late Cretaceous igneous rocks in the vicinity of the Kipper Field using the G99a Kipper 3D seismic survey, and identified a variety of extrusive volcanic styles and intrusive bodies. They showed that volcanic intervals intersected in wells tie to irregular high impedance reflectors that are generally concordant with stratigraphy, which thicken across major ~west-northwest-trending growth faults. Cuttings and sample descriptions indicate these volcanics comprise fine-grained basaltic lavas and tuffs that are variably altered (McPhail, 2000). Interbedded minor floodplain sands, silts and shales are recognised in the volcanic section in the Kipper area and along strike around the Manta Field, and occasional prograding reflection geometries observed in some of the seismic units have been interpreted as lava deltas building out into lacustrine water bodes (O'Halloran and Johnstone, 2001). Amplitude maps reveal the presence of a high impedance circular feature (diameter ~1,600 m) to the south of the South Kipper Fault, which is thought to be a highly weathered, fissure-fed scoria cone that was the primary source for the extrusive material (O'Halloran and Johnstone, 2001). O'Halloran and Johnstone (2001) also identified irregular, ring-like high-impedance bodies that cross-cut stratigraphy and can be mapped as inverted-cones in three dimensions. These bodies appear to concentrate along major fault zones, and are inferred to be intrusive cone sheets that fed overlying eruptive centers. Close relationships between the distribution of igneous rocks and large faults are reported from elsewhere in the northeastern igneous province, which is interpreted as a continental basaltic rift terrain that formed as the northward-propagating Tasman Sea spreading centre passed the Gippsland Basin around 85–80 Ma (Birch, 1987; McPhail, 2000).

IMPACTS OF IGNEOUS ACTIVITY ON PETROLEUM SYSTEMS IN PROSPECTIVE SEDIMENTARY BASINS

This paper is concluded by briefly reviewing some of the potential impacts that igneous activity in sedimentary basins may pose to the key elements and processes of the petroleum system. For a more thorough analysis of the positive and negative ramifications of igneous activity, the reader is referred to Schutter (2003), while a useful evaluation of prospect delineation in sub-basalt plays is provided by Rohrman (2007). In the context of the southern Australian margin, Schofield and Totterdell (2008) provide a valuable assessment of the possible impacts of igneous products and processes on petroleum systems in the Bight Basin.

Source rock maturation

Petroleum systems where maturation is the result of igneous activity rather than burial are considered atypical (Magoon and Dow, 1994), and much previous work has focused on the potential over-maturation risk posed by the interactions of igneous rocks with source rock facies (Schofield and Totterdell, 2008). Extrusive rocks cool rapidly, and so have very little direct impact on maturation (Schutter, 2003). The direct thermal effects of intrusive bodies on source rock maturation appear to be highly varied, with thermal effects generally minimal unless the occurrence of intrusions is dense (Rohrman, 2007). Key factors that will determine the degree of maturation of source

rocks that have been intruded include the composition (and thus melting temperature) of the intrusion, and the thermal conductivity, compaction-state, pore-water volume and degree of maturation of the host rock lithologies at the time of intrusion (Rohrman, 2007). Maturity (e.g. VR) data acquired from wells that penetrate organic rich successions containing multiple thin (i.e. <10 m thick) intrusions typically show significant fluctuations over narrow depth intervals around the intrusions (e.g. well 134/5–1 in the Sea of Hebrides Basin, offshore northwest Scotland; Holford et al, 2010). Estimates of the thermal aureole of an individual intrusion vary from one half to five times its thickness, with most estimates about twice the thickness (Duddy et al, 1994; Schutter, 2003). Conductive numerical models suggest direct thermal effects are likely to be far more profound if multiple thick intrusive sills (i.e. >100 m thick) are emplaced into organic-rich sediments simultaneously, with maximum generation likely at spacings of around five sill thicknesses (Aarnes et al, 2011). Conditions for hydrocarbon generation will be more favourable in a basin where multiple previous intrusions have raised the background geothermal gradient (Aarnes et al, 2011), as may be the case in the Taranaki Basin of New Zealand (Schutter, 2003).

Attempts to replicate levels of maturation around intrusive rocks using conductive cooling models commonly produce underestimates relative to observed data, indicating heating by convective and/or advective processes may be of equal if not greater importance in influencing source rock maturation (Barker et al, 1998; Rohrman, 2007). The intrusion of igneous bodies into porous sedimentary rocks can lead to boiling and expulsion of pore-waters, and the creation of a hydrothermal system capable of transporting heat vertically and laterally away from the intrusion (Einsle, 1988). If igneous rocks are intruded into sedimentary rocks with low bulk permeabilities at shallow depths, hot overpressured fluids may fracture surrounding rocks, resulting in the explosive upwards movement of fluids and the production of hydrothermal vents such as those described from the Vøring Basin (Planke et al, 2005).

Hydrothermal systems driven by igneous intrusions may be responsible for the elevated palaeotemperatures recorded by VR data from Boonah Formation and Eastern View Group sandstones in the Wild Dog–1 well in the Torquay sub-basin (Fig. 14). Another example of a hydrothermal system triggered by igneous emplacement is provided by data from the North West Canning Basin, where numerous large mafic sills and cone sheets were emplaced during the early Permian (Reeckmann and Mebberson, 1984; Duddy et al, 1994). The Perindi–1 well intersected a 156 m thick doleritic intrusion, and VR values from Permian and Devonian sediments adjacent to the intrusion are consistently between 1 and 1.3% across a vertical distance ~550 m above and ~300 m below the dolerite, implying little palaeotemperature variation over a ~1 km depth range (Duddy et al, 1994). This pattern of high palaeotemperatures is attributed to the circulation of fluids in adjacent porous sandstones, triggered by the intrusion (Reeckmann and Mebberson, 1984). The intrusion of extensive doleritic sills and laccoliths at shallow levels into porous sandstones of the Permian Grant Formation in the North West Canning Basin has resulted in distinct thermal effects that can be observed in wells several kilometres away from the most proximal intrusions (Duddy et al, 1994), which may have briefly placed a considerable thickness of the regionally immature Poole Formation into the oil window (Reeckmann and Mebberson, 1984).

Reservoirs, seals and migration pathways

There are many examples from sedimentary basins around the world of hydrocarbon accumulations reservoired in igneous rocks with primary or secondary porosity (Schutter, 2003). The Jatibarang Field on the northwest coast of Java provides a notable example, where large quantities of oil and gas (>1.2 billion barrels and >2.7 TCF) have been produced from fractured late Eocene–early Oligocene andesitic tuffs that form the basal infill in half grabens (Schutter, 2003). There have been few discoveries of commercial accumulations of hydrocarbons reservoired in igneous rocks in offshore passive margin basins, however, with occurrences of igneous rocks acting as seals (e.g. the Kipper Field in the Gippsland Basin [Sloan et al, 1992]) more commonly described. The discovery of the Rosebank oilfield in intra–basaltic sandstones in the Faroe Shetland Basin has produced a new play concept for explorers in volcanic basins along the northwest European Atlantic margin (Helland-Hansen, 2009)

Perhaps more relevant to reservoir and seal assessment in passive margin basins influenced by volcanics are the long-term effects of focused fluid flow and compartmentalisation (Planke et al, 2005). Hydrothermal fluids generated with igneous intrusions can be highly mineralising and thus degrade the quality of potential reservoirs through the temperature-controlled cementation of minerals such as quartz. Fluid inclusion data from several volcanically-influenced basins along the northwest European Atlantic margin, including the Faroe-Shetland Basin, contain evidence for high temperature (>200°C) and short lived (<0.1 to 1 Myr) hot fluid pulses that have precipitated quartz cements in potential reservoir sandstones (Parnell, 2010). Such hot fluid pulses have been attributed to hydrothermal activity related to sill intrusion at deep basinal levels (Parnell, 2010), though similar short-duration hot fluid flow events have also been attributed to periods of inversion, whereby fault reactivation has permitted the up-dip transport of deep, hot basinal fluids (O'Brien et al, 1996; Parnell et al, 2005). Reservoir degradation through hydrothermal activity has been reported from the Bass Basin, where quartzose sandstones have been altered and cemented by hydrothermal fluids originating from nearby intrusions (Cummings and Blevin, 2003). Schofield and Totterdell (2008) have suggested hydrothermal alteration is unlikely to have affected reservoir sandstones in the Bight Basin due to the shallow emplacement depths of most intrusions and the general absence of hydrothermal vents, while the close proximity of igneous rocks to many reservoir horizons in the Gippsland Basin (e.g. Kipper; Sloan et al, 1992) does not appear to have had significant negative impacts on prospectivity.

Long-term effects of igneous activity on reservoirs and seals may also include compartmentalisation by intrusive complexes and puncturing of sealing sequences by igneous structures. Detailed mapping of intrusive systems in the Faroe-Shetland, Vøring and Møre basins of the northwest European Atlantic margin (Planke et al, 2005; Cartwright and Hansen, 2006; Thomson and Schofield, 2008) has revealed these systems often consist of complex, interconnected networks of sills and dykes that cover large vertical and lateral distances. Furthermore, the propensity for sills in these systems to exploit and intrude along ductile shale horizons (Thomson, 2007; Thomson and Schofield, 2008) raises the possibility of compartmentalisation of reservoirs (and indeed source rocks) by sills and dykes in basins containing high densities of intrusives (Fig. 16). The creation of isolated compartments sealed by low-permeability igneous bodies would clearly impact migration pathways and migration efficiency, and may result in differential lateral pressures in reservoir bodies by creation of pressure cages, although 'broken-bridge' structures between distinct lobes in sheet intrusions may offer fluid pathways through laterally-continuous intrusions (Schofield et al, in press). Compartmentalisation may pose an exploration risk in the central Ceduna sub-basin, where closely-spaced networks of sills and dykes have been identified in the reservoir-hosting Hammerhead Sequence in the central

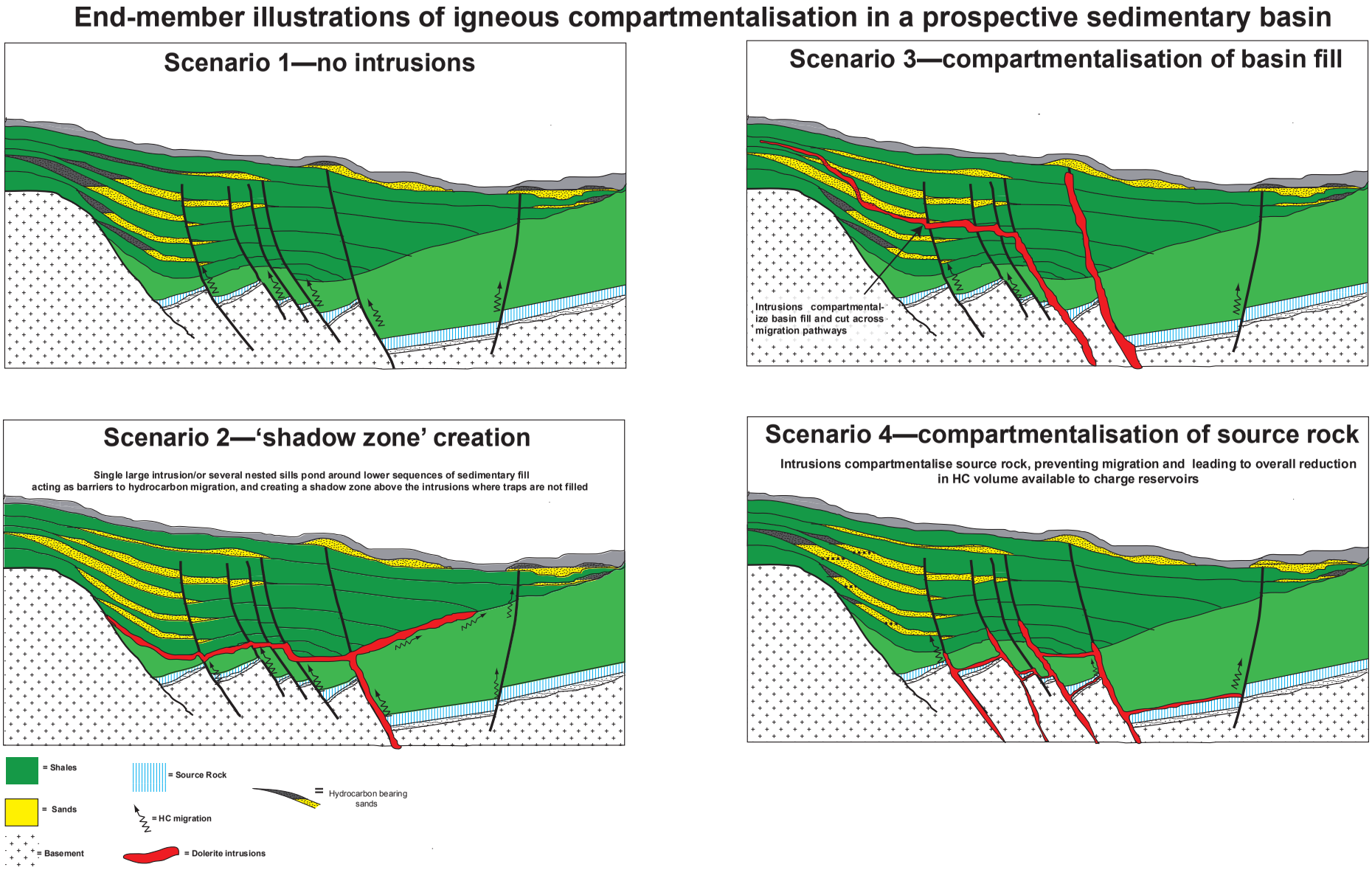

Figure 16. A series of conceptual diagrams illustrating the potential impacts of igneous intrusions on compartmentalisation of source and reservoir units in sedimentary basin. Scenario 1 depicts a basin without igneous intrusions, where hydrocarbons are able to migrate from source rocks to reservoirs without impediment. Scenario 2 depicts the creation of a 'shadow zone', whereby a single large intrusion and/or several nested sills pond at lower levels in the basin-fill, acting as barriers to hydrocarbon migration from deep source rocks, and resulting in a series of unfilled traps above the intrusions. Scenario 3 depicts a series of large intrusions that variably exploit faults or specific stratigraphic layers (e.g. shales), compartmentalising the basin fill and ensuring only sub-intrusion traps (which may be difficult to image on seismic) are filled. Scenario 4 depicts the compartmentalisation of source rocks by sills and dykes, inhibiting migration and leading to a significant reduction in the volume of hydrocarbons available to charge reservoirs located shallower in the basin succession.

Ceduna sub-basin (Schofield and Totterdell, 2008).

The release of volatiles such as CO_2 during magma degassing can impact petroleum migration. The Otway Basin contains a number of natural CO_2 accumulations that are sourced from the degassing of magmas associated with the Newer Volcanics with fields typically show varying levels of CO_2 across relatively short distances (Watson et al, 2003). The Katnook–2 and Ladbroke Grove–1 wells in the Penola Trough, western Otway Basin, are located ~3 km apart, with the main reservoir unit (the Lower Cretaceous Pretty Hill Formation) separated by a large normal fault (the Ladbroke Grove Fault). Ladbroke Grove–1 contains methane and a recorded CO_2 composition of 54%, while Katnook–2 contains almost pure methane (Watson et al, 2003). The Mt Burr volcanics to the southwest of both wells is considered the source of the CO_2 in Ladbroke Grove–1, and the absence of CO_2 in Katnook–2 implies the Ladbroke Grove fault is sealing. Similarly, a number of small gas fields with highly variable CO_2 contents have been discovered in the Port Campbell Embayment in the eastern Otway Basin (Watson et al, 2003). Some of these fields remain undeveloped due to the high CO_2 content of the gas (e.g. 56% at Grumby and 66% at Langley; Woollands and Wong, 2001). The variability in CO_2 content may again be attributable to sealing faults that have influenced CO_2 migration pathways. Detailed structural analysis is thus advisable when attempting to define economic prospects in basins where magmatic degassing may have resulted in a significant CO_2 charge. In some situations, it appears natural CO_2 flooding has completely swept structures. This appears to have been the case in the northern Kaiparowitz Basin in southern Utah, where structures proximal to the Marysvale volcanic centre are full of CO_2, while more distant structures are thought to have had oil displaced off-structure by the strong regional hydrodynamic system associated with the CO_2 flood (Schutter, 2003).

Cartwright et al (2007) have recently reviewed how seal integrity may be compromised by various geological structures that allow fluids to flow vertically or sub-vertically across the seal, including by igneous intrusions and related hydrothermal pipes. Hydrothermal pipes with heights up to several kilometres and widths ranging from tens of metres to ~1–2 km have been recognised on seismic data from many basins containing igneous rocks, where they typically emanate from the inclined lateral margins of sills and are commonly linked to hydrothermal vents that developed at the surface or sea bed at the time of intrusion (Bell and Butcher, 2002; Davies et al, 2002; Cartwright et al, 2007). On seismic data they are commonly characterised by columnar or steep-sided, downward-tapering conical zones of disturbed or collapsed stratal reflection (Cartwright et al, 2007). There is much evidence from seismic data that both hydrothermal pipes and vents act to focus vertical fluid migration through basins for significant timescales (i.e. up to millions of years) subsequent to their formation, which poses important ramifications for seal integrity and secondary hydrocarbon migration (Planke et al, 2005).

Trap formation

Igneous rocks in sedimentary basins can produce a wide range of structural and stratigraphic trapping structures, and around the world there are many examples of commercial hydrocarbons that are trapped in structures associated with igneous rocks (Schutter, 2003). Common examples include domal traps formed above convex-upwards laccoliths, with a notable example being that of the Omaha Dome in the Illinois Basin, where >6.5 million BBL of oil have been produced from a structural closure associated with a so-called Christmas-tree laccolith (Schutter, 2003). Since intrusive rocks commonly exploit faults (with clear examples of this in the Bass, Torquay and Gippsland basins [Birch, 1987]), they can potentially provide fault seal when juxtaposed against reservoirs.

Shallow igneous intrusions such as saucer-shaped sills can produce traps though forced folding (jacking-up) of overburden or through differential compaction (Hansen and Cartwright, 2006a; Rohrman, 2007). The former type of structure should result in seabed deformation at the time of intrusion and onlapping by the overburden, while the latter should give rise to a concordant relationship between the seabed and overburden (Hansen and Cartwright, 2006). The creation of sea floor topography may potentially affect sediment supply routes (e.g. Fig. 17) and thus influence the deposition of reservoir facies. Schofield and Totterdell (2008) have reported forced folding in the late Cretaceous–Eocene upper Hammerhead, Wobbegong and Dugong Supersequences in the central Ceduna sub-basin, which may provide accessible and shallow traps for late stage hydrocarbon migration (Fig. 6), while similar traps occur in reservoir-age sequences in the Otway and Torquay sub-basins (Figs 3 and 4). Such structures offer attractive four-way dip closure, but there are questions regarding their suitability for hosting significant hydrocarbon accumulations due to there being little available data on the degree to which the folded and

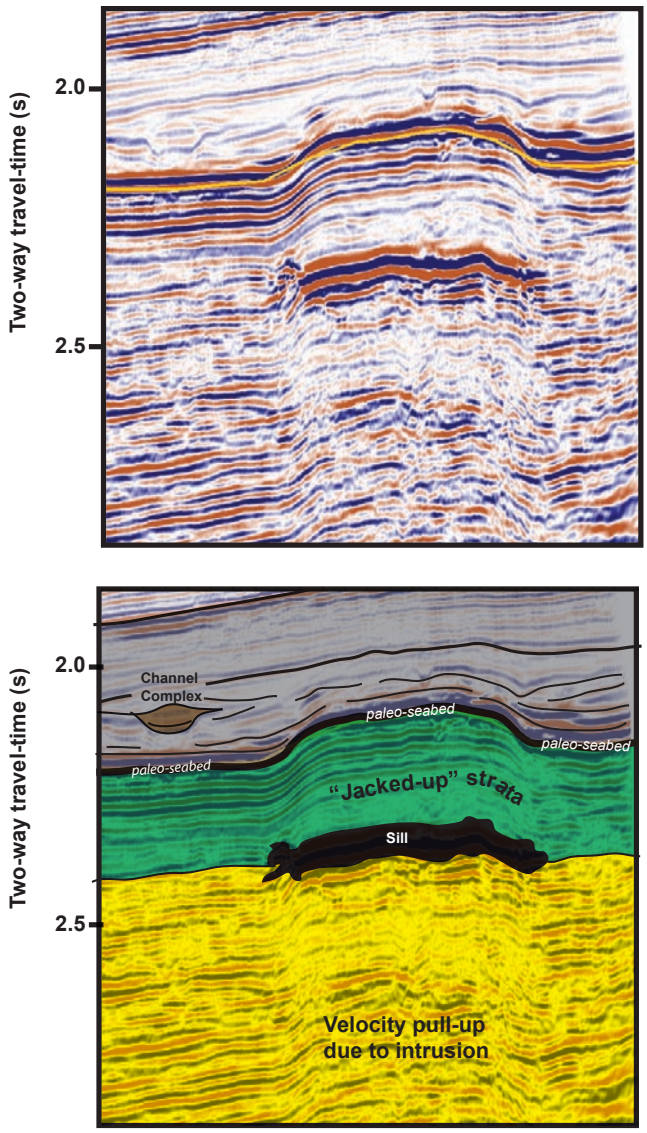

Figure 17. 2D seismic reflection profile from the Ceduna sub-basin, Bight Basin, illustrating a sill that intruded at a shallow level and caused significant jacking-up of overlying sedimentary units and deformation of the sea floor. Such forced-folding can potentially influence sedimentary dispersal pathways, as implied in this case by a small channel located adjacent to the forced-fold.

fractured sediments in such structures have been influenced by contact metamorphism and hydrothermal activity (Hansen and Cartwright, 2006). Additionally, if the saucer-shaped sill that has caused the intrusion related doming and four-way dip closure possesses low permeability, it may act as a barrier and divert hydrocarbon migration away from the trap, decreasing the probability of the trap being filled to spill.

There are also some notable cases of wells that mistakenly targeted four-way dip closures on the assumption of a structural origin, and instead met domal features of magmatic origin. An instructive case study is provided by Archer et al (2005), who describe data acquired from well 164/7–1, drilled in the UK sector of the Rockall Trough, northwest European Atlantic margin. This well targeted a large periclinal structure of presumed Mesozoic age, with the preferred interpretation of the structure being that of a ramp-flat anticline. This diagnosis was poorly constrained by limited 2D seismic data and the presence of overlying Palaeogene volcanic rocks. When drilled, the well interested a 1.2 km thick pile of basaltic lavas that was 2.25 times thicker than predicted. Below the basalt lavas, 121 m of late Palaeocene tuffs and tuff breccias and a Cretaceous claystone sequence intruded by more than 70 dolerite sills were encountered. Following joint consideration of thermal maturity, potential field and 3D seismic data, Archer et al (2005) attributed the origin of the domal structure to the jacking-up and arching of overlying strata by a mafic laccolith, 17 km in diameter and ~7 km thick, situated ~2.5 km below the bottom of the well. Archer et al (2005) advocated that circular and periclinal structures in sedimentary basins where igneous rocks are prevalent and salt domes and shale diapirs are absent should undergo thorough and cautious multi-disciplinary risk assessments.

CONCLUSIONS

As global hydrocarbon exploration increasingly focuses on passive margin basins with evidence for past igneous activity, constraining the distribution, timing and pathways of magmatism is essential to reduce exploration risk. The increasing availability and quality of 2D and 3D seismic data has empowered explorers working in volcanic basins, enabling the development of new interpretative tools and workflows for characterising both extrusive and intrusive igneous rocks and related phenomena, and providing critical new insights into long-standing controversies regarding the storage and transport of magma through the upper crust. This paper has reviewed the styles, distribution and timing of late Cretaceous–Recent extrusive and intrusive igneous activity in both producing and prospective basins of the southern Australian margin, providing illustrative examples based on 2D and 3D seismic reflection datasets. Igneous activity has had both positive and negative impacts on the petroleum systems of these basins. Generic processes relevant to other volcanic basins include the compartmentalisation and degradation of reservoirs by intrusions and hydrothermal fluids, the flooding of reservoirs by CO_2 from degassing magmas, and the creation of shallow traps with four-way dip closure by forced folding or differential compaction above saucer-shaped sills.

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