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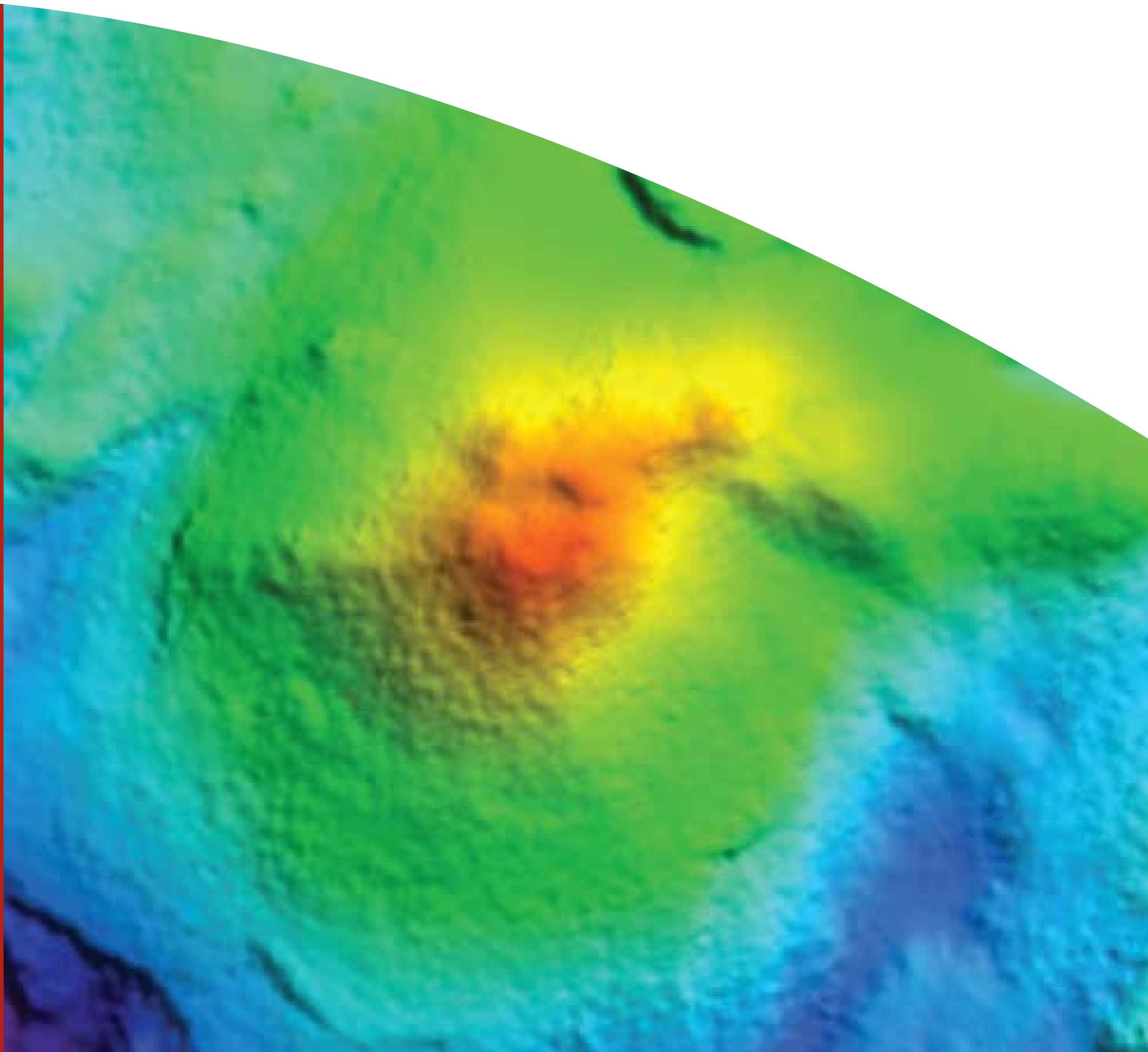

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Distribution, timing and origin of magmatism in the Bight and Eucla Basins

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by

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Executive Summary

The breakup of Gondwana during the Mesozoic resulted in widespread basin formation along Australia's southern margin, of which the Bight Basin is a component. In contrast to many other extensional margins, the Australian southern margin has been classified as a non-volcanic rifted margin, despite the reported occurrence of scattered volcanic and intrusive rocks in the geological literature. Public release of the Flinders 2D seismic survey data in the Bight Basin has allowed these igneous bodies to be accurately studied and mapped for the first time. The igneous rocks are easily identified in the seismic data, and widespread sills, dykes, lava flows and volcanoes have been mapped.

The occurrences of volcanic and intrusive bodies are largely confined to the Ceduna Sub-basin and overlying Eucla Basin, with slight incursions into the Eyre and Duntroon Sub-basins. These igneous rocks are hereafter referred to as the Bight Basin Igneous Complex (BBIC). The complex has a NW-SE orientation and covers an area of approximately 50,000 km^2. The easternmost part of the complex, in the central Ceduna Sub-basin, contains the greatest density of igneous occurrences and the majority of large volcanoes. This igneous field is roughly circular with a diameter of 130 km. Some more isolated igneous occurrences are also mapped in the Duntroon Sub-basin, some 200 km east of the main field.

The timing of igneous activity has been constrained, in the absence of isotopically dated samples, by using the relationship between the igneous rocks and stratigraphic units of known ages. 'Forced folding' of the base of the Middle Eocene to Pleistocene Dugong Supersequence has been observed in the central Ceduna Sub-basin, and indicates a Middle Eocene date for sill intrusion. In addition, several volcanic cones can be traced down to the same horizon. These correlating ages imply that linked intrusive and extrusive activity within the area can be dated to a short-lived period during the Middle Eocene.

These constraints on the timing of magmatism have allowed the BBIC to be placed into a geodynamic framework. The ages obtained correspond to an acceleration of seafloor spreading rates along the southern margin, and are coeval with other major changes in global tectonics. Furthermore, the inferred age of igneous activity in the Bight Basin broadly correlates with other volcanic events along the southern margin and the 'Older Volcanics' in Victoria. The timing and distribution relationships suggest that the BBIC was generated in response to upwelling of the mantle beneath a thinned crust coupled with the interaction of localised, more focused igneous activity centred on the densest clustering of volcanics. Other occurrences outside of this central area may be attributable to smaller thermal anomalies coinciding with areas of crustal weakness.

The influence of these rocks on petroleum systems is uncertain at this stage; however, evidence from other regions suggests that the negative impact will be minimal unless the magmas made direct contact with existing hydrocarbon accumulations. A more important concern is the potential effect a postulated magma reservoir at depth will have on burial history scenarios and petroleum systems modelling for the Bight Basin.

Introduction

The southern margin of Australia, along with the eastern and western margins, represents a divergent plate boundary related to the breakup of Gondwana during the Mesozoic (Teasdale et al., 2003). Rifting along these margins took place in an anticlockwise fashion, beginning at around 155 Ma with extension and continental rifting in the west (Brown et al., 2003), finally progressing to rifting in the Coral Sea at 52 Ma (Gaina et al., 1998; Brown et al., 2003). Rifting and continental breakup on the southern margin between Australia and Antarctica led to the formation of the Bight Basin (Teasdale et al., 2003), which consists of the Ceduna, Duntroon, Recherche, Eyre, Bremer and Denmark Sub-basins (Fig. 1, Stagg et al., 1990; Totterdell et al., 2000; Bradshaw et al., 2003).

The absence of evidence of significant magmatism associated with breakup has led to the classification of the Australian southern margin as a 'non-volcanic' rifted margin (e.g., Sayers et al., 2001). Despite this, several previous workers have identified the presence of scattered volcanic and intrusive bodies within the basin in both seismic data and dredge samples (Fraser and Tilbury, 1979; Stagg et al., 1990; Clarke and Alley, 1993; Lanyon et al., 1995; Totterdell et al., 2000; Sayers et al., 2001; Teasdale et al., 2003; Totterdell and Bradshaw, 2004). These rocks are referred to in this report as the Bight Basin Igneous Complex (BBIC).

Until recently, key questions relating to the true extent, age, and tectonic drivers for the volcanic and intrusive rocks of the BBIC have been unresolved due to widely spaced seismic coverage. The recent public release of Woodside Energy's high-resolution Flinders 2D seismic survey covering much of the Ceduna Sub-basin has allowed these bodies to be accurately mapped for the first time. Line spacing on this survey is considerably closer than that of previous surveys, and is typically 4–8 km, making it highly amenable to investigation of magmatic activity in the area (Fig. 2). This report discusses the BBIC in terms of its distribution, morphology and age, as well as the geodynamic drivers for magmatism and the implications for petroleum prospectivity. This new information enhances the overall understanding of the evolution of the southern margin, and provides a useful input to the analysis of the hydrocarbon potential of this region.

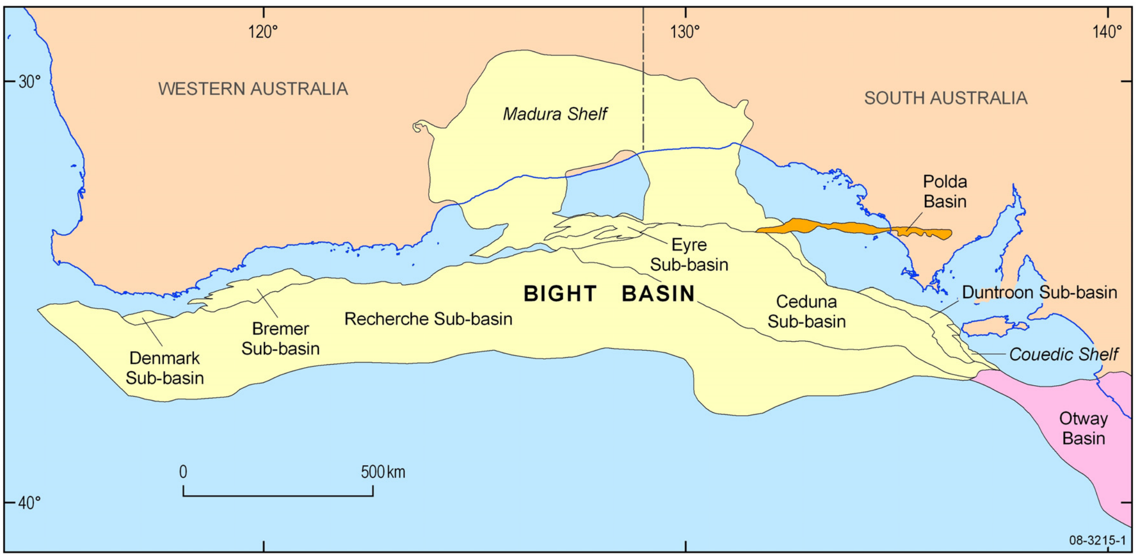

Figure 1: *The Bight and Eucla Basins and component sub-basins.*

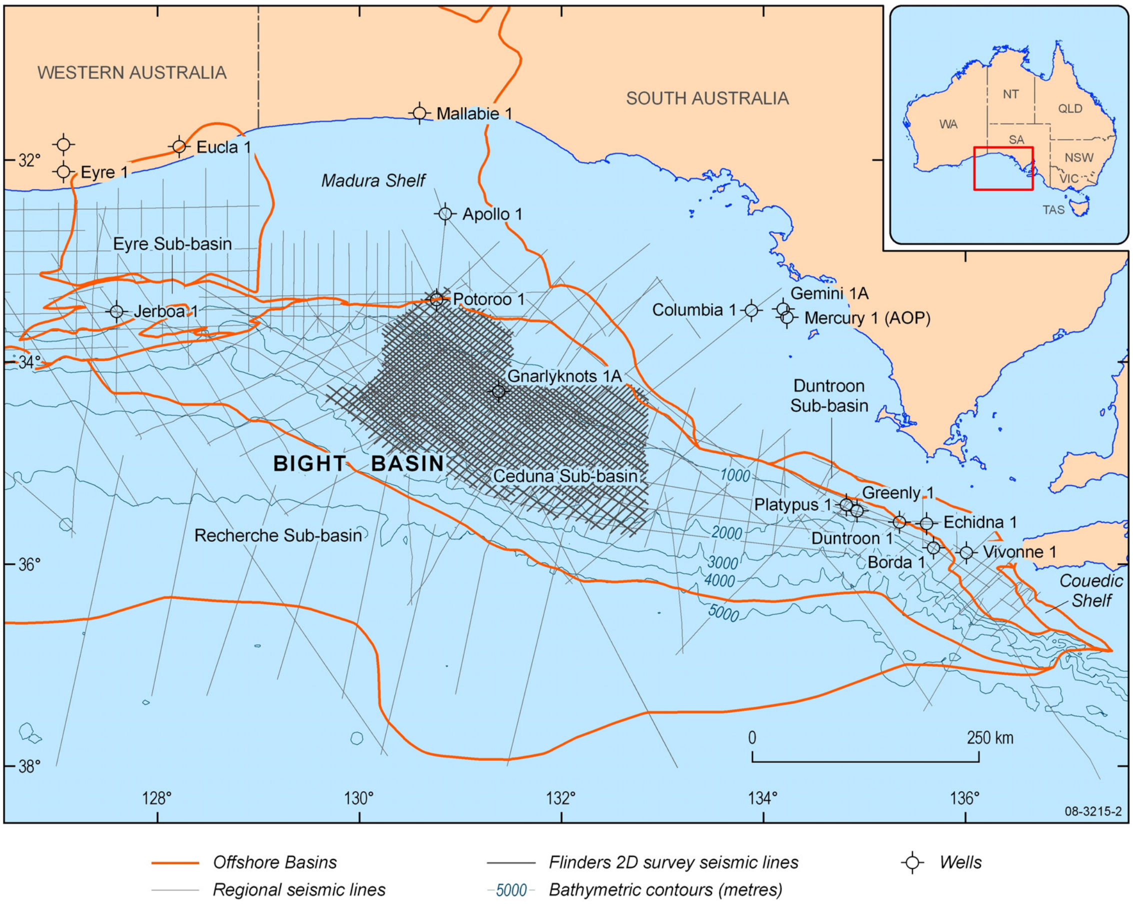

Figure 2: *Available seismic coverage in the vicinity of the Bight Basin Igneous Complex.*

TECTONIC HISTORY

The long and complex development of the Bight Basin has been considerably debated in the geological literature (e.g., Veevers, 1986; Stagg et al., 1990; Norvick and Smith, 2001; Teasdale et al., 2003; Totterdell and Bradshaw, 2004). During continental extension, the Bight and its subsidiary Sub-basins developed under the control of pre-existing E–W and NW–SE trending fabrics within the underlying basement (Teasdale et al., 2003; Totterdell and Bradshaw, 2004). The opening of the basin has been interpreted by Totterdell and Bradshaw (2004) to be generally consistent with the Southern Rift System (SRS) history outlined by Stagg et al. (1990). Those authors identified a two-stage formation process for the SRS:

1. An initial NW–SE extension during the late Jurassic; and
2. Reorientation of the stress field to a NNE–SSW direction during the Early Cretaceous. This event initiated the formation of the Otway and Gippsland Basins.

Therefore, extensional tectonics along the SRS took place in a progressive fashion, with the centre of extension moving from west to east, with the formation of depocentres accompanying the moving locus of extension.

The first phase in the complex development of the Bight Basin took place during the Middle to Late Jurassic (Totterdell and Bradshaw, 2004), corresponding to phase one in the SRS development scheme of Stagg et al. (1990). During this period, a triple-junction existed at the southern tip of

Western Australia. Crustal stretching and thinning along the southern margin during the Late Jurassic to Early Cretaceous led to the formation of intracontinental extensional basins (Teasdale et al., 2003; Totterdell and Bradshaw, 2004). By the Early Cretaceous, rifting had led to the generation of oceanic crust along the western margin, but did not progress to that stage in the south (Totterdell and Bradshaw, 2004).

Cessation of upper crustal extension was accompanied by initially slow thermal subsidence during the Early Cretaceous, followed by more rapid rates from the Middle Albian, as shown in subsidence curves from wells and pseudo-wells in the Bight Basin (Totterdell et al., 2000). Other basins along the southern margin have also been noted to experience increased subsidence rates during this time (Hegarty et al., 1988). This has been interpreted by some (e.g., Gurnis et al., 1998; Brown and Müller, 2002) to reflect the passage of the Bight area over a remnant subducted slab that cooled the underlying mantle by up to 50^{o}C. Alternatively, the acceleration in subsidence rates may have been controlled by lower crustal processes (Totterdell et al., 2000). Work on other rifted margins has led to the proposal that the formation of rifted continental margins is preceded by depth-dependant stretching of the crust, where the lower crust and upper mantle undergo significantly more stretching and thinning than the upper crust (e.g., Kusznir and Ziegler, 1992; Davis and Kusznir, 2004; Kusznir and Karner, 2007).

Seafloor spreading commenced in the Late Cretaceous (Fig. 3). Estimates on the date of continental breakup range from ~125 Ma to ~83 Ma (Cande and Mutter, 1982; Veevers, 1986; Stagg and Willcox, 1992; Tikku and Cande, 1999; Sayers et al., 2001). However, seismic evidence presented by Sayers et al. (2001) reassigning the oldest seafloor spreading anomaly to anomaly 33 of Cande and Mutter (1982), provides a compelling case for breakup commencing in the Late Santonian (~83 Ma). This interpretation is supported by the structural evolution of the Bight Basin and biostratigraphic dating of the regionally important Hammerhead Supersequence boundary, which is interpreted to represent breakup (Fig. 3; Totterdell and Bradshaw, 2004).

The Late Cretaceous episode of extension resulted in the generation of the first true oceanic crust, and is therefore interpreted to reflect the onset of intercontinental rifting between Australia and Antarctica (Sayers et al., 2001; Totterdell and Bradshaw, 2004). Half-spreading rates were extremely slow until the Middle Eocene, reaching a maximum of around 10 mm/year (Tikku and Cande, 1999), although spreading rates were generally much less. From around 43 Ma, half-spreading rates rapidly increased to about 20 mm/year in a N – S orientation (Tikku and Cande, 1999). In the post Eocene period, deposition of marine carbonates reflects deepening water and the end of the effect of regional tectonics on the development of the Bight Basin (Fraser and Tilbury, 1979).

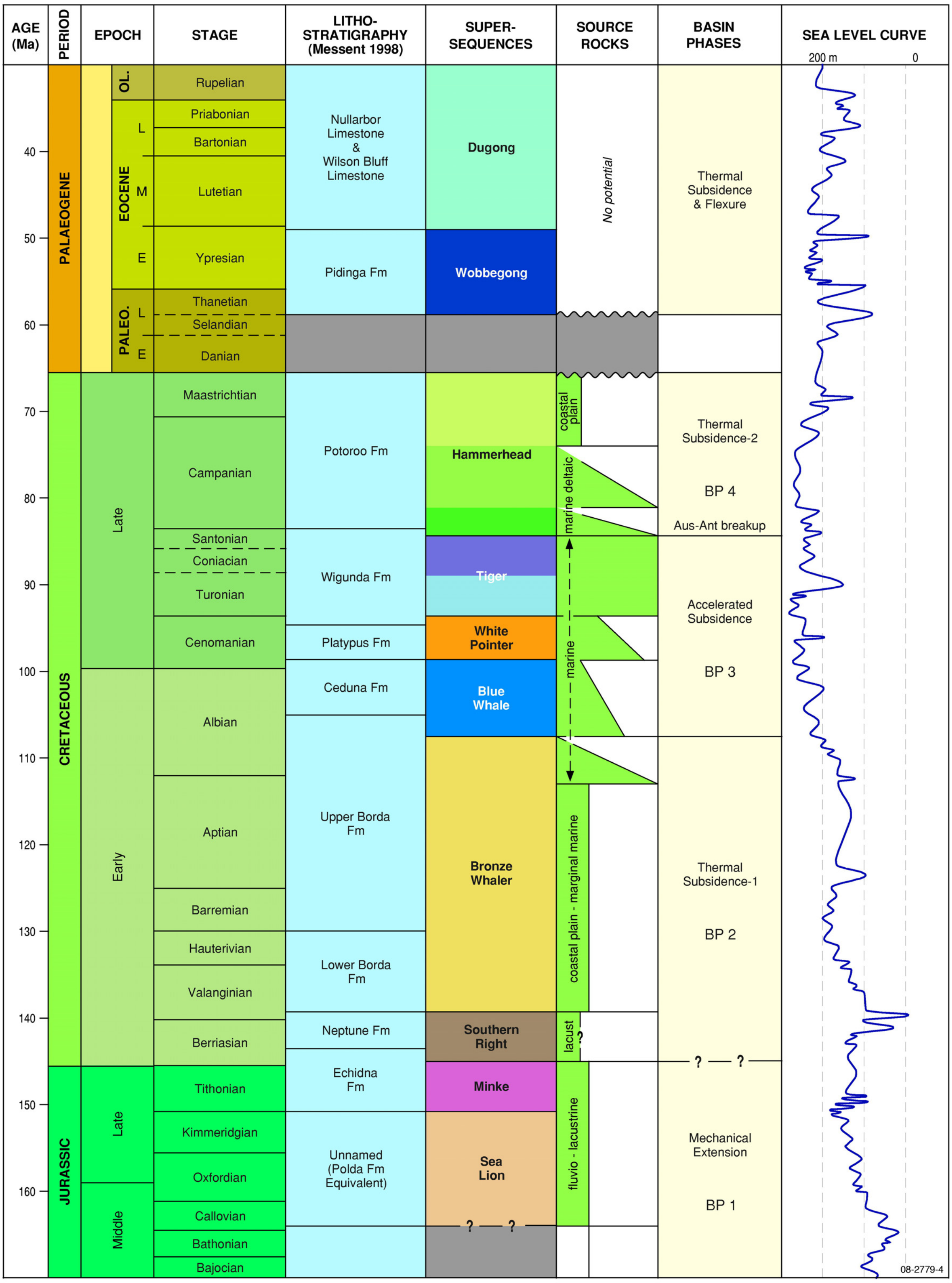

Figure 3: Bight Basin stratigraphy, basin phases and predicted source rock intervals. Figure taken from Totterdell et al.(2008), and is modified from Blevin et al. (2000) and Totterdell et al. (2000). The sea-level curve (Haq et al., 1988) is modified to the time scale of Gradstein et al. (2004).

Igneous bodies

Using the newly available seismic data, widespread intrusive and extrusive bodies within the Bight and Eucla basins have been mapped in detail (Fig. 4). Numerous sills, dykes, volcanic cones and lava flows are spectacularly imaged in seismic data, showing a range of morphologies. These rocks are easily identified owing to their distinctive seismic characteristics which arise from the inherent rock properties and emplacement mechanisms. The igneous bodies typically display high amplitude positive seismic responses due to large velocity contrasts with the surrounding country rock. These high responses have the effect of reflecting large amounts of seismic energy, resulting in a characteristic 'wash-out' effect below many of the bodies. Additional distinguishing criteria include discordant relationships with adjacent strata, a 'chattery' seismic character, and typically igneous morphologies such as cone structures.

The distribution of igneous bodies within the Bight Basin is largely confined to the Ceduna Sub-basin, with only very slight incursions into the Eyre and Duntroon Sub-basins (Fig. 4). The densest clustering of volcanics and intrusives occurs in a broadly circular, 130 km wide area encompassing ~10,000 km^2 in the central Ceduna Sub-basin. Notably, this region also contains most of the large volcanic cones (i.e., those with base diameters of around 10 km) and sills. Towards the western extent of the BBIC, igneous occurrences become more discrete and diffuse. In addition, the relative size of volcanic cones and sill complexes significantly decreases, reflecting much lower magma volumes (although one notable 10 km wide cone has been observed). In general, most of the magmatic occurrences observed can be grouped into a field approximately 400 km long by 140 km wide extending in an approximately NW – SE orientation parallel to the margins of the Ceduna Sub-basin. Scattered outliers towards the east in the Duntroon Sub-basin extend this field to over 650 km when included.

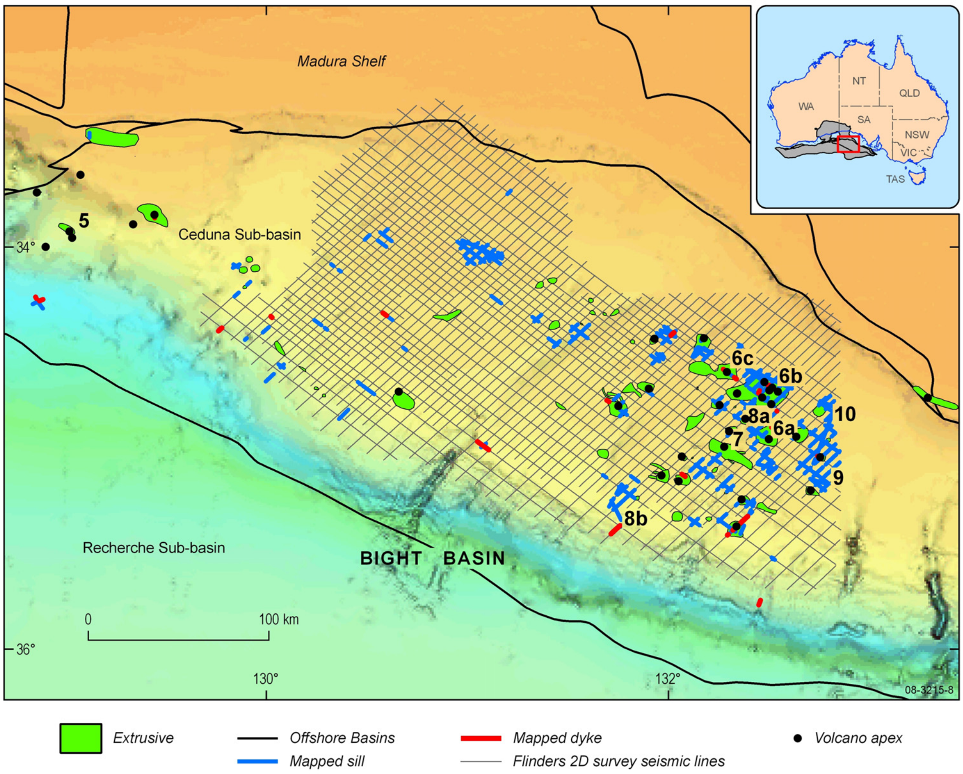

Figure 4: *Distribution of volcanic features, sills and dykes, Ceduna Sub-basin. Locations for figures 5 to 10 are shown.*

VOLCANIC FEATURES

Volcanoes in the Bight Basin have been imaged in both seismic data and in limited high resolution bathymetry. Several examples of igneous material have also been dredged from partially unburied volcanoes in the western BBIC, and have been described as amygdaloidal, possibly pillowed, basalts (Clarke and Alley, 1993). Volcanoes are typically broad structures, with base diameters several times their height. This is more characteristic of shield-like volcanoes, and suggests that volcanism was predominately effusive rather than explosive in character.

When viewed in seismic data, volcanoes often display a series of internal stacked cones, providing evidence of progressive volcano growth. Other volcanoes reveal much more chaotic internal reflections. Lava flows are typically more 'rubbly' in character, which together with the observed presence of possible pillow lava textures, suggests a subaqueous environment at the time of extrusion.

Volcano morphologies vary across the BBIC. The most commonly observed are broad conical shapes (Fig. 5). These occur as stand-alone cones ranging in size from less than 2 km to 11 km across the base (Fig. 6a), and as voluminous volcanic complexes with up to seven large extrusive centres confined within a small area (Fig. 6b). Other volcanoes have mound-like characteristics, potentially suggesting more viscous magmas (Fig. 6c). One rare example of a flat-topped buildup was also observed. Comparison with adjacent seismic lines, which image the same volcanic cone, lack any sign of planation, suggesting that this represents mass wasting of the western flank of the volcano. Many volcanoes are associated with large lava flow aprons (Fig. 7). Lava flows also occur independently of volcanic cones, suggesting potential fissure-style eruptions.

Stratigraphic patterns adjacent to most of the larger volcanoes generally reveal the presence of a moat incised into the surrounding sediments (e.g., Fig. 6c). These moats were subsequently backfilled, as evident in parallel filling patterns. The moats typically occur some distance up the volcano flanks, indicating that they are not a syn-extrusional feature. Therefore, they are not interpreted to be a response to loading, but rather are attributable to localised eddy currents.

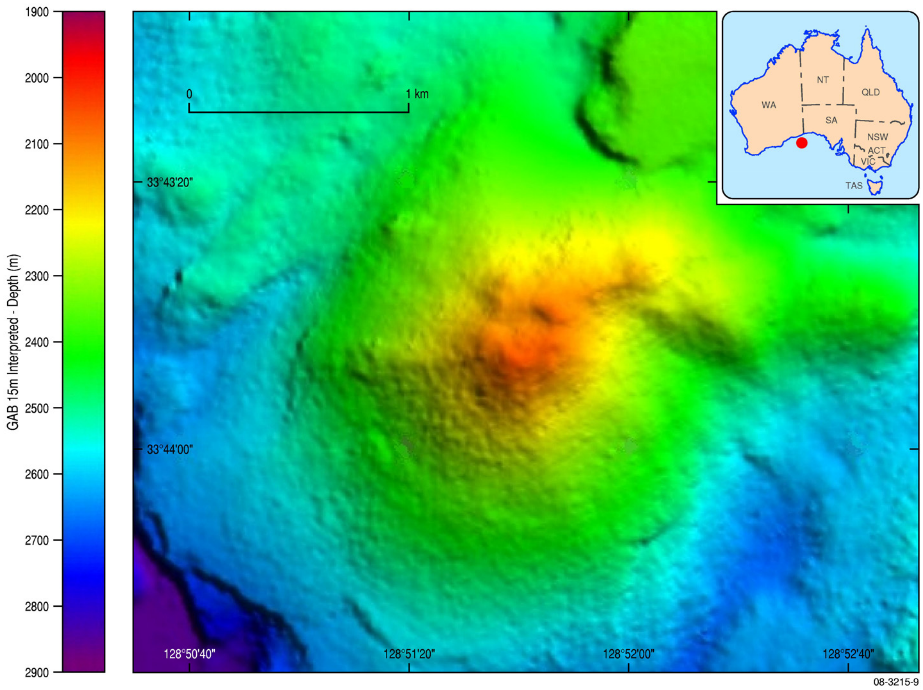

Figure 5: *Swath bathymetry image of conical volcano from western Ceduna Sub-basin. Note the presence of a crater at the apex of the cone.*

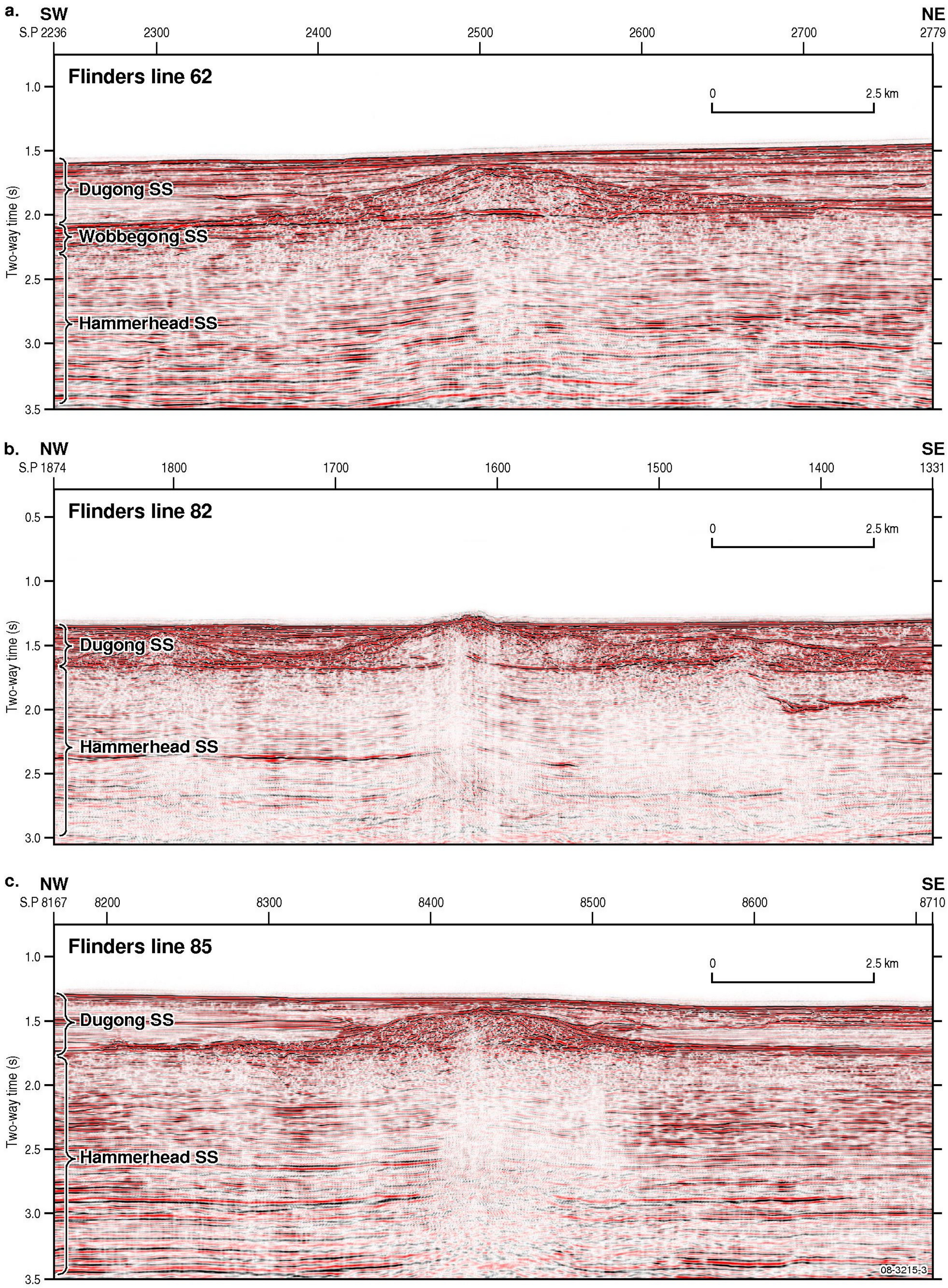

Figure 6: *Some of the volcanic morphologies observed in the central Ceduna Sub-basin; a) example of a single cone rising from the palaeo seafloor; b) example of an igneous complex formed by several extrusive centres; and c) example of a more mound-like morphology.*

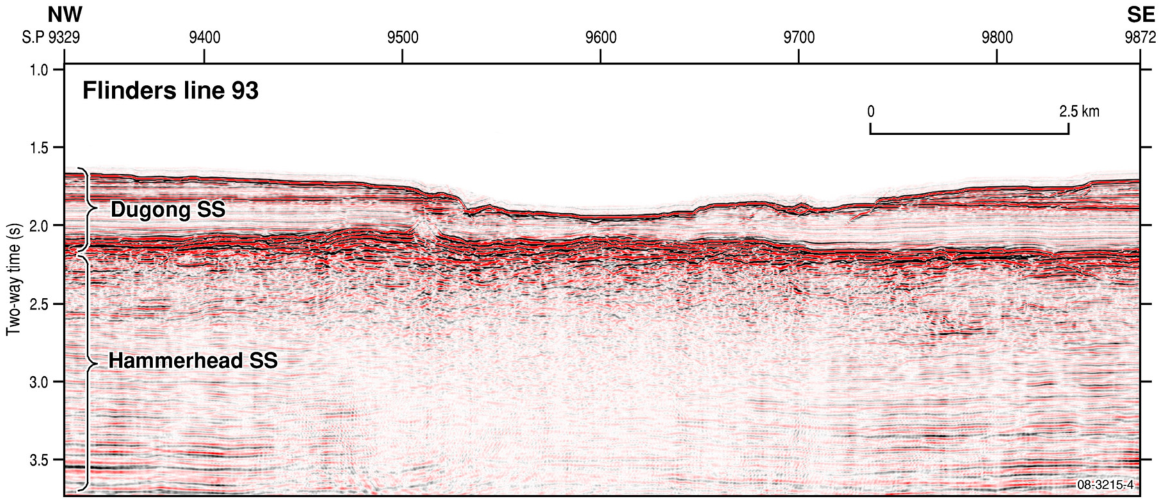

Figure 7: *A large lava flow observed in the central Ceduna Sub-basin. The lack of a large volcano in association with this flow suggests that it may represent a fissure-style eruption.*

SILLS AND DYKES

Many of the volcanoes and volcanic flows are underlain by large sill complexes of variable morphologies, although there is not always a volcanic association. Sill morphologies range from simple sheet-like or tabular structures, which are the most commonly observed, through to lesser domal and 'saucer' shaped morphologies (Fig. 8a) similar to those observed in other extensional settings (e.g., Hansen and Cartwright, 2006; Rohrman, 2007). Dykes are typically intruded at various levels in the late Santonian–Maastrichtian Hammerhead Supersequence, although some bodies have been observed intruding the top of the Turonian–Santonian Tiger Supersequence. This evidence suggests a post–Maastrichtian age for sill intrusion.

Emplacement of sills is often associated with 'forced' folding in the overlying strata. The distribution of significant forced folding coincides with the densest clustering of igneous bodies in the central Ceduna Sub-basin. The absence of forced folding in other areas may reflect insufficient magma volumes to 'jack up' the overlying strata, and correlates well with an observed decrease in density and scale of volcanics and intrusives in the western Ceduna Sub-basin (Fig. 4). Small feeder dykes were imaged beneath a small subset of sills, although larger feeders are only occasionally observed. Larger stand-alone dykes with minor parasitic sills were also imaged (Fig. 8b).

Discussion

Using the new information obtained in this study, key questions relating to the timing, tectonic setting and origin of the BBIC can be addressed. The timing of magmatism has important implications for the hydrocarbon prospectivity in the Bight Basin, specifically in relation to maturation, trap formation and trap integrity. Until now, the BBIC has not been placed into the complex continental breakup-related evolution of the Bight Basin. In order to achieve this, an accurate constraint on the timing of magmatism is required.

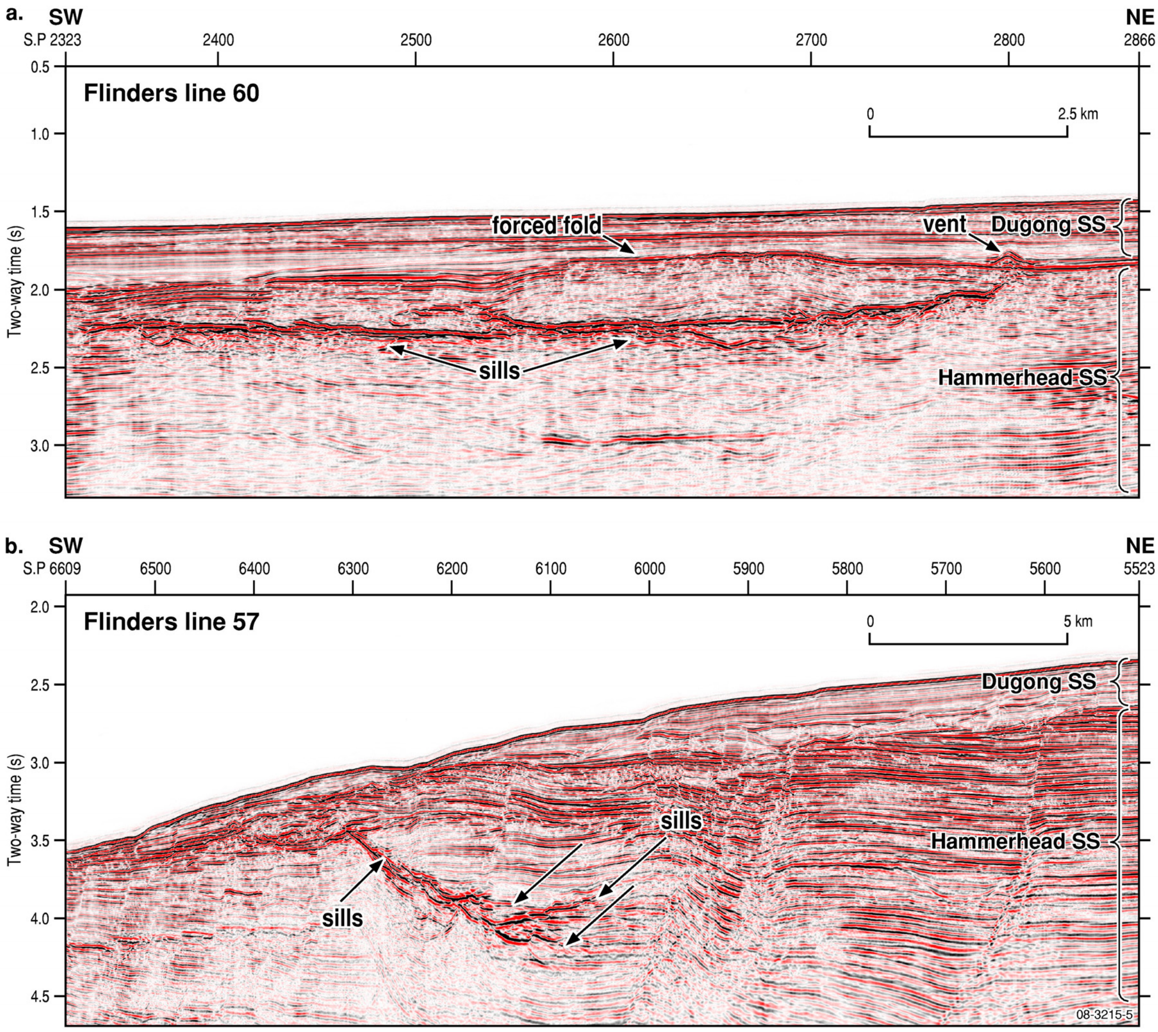

Figure 8: *Examples of intrusive morphologies observed in the Ceduna Sub-basin: a) example of a saucer-shaped sill. This feeds up into a small vent, showing the link between intrusive and extrusive bodies. The sills here intrude the upper sections of the Late Santonian – Maastrichtian Hammerhead Supersequence; b) example of a large dyke with parasitic sills extending laterally from the main feeder.*

DATING OF THE BIGHT BASIN IGNEOUS COMPLEX

Although isotopic dating is lacking for the igneous rocks of the BBIC, a constrained interval of time can be derived using detailed seismic mapping and relative dating techniques. Previously, based on interpretation of regional-scale seismic datasets, it was not possible to determine the exact age of the igneous activity, and it was believed to be either Latest Maastrichtian–Paleocene or Middle Eocene in age (Totterdell et al., 2000; Teasdale et al., 2003; Totterdell and Bradshaw, 2004). This age uncertainty is attributable to the difficulty in many parts of the basin in distinguishing between the basal Wobbegong Supersequence (Late Paleocene–Early Eocene) and the base of the overlying Dugong Supersequence (Middle Eocene–Recent; Fig. 3), due to the limited thickness of the former. More detailed mapping undertaken using the Flinders seismic grid has allowed the distinction between the Wobbegong and Dugong Supersequences to be better resolved.

All volcanic build-ups mapped during this study appear to have their basal contact on the unconformity at the base of the Dugong Supersequence, where it is able to be distinguished from the underlying Wobbegong Supersequence. This would appear to imply a Middle Eocene age for extrusive magmatism. This date is independently supported by constraints on the dating of intrusive sills.

Several authors have proposed a technique for the relative dating of intrusive sills based on the forced folding of overlying strata by the intrusion (e.g., Trude et al., 2003; Hansen and Cartwright, 2006). The age of onlapping strata can be used to constrain the timing of intrusion-related deformation (thereby dating sill intrusion); while the age of the overlying folded strata can be used to provide a maximum age date for sill intrusion. Ages determined using this technique in the Faeroe–Shetland Basin have been proven to correlate well with available isotopic dating (Trude et al., 2003). In the Bight Basin, high amplitude forced folding related to sill intrusion occurs in the central Ceduna Sub-basin. Here, intrusives fold the basal or near-basal Dugong or coincident Dugong/Wobbegong Supersequences. While most forced folds appear to be draped by Dugong strata, some appear to be onlapped by the earliest Dugong sediments (Fig. 9), implying intrusion early in the depositional history of the Dugong Supersequence. These data indicate an intrusive date during the early Middle Eocene. Both intrusion and extrusion occurred concurrently over a constrained time period, with coincident late intrusion and earlier extrusion evident in some cases.

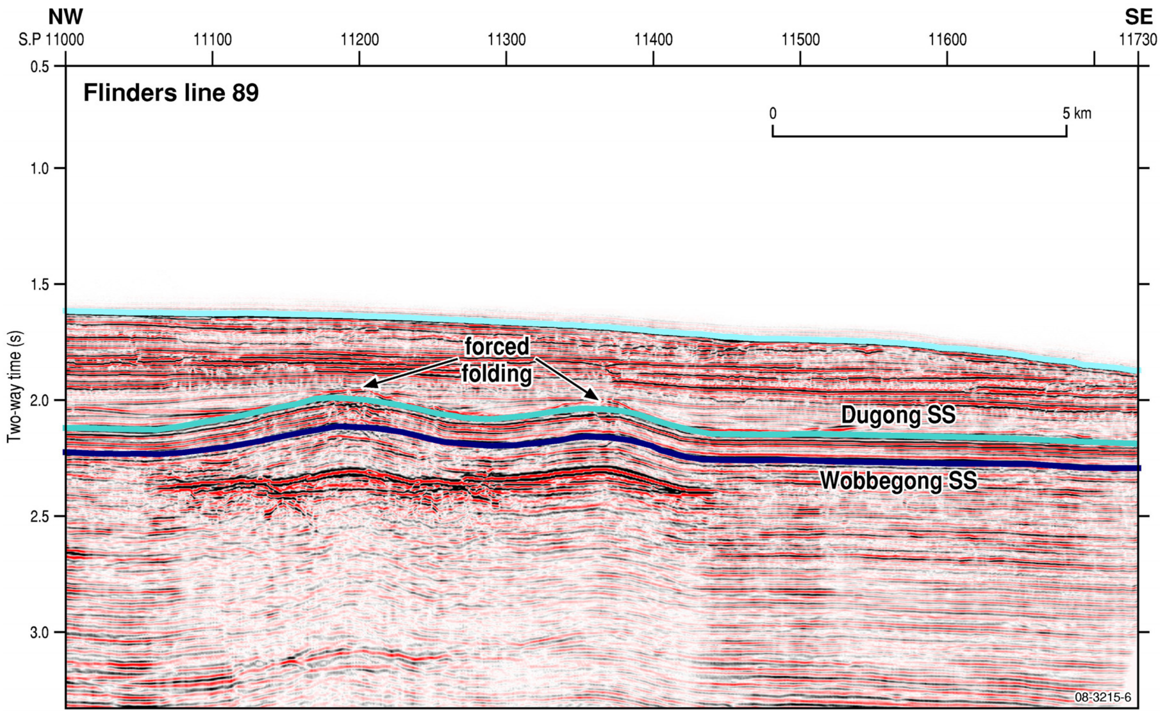

Figure 9: Forced-folding of the basal Dugong Supersequence (teal horizon) resulting from high- level sill intrusion in the upper Hammerhead Supersequence. This enables the age of intrusion to be accurately constrained to the Middle Eocene.

The Middle Eocene constraint on igneous activity in the Bight now allows the BBIC to be placed into the tectonic framework of the southern margin. Based on the chronology of events outlined by Totterdell and Bradshaw (2004), magmatism corresponds broadly to the rapid onset of accelerated rates of seafloor spreading in the Middle Eocene (Tikku and Cande, 1999). This date further corresponds to a suite of other major changes in global tectonics (Veevers, 2000; Teasdale et al., 2003), as evidenced by the cessation of spreading in the Tasman Sea, the kink in the Emperor-Hawaii seamount chain, the collision of India with Asia, and plate rearrangements near New Zealand (Teasdale et al., 2003). A Middle Eocene date is also significant as it broadly correlates with intraplate magmatism along the east and southeast margins of mainland Australia.

ASSOCIATION WITH OTHER VOLCANICS

Volcanism attributed to hotspot migration occurred throughout eastern Australia between latitudes of about 20–40°S from around 35 Ma (Johnson et al., 1989; Sutherland, 2003). Onshore magmatism is particularly well represented in Victoria, where almost continuous terrestrial volcanism occurred throughout the Cenozoic, with volumetric peaks at 42–57 Ma and 0–5 Ma ('Older' and 'Newer' Volcanics, Price et al., 2003). Onshore activity is also recorded in Gippsland (27–25 Ma) and the eastern highlands (27–14 Ma) by Norvick and Smith (2001). Offshore, volcanics and intrusives have also been observed in the Bass and Otway Basins, as well as on the seafloor northeast of Tasmania (Gill and Segnit, 1986; Sutherland et al., 1989; Hill et al., 1998; Norvick and Smith, 2001; Price et al., 2003; Dance et al., 2004). These have been variously been dated as 58 and 37 Ma (Price et al., 2003) and ~3–0 Ma (Norvick and Smith, 2001) for the Otway Basin, and ~30–20 Ma (Sutherland et al., 1989) and 32–18Ma (Dance et al., 2004) for the Bass Basin.

The large spatial separation between the inferred plume head and the BBIC suggests that magmatism in the Bight Basin is not attributable to the southward migrating hotspot magmatism seen along the eastern seaboard of Australia. However, the close temporal correlation with intraplate, non-hotspot-related volcanism in onshore and offshore Victoria alludes to a potential geodynamic link. The extensive distribution of igneous occurrences suggests that mantle conditions along parts of the southern margin were relatively unstable and fertile for magma generation without necessitating the involvement of 'classical' mantle plumes. A similar view is taken by Price et al. (2003), who have attributed the Cenozoic volcanics in Victoria to unstable mantle conditions reaching back to the Mesozoic as a result of the breakup of Gondwana, rather than long-lived and deep-seated mantle plumes.

MAGMATIC DRIVERS FOR THE BIGHT BASIN IGNEOUS COMPLEX

Causes of mantle-derived igneous activity include mantle decompression, fluxing, and anomalous mantle temperatures. Any genetic model for magmatism in the Bight region must successfully account for the occurrence of these volcanics long after the initial onset of sea floor spreading and their distribution away from the active spreading centre. Melting as a result of mantle decompression is often associated with extension and rifting, and is most likely to occur where the crust is most attenuated (i.e., closest to the active spreading centre). Although the crust beneath the BBIC was somewhat thinned at the time of igneous activity in the Bight region (Totterdell and Bradshaw, 2004), lack of evidence in the seismic data for significant upper crustal extension at that time indicates that rifting is not likely to have been a driver for magmatism. It is possible that stretching in the lower crust may have permitted a degree of mantle decompression, however this is unlikely, since the extensional regime by this time had progressed to seafloor spreading rather than ductile extension (Teasdale et al., 2003).

Fluxing of the mantle is unlikely to be the cause of magmatic activity in the Bight region, since this explanation requires the presence of a subducting slab in order to release necessary volatiles to trigger mantle melting. A subducted slab in the vicinity of the BBIC has been invoked previously to account for accelerated subsidence in the Middle Albian–Late Santonian (Gurnis et al., 1998; Brown and Müller, 2002). If the presence of a subducted slab was likely to trigger magmatism, then some evidence of earlier magmatism, from the time when the region is proposed to have moved over the slab (Albian–Maastrichtian), would be expected. However, there is no indication of earlier volcanism and related intrusive rocks in the Bight Basin.

With the elimination of decompressive melting due to rifting and fluxing of the mantle due to subduction as possible origins for magmatism in the Bight region, it becomes more likely that the igneous occurrences of the BBIC can be attributed to some form of hotspot activity. A migratory Hawaiian-style form of hotspot activity ('primary' plumes of Courtillot et al., 2003) can be rejected for the BBIC based on the distribution and timing of igneous occurrences. This is primarily based on three reasons:

1. The approximate NW–SE distribution of the BBIC is inconsistent with the known movement of the Australian plate at that time;
2. Large migratory hotpots are active for long periods of geological time, whereas magmatism in the Bight region was short-lived; and
3. A link between the known hotspot-driven volcanism in eastern Australia and igneous activity represented by the BBIC is not consistent with the known hotspot tracks (e.g., Sutherland, 2003), and may therefore be rejected.

Another hypothesis which accounts for hotspot-like activity while not requiring evidence of migratory plume tracks has been proposed by King and Anderson (1998) and King (2007). Their model interprets many hotspots to be reflective of edge-driven convection cells in the mantle set up between continental and oceanic crust, or younger crust and cratonic root zones. This is based on the recognition that temperature distribution within the mantle is anisotropic, with temperature variations of up to 200^{o}C permitting the development of small-scale convection cells in the upper mantle (Anderson, 2000). King (2007) suggests that such convective flow could occur at distances of up to 1000 km from the cratonic root. Such hotspot activity corresponds to the 'tertiary' hotspots of Courtillot et al. (2003). This mechanism is plausible, since all of the mapped igneous occurrences occur within 300 km of the margin of the Gawler Craton, and the NW distribution of igneous rocks parallels its margin.

There are indications that magma supply was not uniform across the entire Ceduna Sub-basin. Evidence of this is seen in the increased density of igneous occurrences, larger volcanoes and sills, and the abundance of forced folding in the central Ceduna Sub-basin (Fig. 4). On the other hand, the western portion of the field displays smaller, less concentrated igneous occurrences, and a marked lack of significant forced folding. Based on this evidence, it is interpreted that the central Ceduna Sub-basin has been influenced by increased levels of concentrated mantle melting manifested as hotspot activity. This is consistent with a 'tertiary' plume type in the terminology of Courtillot et al. (2003). The effective duration of 'plume' activity would correspond to a short interval of time equivalent to the basal section of the Dugong Supersequence, as suggested by the chronological evidence presented above. In order to explain the occurrences outside of this main zone, it is interpreted that these are attributable to smaller thermal anomalies coinciding with areas of crustal weakness.

It has already been discussed above that the occurrence of BBIC cannot be explained by a plume system similar to that of Hawaii or Iceland with a deep plumbing system. Similarly, it is unlikely that magmatism was a result of a 'secondary' plume in the terminology of Courtillot et al. (2003) for similar reasons. Therefore, it is interpreted that the Bight 'plume' is likely to be sourced from the upper mantle. As such, the typical geochemical features characteristic of deep-seated mantle plumes (such as primitive isotopic compositions) are not expected to be present. This third category of mantle plume is interpreted by Courtillot et al. (2003) to represent passive responses to changes in the lithosphere and to be linked to the asthenosphere. Therefore, it is postulated that this 'plume' would geochemically be a 'MORB-plume' (i.e., having geochemical characteristics similar to mid ocean ridge basalts and the upper mantle). This plume may therefore be best thought of as concentrated mantle upwelling rather than a 'plume' in the true sense.

Based on this interpretation, a four-stage geodynamic model for the BBIC is inferred:

1. Breakup of Gondwana during the Mesozoic resulted in the development of the Bight Basin. Extension was preceded by voluminous, plume-related basaltic magmatism of the Ferrar flood basalt province, which is evident as far west as Kangaroo Island (Hergt and Brauns, 2001; Foden et al., 2002). Basin orientation was controlled by pre-existing NW–SE and E–W trending basement fabrics (Teasdale et al., 2003; Totterdell and Bradshaw, 2004). This rifting event resulted in a partially destabilised mantle fertile for melt generation;
2. Slow spreading rates during the Late Cretaceous to Early Eocene allowed the mantle to remain relatively stable. The onset of rapid seafloor spreading in the Middle Eocene destabilised the upper mantle and acted as a stressor for magma generation. Mantle upwelling due to this event combined with a small, short-lived, reactionary 'plume' centred in the central Ceduna Sub-basin. The locus of plume-like activity was probably dictated by edge-driven mantle convection involving the Gawler Craton in a manner similar to that suggested by King and Anderson (1998) and King (2007);
3. Mantle upwelling and hotspot activity resulted in the extrusive and intrusive bodies of the BBIC. Magmatic activity was centred in the central Ceduna Sub-basin. Other occurrences outside of this zone may be attributable to the interaction of smaller thermal anomalies coinciding with areas of favourable crustal weakness. The NW–SE orientation of the BBIC suggests that magmatism was controlled by the same fundamental basement fabrics that controlled the architecture of the Bight Basin and its sub-basins (particularly the Ceduna); and
4. Plume-like activity ceased after a very short period of time once the upper mantle had re-equilibrated, marking the end of igneous activity in the Bight.

Implications for hydrocarbon resources

Igneous activity in potential hydrocarbon systems can have both positive and negative impacts (Schutter, 2003a), although much of the literature on this subject has emphasised the negative influences. The effects of magmatism on hydrocarbon systems can be grouped into three broad categories: heating and maturity, reservoirs and seals, and trap formation.

HEATING AND MATURITY

Much of the previous work on the implications of igneous activity in hydrocarbon systems has been focused on the potential overmaturity risk posed by the heat input of these bodies. In the Bight Basin, this effect has been observed in the Echidna-1 well in the Duntroon Sub-basin, where the presence of overmature organic material, including coke, has been attributed to a large underlying intrusion (Newman Energy Research Ltd., 2004; Totterdell and Bradshaw, 2004). Although the existence of overmaturity haloes is well documented, estimates on the lateral and vertical extents of overmaturity vary markedly (e.g., Bishop and Abbott, 1995; Archer et al., 2005; Rohrman, 2007).

Murchison and Raymond (1989) and Raymond and Murchison (1988; 1991) have argued that the extent of the thermal aureole surrounding an intrusion is primarily influenced by the level of compaction and water saturation of the surrounding sediments. Their studies revealed that the largest thermal aureoles were developed around sills intruded later in the compaction history of the basin, with widths several times the thickness of the sill. In contrast, sills intruded into less consolidated sediments were observed to have developed very small thermal aureoles, due to the dissipation of thermal energy via heating and evaporation of pore fluids. In the Bight Basin, sills are predominately intruded into the upper sections of the Hammerhead Supersequence, which would have been relatively young and unconsolidated at that time, and would allow for a large volume of pore water. As such, it is interpreted that the thermal effect from these intrusions on the surrounding rocks would be minimal unless direct contact is made between the intrusion and a potential hydrocarbon reservoir.

In contrast to this, Schutter (2003a) suggested that heated pore fluids may act as a transport medium by which heat derived from an igneous body may be carried away from the site of intrusion. The destructive effect of hydrothermal fluid flow driven by heating from igneous intrusion has been demonstrated in Echidna-1, where localised coke formation has resulted from hot fluids (Newman Energy Research Ltd., 2004). Although this suggests the presence of active hydrothermal systems, hydrothermal vents are rarely observed in the Bight region. This contrasts other basins, such as the Bass Basin, where hydrothermal vents associated with igneous activity are common (Cummings and Blevin, 2003). This observation suggests that shallow-level hydrothermal activity is limited. The mobility of these fluids will be highly influenced by the availability of suitable fluid conduits such as faults and joints. Therefore an area with extensive fracturing may pose a greater overmaturity risk, although this effect will be highly localised to conduit fracture systems.

It has been noted that the thermal input from sill intrusion is minimal unless sill occurrence is dense (e.g., Rohrman, 2007). A more influential factor to the maturity within a basin may be an elevated regional heat flow caused by a magma source at depth, such as underplated igneous material (Schutter, 2003a). The density of igneous occurrences should approximate the locations of any such potential deep magma reservoirs. Based on this premise, it would seem likely that the largest thermal contribution would be localised in the central Ceduna Sub-basin, which agrees with the geodynamic model discussed above. Limited seismic evidence showing unusual folding of strata in the deeper sections of the basin seems to agree with this. If this folding is attributable to igneous-related deformation, then the thermal input of these bodies will be significant, and will have the most pronounced effect on the Middle Jurassic–Santonian succession (Sea Lion to Tiger Supersequences).

RESERVOIRS AND SEALS

Sufficient porosity may develop in igneous rocks to enable them to act as viable hydrocarbon reservoirs, and numerous examples of this reservoir type occur throughout the world (Schutter, 2003a). Porosity may be developed during primary processes (e.g., vesicles, brecciation), or as secondary porosity (e.g., fracturing, alteration). Without the availability of reasonably fresh samples of igneous material, it is not possible to make a detailed assessment of the potential of the igneous rocks of the BBIC to act as a viable reservoir rock at this stage.

Hydrothermal fluids can deleteriously affect reservoir quality. Studies of quartz sandstone reservoir facies adjacent to intrusive and extrusive igneous rocks in the Bass Basin have shown that hot hydrothermal fluids have altered quartz grains and acted to cement the rocks (Cummings and Blevin, 2003). The minimal evidence of hydrothermal activity associated with the BBIC, and the high stratigraphic level of most of the intrusive units, may indicate that hydrothermal alteration of reservoir sandstones may not be a significant concern in the Bight Basin.

Schutter (2003a) has noted several occurrences of suitable seals formed by igneous rocks (primarily extrusive lithologies). Examples of this include the Kipper field in the Gippsland Basin, where a thick volcanic unit effectively seals the underlying reservoir sands (Sloan et al., 1992). Igneous rocks may act as both seal and reservoir in some cases, if the upper sections of the body are weathered sufficiently to form impermeable clays, and there is adequate porosity within the igneous body itself (Schutter, 2003a). While this type of reservoir-seal relationship is possible in the Bight Basin, it is not possible to make a more detailed evaluation, and the viability of this system will be highly dependant on the timing of formation and migration of any potential hydrocarbon resource.

TRAPS

The suitability of igneous rocks as hydrocarbon traps has been advocated by several authors (e.g., Archer et al., 2005; Rohrman, 2007), and numerous real-world examples exist (see Schutter, 2003b). Igneous-related traps may be formed by intrusives with domal morphologies, intrusive-related deformation (e.g., forced folds), igneous-related reservoir closure (i.e., dykes operating in a similar manner to fault sealing), overlying extrusives, and faulted sills. All of these potential trap styles are observable in the Bight Basin, and recent evidence suggesting active hydrocarbon generation and expulsion until the present day indicates that there is the potential for these to act as traps (Totterdell et al., 2008).

Domal sill structures are rare in the BBIC, and thus have a low likelihood for acting as a suitable exploration target. Structural closure of sills may form a viable trap, and limited examples have been observed. While igneous-related reservoir closure is viewed as a potentially feasible trapping mechanism, the paucity of observable dykes encountered during seismic mapping renders this trap type as a difficult exploration target. Forced folding of overlying strata by igneous intrusion is viewed as the most likely viable trapping mechanism, and several examples of this style of trap have been documented globally (Schutter, 2003a; Archer et al., 2005; Hansen and Cartwright, 2006; Rohrman, 2007). In the Bight and Eucla basins, intrusion-related deformation generally occurs within the upper Hammerhead, Wobbegong and Dugong Supersequences in the central Ceduna Sub-basin, potentially providing an easily accessible, shallow trap for late stage migration of fluids (Fig. 10).

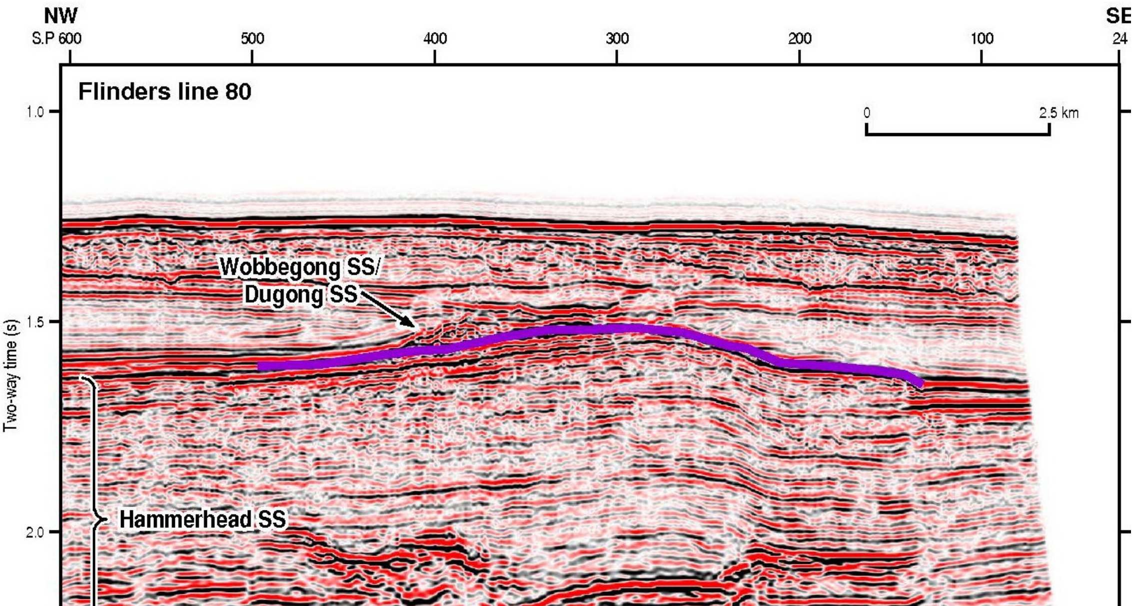

Figure 10: *Example of a potential high-level trap formed in the base of the combined Wobbegong and Dugong supersequence boundaries.*

Conclusions

New data has enabled documentation of the distribution and morphology of the BBIC, and a discussion of both the potential geodynamic drivers for magmatism, and implications for hydrocarbon resources in the Bight Basin. Igneous occurrences have been delineated using closely-spaced 2D seismic data across 650 km of the Ceduna and adjacent sub-basins. These have been dated as Middle Eocene, based on sill-related forced folding of the basal Dugong Supersequence horizon and by identifying extrusive occurrences at the same stratigraphic horizon. This age correlates with the onset of accelerated seafloor spreading rates between Australia and Antarctica (Cande and Mutter, 1982; Tikku and Cande, 1999; Totterdell and Bradshaw, 2004), as well as other major events in global tectonics (Veevers, 2000; Teasdale et al., 2003).

A geodynamic model involving a rapid acceleration in spreading rates on the southern margin, mantle convection and destabilisation, and the interaction of a small, transient plume-like hotspot rooted in the upper mantle is the favoured explanation for igneous activity in the Bight. It is interpreted that edge-driven convection at the margin of the Gawler Craton is likely to play an important role in this process. The plume head is interpreted to have been located in the central Ceduna Sub-basin, where there is a net increase in the size and density of igneous occurrences.

Due to the inferred high pore water content and low degree of compaction in the Hammerhead Supersequence at the time of igneous activity, it is interpreted that the extent of thermal overmaturity surrounding intrusive bodies will be minimal unless direct contact is made between the source rocks or reservoirs and the intrusion. For the limited quantity of sills and related igneous bodies intruded at deeper levels, the thermal aureole is expected to be more extensive. A greater influencing factor will be the postulated longer-lived and more regional effect resulting from the deeper magma source (and potentially underplated igneous material). It is possible that this may have a positive effect on hydrocarbon generation due to relatively gentle heating effects in the upper sections of the basin.

The potential of these rocks to act as suitable seals and reservoirs is unquantified at this stage. It is concluded however that there is some potential for igneous-related processes to have formed viable hydrocarbon traps. The most likely trap style is related to forced-folding structures observed in the central Ceduna Sub-basin. However, much depends on the precise timing of hydrocarbon generation and migration from the various potential source rocks in the basin (see Totterdell et al., 2008). If migration occurred post-magmatism, then the forced folds generated by sills may have provided viable high-level traps, and the residual heat from intrusion and deep-seated magma sources may benefit localised maturation. On the other hand, if hydrocarbons existed prior to magmatism, then it is possible that these may have been locally destroyed by the ascending magmas and related hydrothermal fluids.

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