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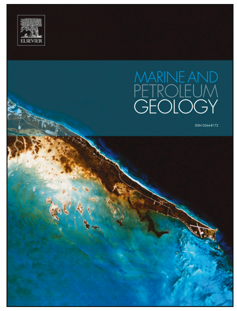

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Failure to predict igneous rocks encountered during exploration of sedimentary basins: a case study of the Bass Basin, Southeastern Australia

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Abstract: The Bass Basin, a Mesozoic-Cenozoic intra-continental rift basin along the southern Australian continental shelf, offers an excellent natural laboratory for examining igneous rocks in the subsurface. Igneous material within the basin is manifested as a mixture of predominately mafic extrusive and intrusive rocks, mainly Cretaceous-Palaeocene and Oligo-Miocene in age. Igneous rocks have been encountered in 20 out of 36 (55.6%) exploration wells drilled within the Bass Basin, but the presence of these has historically been poorly predicted; of the first 11 exploration wells to penetrate igneous rocks, their presence was not predicted in pre-drill interpretations. We present a series of case studies from wells that unexpectedly encountered igneous rocks. The first of these wells (Bass-1) targeted a carbonate reef structure which instead penetrated the flank of a submarine volcano. In another notable example (Flinders-1 well), a relatively discontinuous high-amplitude seismic reflection thought to be a clastic reservoir was found to be an igneous intrusion with a relatively unusual composition. A number of these incidents, where igneous rocks were unexpectedly encountered, can be accounted for by human factors, such as a sparsity of good quality data and a lack of knowledge transfer as companies entered and left basin during different phases of exploration. However, a number of examples, particularly the unexpected occurrence of igneous intrusions, appear to have been caused by anomalously low acoustic impedance contrasts between igneous rocks and surrounding sedimentary sequences. Our findings have generic implications for other sedimentary basins impacted by magmatic activity, such as the importance of integrating available outcrop data in the absence of nearby well control, and the value of fully appraising previous exploration results.

Keywords:

Volcanics
Exploration
Pre-drill prediction
Southern Australia
Bass Basin

1. Introduction

Igneous rocks are routinely encountered within sedimentary basins undergoing active hydrocarbon exploration and production, notably including basins on the North Atlantic continental margin such as the Faroe-Shetland Basin (Rateau et al. 2013; Schofield et al. 2015; Mark et al. 2018; Hardman et al. 2018) and the Vøring and Møre basins (Planke et al. 2000; 2005; Gernigon et al. 2004; Mjelde et al. 2007; Hansen et al. 2011; Omosanya et al. 2016, 2017), the South Lokichar Basin of the East African Rift (Christopherson 2016; Purcell 2017), the Neuquen Basin, Argentina (Rabbel et al. 2018) and the Santos Basin, Brazil (Ojeda 1982; Chang et al.1992; Fiduk et al. 2004; Alves et al. 2015). Within the last two decades there has been a plethora of fieldwork and sub-surface research concerning igneous rocks in sedimentary basins, such as continental flood basalts (Self et al. 1997; Single & Jerram 2004; Jerram & Widdowson 2005; Nelson et al. 2009) and igneous intrusion plumbing systems (Davies et al. 2002; Smallwood & Maresh 2002; Thomson & Schofield 2008; Jackson et al. 2013; Magee et al. 2015; Schofield et al. 2015; Senger et al. 2017). This research has revealed a wealth of complex architecture and internal heterogeneity, for example stacked, anastomosing compound subaerial lava flows, laterally extensive subaerial tabular lava flows and air-fall tuffs and saucer-shaped igneous intrusions. For hydrocarbon explorationists, understanding the internal and lateral heterogeneity of igneous rocks in the subsurface is critical for accurate time-depth conversion of sub-basalt (Lennon et al. 1999) and intra-basaltic reservoir intervals (Duncan et al. 2009; Poppitt et al. 2016; Hardman et al. 2018), mapping the lateral continuity of seals (O'Halloran and Johnstone 2001; Schutter 2003 and references therein; Loizou et al. 2014) and predicting potential drilling issues such as low rates of penetration through abrasive, crystalline extrusive and intrusive rocks (Archer et al. 2005; Millet et al. 2016; Mark et al. 2018).

Within the Bass Basin, located offshore southern Australia between Victoria and Tasmania, 20 out of 36 (55.6%) of exploration wells drilled to date have encountered igneous lithologies. These igneous rocks are present within strata above and below the reservoirs of the producing Yolla gas field in the Bass Basin (Lennon et al. 1999) whilst Campanian extrusive lava flows form the top seal of the Kipper Field in the contiguous Gippsland Basin (O'Halloran and Johnstone, 2001), emphasising the importance of detailed, regional characterisation. There have been several previous studies of the igneous rocks in the Bass Basin, including investigation of their geochemical composition and age (Blevin et al. 2003; Meeuws et al. 2016), the mode of emplacement and seismic expression of the volcanics (Reynolds et al. 2018), and the impact of the intrusive and extrusive volcanics on the petroleum system (Holford et al. 2013). Previous work however, has generally overlooked the fact that explorers have consistently failed to predict the presence of igneous material prior to drilling in the Bass Basin; of the 20 exploration wells to encounter igneous rocks, on 13 occasions (65%) the igneous rocks were not predicted prior to drilling.

This study focuses primarily on the geophysical properties of these igneous rocks and the surrounding lithologies, which ultimately governs their expression in seismic reflection data, with lithological calibrations provided by thin-section petrography and whole rock geochemistry. Geological interpretations are synthesised with well-specific exploration contexts, in order to establish holistic understandings as to why particular penetrations of igneous material were unexpected. We propose that the difficulties in predicting these igneous rocks can be traced back, in part, to their magmatic composition and the nature of the surrounding host rock. In particular, the acoustic impedance contrast between the igneous rocks and host rock strata, generally high in sedimentary basins (Planke et al. 2000; Smallwood & Maresh 2002; Schofield et al. 2015; Magee et al. 2015; Mark et al. 2018), appears markedly lower within the Bass Basin. This is due to several lithological factors, including an abundance of high acoustic impedance coals in the overburden acting as a seismic transmission filter. A failure to transfer and absorb knowledge as companies left the basin and new ones entered, also appears to be a contributing factor to the failure to accurately predict subsurface igneous rocks. Our findings have wider implications for future exploration within the Bass Basin, and also for other sedimentary basins impacted by volcanism, including the importance of integrating outcrop data in the absence of offset well data.

2. Regional Geology

The Bass Basin is an intracratonic rift basin that forms part of a failed arm of the Southern Margin Rift System, located along Southern Australia (Fig. 1a), which formed as a result of the initial continental break up of Eastern Gondwana as Australia and Antarctica began to separate (Stagg et al. 1990). Australia's Southern Margin, including the Bass Basin, underwent multiple phases of Late Mesozoic to

Early Cenozoic rifting (Cummings et al. 2004; Blevin & Cathro 2008), punctuated by periods of post-rift uplift and inversion (Holford et al. 2014). The Bass Basin did not evolve into a passive-margin basin, in contrast to the contiguous Otway Basin (to the northwest) and Gippsland Basin (to the northeast), as the locus of rifting moved to the south of Tasmania (Palmowski et al. 2004; Blevin et al. 2005; Meeuws et al. 2016).

The Bass Basin is bounded by major basement structural highs (the King Island High to the northwest and the Bassian Rise to the east) and is divided into two sub-basins (Fig. 1a), which are both composed of a series of grabens and half-grabens characterised by variable amounts and rates of subsidence (Blevin 2003). The Cape Wickham Sub-basin forms the western portion of the Bass Basin, and is characterised by normal faults that generally dip, and therefore result in sedimentary packages that thin, towards the southwest. The Durroon Sub-basin, conversely, contains normal faults predominantly dipping toward the northeast. The Cape Wickham and Durroon sub-basins are separated by the Chat Accommodation Zone, an ~NNE-SSW trending zone of accommodation, likely related to a terrane boundary between Proterozoic metasediments to the west (Cape Wickham Sub-basin) and Palaeozoic metasediments and granitic intrusions to the east (Durroon Sub-basin) (Blevin et al. 2003).

The sedimentary succession of the Bass Basin ranges from Early Cretaceous to Recent in age (Lennon et al. 1999) (Fig. 2). Several stratigraphic nomenclatures have been used, with this study adopting the lithostratigraphic framework of Lennon et al. (1999) and Cummings et al. (2002); the megasequences (tectonically controlled cycles) defined by Blevin (2003) & Cummings et al. (2004) are also shown for reference (Fig. 2). From the Cretaceous to early Eocene, sedimentation was predominantly lacustrine to fluvial-deltaic, represented by the Eastern View Coal Measures (EVCM) Group. From the Mid-Eocene onwards, marine conditions prevailed with initial deposition of shallow marine mudstones (Demon's Bluff Formation), then later open marine calcareous siltstones, marls and carbonates (Torquay Group) (Lennon et al. 1999; Blevin et al. 2003).

2.1. Magmatic & volcanic history of the Bass Basin

The magmatic and volcanic history of the Bass Basin is broadly divided into four phases (Meeuws et al. 2016). The earliest evidence for volcanism recognised is the apparent presence of *Early Cretaceous* volcaniclastic sediments within the Otway Group, possibly sourced from the northwest from basaltic volcanism near the Hawkesdale area of Western Victoria (Duddy 2003). *Mid-Cretaceous* syn-rift weathered amygdaloidal basalts, interbedded with Aptian aged sediments, are encountered in the Durroon Sub-basin (within the Durroon-1 well), with a possible origin related to the onset of rifting in the Tasman Basin (Blevin 2003; Meews et al. 2016). The extent of these volcanics is unclear, particularly within the Cape Wickham Sub-basin, due to a lack of well penetrations of Middle Cretaceous strata (Blevin 2003; Meeuws et al. 2016). A *Late Cretaceous-Palaeocene* syn-rift volcanic event, manifested as lava flows, is more widely recognised, for instance in the Yolla and Dondu troughs of the Cape Wickham Sub-basin, and in the Bark Trough of the Durroon Sub-basin (Meeuws et al. 2016). The age of these lava flows is determined through dating of the palynoflora of the interbedded sediments (Baillie 1993). Finally a basin-wide *Oligocene-Miocene* post-rift magmatic episode is represented by a series of submarine monogenetic volcanoes and associated feeder intrusions (Meeuws et al. 2016; Holford et al. 2017; Reynolds et al. 2018).

2.2. Exploration History and Petroleum System Elements of the Bass Basin

Hydrocarbon exploration has been ongoing in the Bass Basin since the 1960s and has occurred in distinct cycles (Blevin 2003). In total 45 wells have been drilled, 36 of which are exploration wells (Fig. 1b). The Bass Basin hosts a working, terrestrial-based petroleum system (Blevin 2003) with Palaeocene to Early Eocene EVCM coals forming the dominant source rock (Boreham et al., 2003), and is prospective for both oil and gas (Blevin 2003). Proven reservoirs are mainly present within Palaeocene and lower Eocene fluvial-deltaic sandstones of the EVCM (Boreham et al., 2003). The Demon's Bluff Fm. forms the regional seal (Lennon et al. 1999; Blevin 2003). Hydrocarbon shows have been identified in a number of wells, though hydrocarbon accumulations are observed only in the Pelican, Rockhopper, Trefoil, White Ibis, Bass and Yolla structures. These discoveries are mainly gas with minor oil accumulations (Blevin 2003). Presently, Yolla (gas and gas condensate) is the only producing field.

3. Data and methodology

3.1. Data

The main dataset used in this study is the publicly released commercial hydrocarbon well data from the Bass Basin (Fig. 1b). From these wells a range of datasets were examined and synthesised, including; wireline data (e.g. gamma ray, resistivity, neutron porosity etc.), composite well logs, geological end of well reports, and core and ditch cuttings. Seismic datasets were also examined, including regional 2D lines and the Shearwater Marine and Yolla 3D seismic surveys (Fig. 1b) to characterise seismically identifiable volcanic units, and to understand the basin architecture.

3.2. Subsurface Identification and classification of igneous rocks

3.2.1. Micro-scale (<0.5 m): core and ditch cuttings

Within the Bass Basin a variety of igneous rocks are present throughout the stratigraphy, which can be recognised at a number of different scales. We define micro-scale as any dataset at hand-specimen scale. Figure 3 summarises the main micro-scale datasets and workflow utilised in this study, with each source of information detailed further below.

Ditch cuttings, the rock fragments brought to the rig site via the drilling fluid, provide a ubiquitous source of information with regards to the igneous rocks encountered in the Bass Basin. Core is rarely obtained through the igneous rocks of the Bass Basin, though side-wall cores are more commonly acquired. Thin-sections from side-wall cores are critical to elucidating the grain-size and mineralogy, both of which are key to determining magmatic mode types. Thin-section micrographs, and associated mineralogy descriptions, were collated from geological end of well reports, and from an unpublished study commissioned by Geoscience Australia.

Mineralogical descriptions are supported by geochemical data, and this study in particular utilised x-ray fluorescence (XRF) analysis carried out by Geoscience Australia (GA) on a number of igneous rock samples (including ditch cuttings and core) from the Bass Basin. Plotting the major oxides (on a Total Alkali Silica diagram, e.g. Le Bas et al. 1986) and trace elements (on a Winchester & Floyd, 1977, discrimination diagram) allows determination of the magma type, which in turn influences the well log character (detailed in the succeeding "*Meso-scale: geophysical logs*" sub-section of this paper).

Thermal maturity data, such as spore colour index and vitrinite reflectance, provide further micro-scale information for characterising subsurface igneous rocks, particularly in demonstrating zones of elevated palaeotemperature. The significance of elevated palaeotemperature is underpinned by a number of studies that document the negligible thermal impact of extrusive lava flows (e.g. Archer et al. 2005; Grove 2014; Schofield et al. 2015) relative to igneous intrusions (Jolley & Bell 2002; Archer et al. 2005; Holford et al. 2013). Ultimately, evidence of elevated palaeotemperature above and below a particular igneous unit can help distinguish it as intrusive in origin.

Meso-scale (>0.5 m): geophysical logs

Geophysical logs, such as gamma ray, electrical resistivity and sonic velocity, offer a useful dataset for examining the igneous rocks in the Bass Basin at a scale >0.5 m (the vertical resolution of common downhole tools c.f. typical sampling rates of ~0.15 m). Igneous rocks exhibit a wide variety of log motifs, which are largely controlled by mineralogy (summarised in Fig. 4). Mafic igneous rocks, such as basalt, represent the most common type of igneous rock in the Bass Basin (Meeuws et al. 2016) and these typically exhibit low gamma values (10-40 API) (Fig. 4a). This reflects the abundance of minerals such as pyroxene and plagioclase which contain little potassium, thorium and uranium (Serra et al. 1980; Planke 1994; Bartetzko et al. 2005). Silicic igneous rocks, in contrast, typically measure higher gamma values (40-100 API) (Fig. 4b) due to the presence of minerals such as potassium feldspar (Serra et al. 1980; Delpino & Bermudez 2009; Mark et al. 2018). Igneous rocks can also be divided into crystalline and volcaniclastic units (clastic rocks containing a high proportion of volcanic derived material) (Mathisen & McPherson, 1991). Crystalline igneous rocks, such as compound lavas (Fig. 4c), tabular lavas (Fig. 4d) and igneous intrusions (Fig. 4e) typically display high resistivity (2-300 Ohm m) and low neutron porosity values (0.08-2%), reflecting their typically low primary porosity (Planke 1994; Bartetzko et al. 2005; Millet et al. 2015 ; Watson et al. 2017; Mark et al. 2018). Volcaniclastic rocks, which includes tuffaceous rocks (lithified ash) (Fig. 4f), hyaloclastites (Fig. 4g) and intra-lava claystones (Fig. 4g), demonstrate lower resistivity (2-20 Ohm m) and higher neutron porosity values (~45-30%) due to the presence of clay-bound water (Planke 1994; Bartetzko et al. 2005; Watton et al. 2014; Watson et al. 2017).

3.2.2. Macro-scale (>30 m): Seismic Data

Igneous rocks within the Bass Basin can be also investigated at a macro scale i.e. rock units that are sufficiently thick as to be visible in seismic reflection datasets. Within the Bass Basin mafic igneous rocks such as basalts and dolerites predominate, which are typically characterised by high densities (>2.7 g/cc) and fast sonic velocities (>4000 m/s; >80 ms ft^{-1}). There is generally a significant acoustic impedance contrast between mafic igneous material and the surrounding, lower density sediments (Smallwood & Maresh 2002; Holford et al. 2012; Magee et al. 2015; Schofield et al. 2015; Eide et al. 2017; Mark et al. 2018). Some previous studies have investigated volcanic architectures in the Bass Basin using seismic reflection data, particularly vent complexes and associated feeder intrusions (Reynolds et al. 2018). The seismic datasets examined in this study are displayed in time with a standard polarity (Sheriff & Geldart 1995), by which a downwards increase in acoustic impedance corresponds to a positive amplitude (a hard kick), displayed in red, while a downwards decrease in acoustic impedance is represented by a negative amplitude (soft kick) displayed in blue (Fig. 5). Three broad sets of igneous rocks are recognised in seismic (Fig. 5) and in wells throughout the Bass Basin, as described in detail in Section 4 of this paper. The igneous rocks within the Bass Basin are broadly present within two major lithostratigraphic sections: (1) the Torquay Group (Oligocene) and (2) the Eastern

View Coal Measures (EVCM) (Late Cretaceous to Early Eocene). The igneous rocks within the Torquay Group have velocities ~3000 m s^{-1}, with a dominant frequency in the seismic surveys examined between 39-45 Hz (Reynolds et al. 2018). This yields a vertical seismic resolution between 17-19 m and a vertical detectability of 8-10 m for igneous units within the Torquay Group, based on λ/4 (resolution) and λ/8 (detectability) (Widess 1973; Simm & Bacon 2014). For igneous rocks within the EVCM velocities range from 5000-6600 m s^{-1}, with a dominant frequency between 29-40 Hz. The seismic resolution of igneous material present within the EVCM is therefore estimated at approximately 41-43 m, with a vertical detectability between 21-22 m.

4. Igneous rock varieties within the Bass Basin

In order to investigate why igneous units have historically been poorly predicted in the Bass Basin, the character of the different igneous lithologies present needs to be established. In this section we detail the well log character of the igneous rocks encountered within the Bass Basin, which can be broadly divided into three different sets based on their mode of emplacement: (1) submarine volcanic rocks (2) igneous intrusions and (3) subaerial volcanic material. These different types of igneous lithologies are each characterised by a unique well log character (Fig. 6) and exhibit variable geographic and stratigraphic distribution across the basin (Fig. 7).

4.1. Submarine volcanism products- hyaloclastites and volcaniclastic rocks

The shallowest and most widespread of the main sets of igneous rocks recognised within the Bass Basin is represented by a series of seismically imaged volcanic vents, between 0.3-1.2 km in diameter (Reynolds et al. 2018) within the Torquay Group. These vents are interpreted to be submarine volcanoes due to the presence of underlying feeder intrusions, downlapping reflections within the vents that are typical of extrusive volcanism, and the fact that the vents sit within a succession of marine sedimentary rocks (Reynolds et al. 2018). These submarine volcanoes are present throughout the Bass Basin, and several wells have penetrated the flanks of the structures, including Bass-1 (Cormorant Trough), Tilana-1 (Dondu Trough), Yolla-1 and Trefoil-1 (Yolla Trough). Core was acquired through the volcanic section within the Bass-1 well, and in hand-specimens the recovery material consists of a clast supported conglomerate of dark grey micro-vesicular basalt (Fig. 8) with infilled calcite. A degree of reworking of the primary volcanic material is indicated by rounded clasts (Fig. 8b) and normally graded beds 0.2-3 cm in thickness (Fig. 8d). There are also pyroclastic components within this material, with several sub-angular vesicular pumice clasts recognised (Fig. 8c).

In general, limited wireline log data has been acquired through these submarine volcanic rocks due to the fact they are hosted within the Torquay Group, which represents uneconomic overburden within the Bass Basin. The Tilana-1 well, within the Dondu Trough, contains amongst the best suite of wireline logs acquired through the volcanics (upper section of Fig. 6). The log motif is characterised by a generally low, blocky gamma (11-22 API) (Fig. 6a) and moderately high, serrated resistivity (2-15 Ohm m) (Fig. 6b) typical of relatively heterogeneous hyaloclastite (e.g. McLean et al. 2017). Sonic velocity is moderately fast with a serrated profile (with an average value of 97 ms ft^{-1}) (fig. 6d). Density and neutron logs have not been acquired through any of the submarine volcanics packages throughout the Bass Basin, though a sonic velocity-derived density can be calculated (Fig. 6c) (using the method of Bartetzko et al. 2005). This gives values generally ranging from 2.15-2.55 g cm^{-3}, with lower density zones (<1.95 g cm^{-3}) possibly representing less compacted volcaniclastic (e.g. tuffaceous) material.

A volcanic edifice was also drilled by the Tasmanian Devil-1 well, located in the southwest of the Bass Basin, though the well penetrated the crest of the structure, in contrast to the Yolla-1, Bass-1 and Tilana-1 wells which intersect the flanks of submarine volcanoes. The volcanic rocks in Tasmanian Devil-1 exhibit high resistivity (5-2000 Ohm m) and densities (2.75-2.85 g cm^{-3}) and fast sonic velocity (72-50 ms ft^{-1}) typical of crystalline material, which is mirrored in thin-section by fine grained crystalline basaltic material. A prominent gradual decrease in gamma ray and resistivity upwards within the Tasmanian Devil-1 volcanic succession is similar in log profile to pillow lavas described by Bartetzko et al. (2005). We therefore interpret the volcanic rocks intersected in Tasmanian-Devil-1 as pillow lavas, representing the up-dip equivalent of the reworked hyaloclastite and volcaniclastic material encountered in Bass-1, Yolla-1 and Tilana-1. Such a lateral facies variation also corroborates with observed lateral seismic amplitude changes within the Yolla submarine volcano previously attributed to facies changes (Faustmann 1995).

4.2. Intrusive magmatic products- igneous intrusions

Intrusive igneous rocks are predominantly hosted within the Middle EVCM (Tilana and Narimba sequences) and have been penetrated in 14 exploration and appraisal wells (see Fig. 7 for examples). A 64m thick intrusion intersected within Flinders-1, located along the southern flank of the Pelican Trough, captures much of the principal features of the igneous intrusions encountered throughout the Bass Basin (middle section of Fig. 6). The Flinders-1 intrusion log motif is manifested by relatively low gamma (15-20 API) (Fig. 6e), with high resistivity (17-92 Ohm m) (Fig. 6f), density (2.75-2.84 g cm^{-3}) (Fig. 6g) and fast sonic velocity values (58-52 ms ft^{-1}) (Fig. 6h) typical of mafic intrusions (e.g. dolerite). In the upper third section of the intrusion, however, there is a notable zone of higher gamma (48-74 API) (Fig. 6i) and marginally lower density (2.62-2.72 g cm^{-3}) and slower sonic velocity (69-62 ms ft^{-1}). This high-gamma log character, specifically positioned in the upper third of the intrusion, is also observed in the Koorkah Terrace (Seal-1) and Cormorant Trough (Toolka-1A) (Fig. 9). XRF geochemistry from the Seal-1 well depicts two different magmatic compositions (Fig. 9); the lower gamma material plots as basaltic in composition, whereas the higher gamma material plots as tephra-phonolite in composition.

4.3. Subaerial volcanism products- lava flows and interbedded volcaniclastic rocks

The third broad set of igneous rocks recognised within the Bass Basin is represented by subaerial volcanic material, such as extrusive lava flows and associated volcaniclastic units which are interdigitated with terrestrial EVCM sedimentary rocks (e.g. coals and fluvial sandstones, predominantly within the Middle EVCM). These extrusive lavas are penetrated in 6 structures throughout the basin (Aroo-1/ Rockhopper-1, Trefoil-1, Chat-1, the greater Yolla Field, Tilana-1, Duroon-1; see Fig. 7 for examples). A number of these subaerial lava successions are characterised by poor wellbore conditions (e.g. hole washout), and therefore geophysical log quality is generally poor. The Trefoil-1 well, however, contains a diverse suite of good quality log data (lower section of Fig. 6). Between 3389.6-3460 m there are several units exhibiting low gamma (18-35 API) (Fig. 6j), high resistivity (20-1800 Ohm m) (Fig. 6k) and high density values (2.6-2.82 g cm^{-3}) (Fig. 6l) characteristic of tabular classic lava flows. A zone of compound lavas (between 3412-3419 m MD) is recognised by marginally lower density and resistivity (compared to tabular lavas) and a “double peak” in sonic velocity (Fig. 6m) (e.g. Nelson et al. 2009). Decreases in density and resistivity distinguish intra-basaltic sandstones from the surrounding low gamma lavas. Underlying this, from 3460-3524 m (MD,) a package of interbedded shales and sands, and minor volcaniclastic claystone units are present. Within the Cape Wickham Sub-basin these terrestrial extrusive lava flows range in age from Late Cretaceous (*T lilliel* pollen zone, Campanian-Maastrichtian) (Trefoil-1 & Yolla-1) to Maastrichtian-Danian (Tilana-1). Within the Duroon Sub-basin an older Cenomanian subaerial extrusive lava succession is present (Duroon-1) (Fig. 7).

5. Case studies of wells where igneous rocks were not predicted prior to drilling

44 wells in total have been drilled within the Bass Basin, 36 of which are designated as exploration wells. These 36 exploration wells are used as the basis for a statistical review of pre-drill prediction of igneous rocks in the study area; further detail on these wells is included as Supplementary Material. Appraisal and development wells (e.g. Yolla-2 to 6) are not included as part of the statistical review as the presence or absence of igneous rocks would have been already established by the prior exploration well. Pre-drill lithological predictions versus post-drill actual lithologies encountered were found in publically released Geological End of Well Report for the respective wells, sourced from the Australian National Offshore Petroleum Information Management System (NOPIMS); see Figures 12 and 13 for specific examples of a pre-drill versus post-drill lithology column. In instances of wells where igneous rocks were encountered though not predicted pre-drill, we also noted whether the operator was new to the basin, i.e. whether the well was the first drilled by the operator or part of their first drilling campaign. The following results have been established from the wells within the Bass Basin:

- 20 out of 36 exploration wells encountered igneous rocks (55.6%)
- In 13 of those 20 exploration wells the igneous rocks encountered were not predicted pre-drill (65%)
- Of the 13 wells where igneous rocks were unexpectedly drilled, on 7 occasions the well was operated by a company new to the basin (53.8%).

During the various cycles of exploration within the Bass Basin the incidence of igneous rocks not being predicted prior to drilling is consistently high (ranging from 40-87.5% of exploration wells in a given cycle; Table 1). Of the 13 exploration wells that failed to predict the presence of igneous rocks prior to drilling, the following section focuses on four noteworthy examples where the pre-drill reservoir target instead was found to be high seismic amplitude igneous rocks (Trigg et al. 2003; Meeuws et al. 2016).

Table 1: Statistical breakdown of the number of wells to encounter igneous rocks within the Bass Basin, and the proportion of those wells where the presence of those igneous rocks was not predicted pre-drill.

Time Period	Total Number of Bass Basin Exploration wells	Number of exploration wells that encountered igneous rocks	Proportion of exploration wells where igneous rocks were not predicted
1965-1974	17	8 (47.1%)	7 (87.5%)
1979-1986	7	5 (71.4%)	2 (40%)
1992-1999	6	3 (50%)	2 (66.7%)
2004-present	6	4 (66.7%)	2 (50%)

5.1. Bass-1 (1965): Pre drill- Carbonate reef/Post drill- Submarine volcano

Bass-1 was drilled in the Cormorant Trough in 1965 by Esso Australia, and was the first well drilled in the Bass Basin. The purpose of the well was to gain stratigraphic information from the Cenozoic and Upper Mesozoic sedimentary succession, and to test the petroleum potential of a postulated Miocene carbonate reef build up (Fig. 11) (Blevin et al. 2005). The pre-drill interpretation of carbonates was based on presence of Miocene limestones in the adjacent Gippsland Basin (stratigraphic equivalent of the Torquay Group (Lennon et al. 1999)), where the nearest offset wells were located. Instead of Miocene carbonates however, ~130 m of interbedded volcaniclastic rock was intersected instead (Fig. 11). No hydrocarbon shows were recorded within the volcaniclastic rocks, or indeed the entire drilled succession.

5.2. Aroo-1 (1974): Pre drill- Stacked fluvial deltaic sandstones/Post drill- extrusive lava flows

Aroo-1 is located on the north flank of the Yolla Trough, and was drilled by Hematite Petroleum in 1974. The primary target of Aroo-1 was an amplitude anomaly at the top of an intra-basin fault block (Fig. 12) (Blevin & Cathro 2008). The amplitude anomaly was interpreted to be hydrocarbon-bearing sandstones, likely between the *M. diversus* and *L. balmei* zones within the Middle EVCM (Fig. 12, *predicted*), which are hydrocarbon bearing within the Pelican Field (Trigg et al. 2003). Upon drilling (Fig. 12, *actual*) the amplitude anomaly was discovered to be related to a series of stacked subaerial lava flows and volcaniclastics, and thin (<1m) siltstone and sandstone beds. In total over 500 m of volcanics and interbedded non-volcanic sedimentary rocks were encountered before the well terminated 270 m early at 3692 m MD, without having drilled through the base of the volcanic pile (Fig. 12). Despite the pre-drill misdiagnosis of the lithological character of the amplitude anomaly, sub-economic gas condensate shows were logged within sandstones interbedded with the extrusive volcanics (Trigg et al. 2003). On 3D seismic (from the Shearwater Marine survey) the top of the extrusive lavas corresponds to a bright hard kick (the pre-drill target) (Fig. 12). The volcanic pile is relatively laterally discontinuous, with the underlying strata becoming clearer as the volcanics pinch out to the southwest. A climbing reflection beneath the extrusive volcanics (~2.7 sec TWT) exhibits a strata discordant character, and therefore may represent the underlying intrusive plumbing system of the subaerial lava flows penetrated in Aroo-1.

5.3. Tasmanian Devil-1 (1984): Pre-drill- EVCM Horst block/Post-drill- Extrusive lava flows

Tasmanian Devil-1 is located over a horst block 20 km south of the Pelican Trough, and was drilled in 1984 by Weaver Oil & Gas Corporation Australia. In 1984 the nearest offset well was Pippipa-1, 53 km to the northwest. The purpose of Tasmanian Devil-1 was to test the hydrocarbon potential of the lower section of the EVCM (below *M. diversus*) within an interpreted horst block on the flank of a broad graben structure (Fig. 13a). A bright seismic amplitude reflection overlying the crest of the structure was interpreted pre-drill as a near-top EVCM sandstone reservoir.

The drilled succession matched the pre-drill prognosis until the base of the Torquay Gp., markedly differing thereafter (Fig. 13b/c). Instead of the Demon's Bluff Formation and EVCM being encountered (Fig. 13b), Tasmanian the drilled section passed from Torquay Group siltstones to Cenozoic extrusive lava flows (Fig. 13c). The bright reflection that was interpreted prior to drilling as marking the top EVCM instead corresponded to the top of the volcanic pile. After 120 m of basaltic rock was penetrated the decision was taken to terminate the well prematurely (~959 m MD), around 130 m shallower than planned termination at 1089 m.

5.4. Flinders-1 (1992): Pre-drill- Middle EVCM amplitude anomaly/Post-drill- Igneous intrusion

Flinders-1 was drilled in 1992 by SAGASCO Resources along the southwestern flank of the Pelican trough. The well was designed to test an amplitude anomaly within a fault-bounded 3-way closure along a structural tend up-dip of the Pelican Field (Fig. 14). A major part of the rationale behind the Flinders prospect was that hydrocarbon shows (in the form of fluorescence and elevated gas readings) were encountered by the Pipipa-1 well drilled 10 years earlier in 1982, located 2 km to the northeast of the proposed Flinders-1 well (Fig. 14). The shows in Pipipa-1 were encountered within good reservoir quality sandstones (19-31% porosity, 53-630 md) within the Upper EVCM. However, the gas volumes in Pipipa-1 were sub-economic and the well was terminated within the Upper EVCM. The primary objective of Flinders-1 was interpreted as fluvial sandstones of the lower *M. Diversus* to middle *M. diversus* within the Middle EVCM, which is at a deeper stratigraphic level than gas encountered within the Upper EVCM in Pipipa-1.

Upon drilling of Flinders-1, the amplitude anomaly proved to be a 70 m thick dolerite intrusion, and all sandstone units within the well were water bearing. Modelling the synthetic seismic response (Fig. 14) through the EVCM confirms that the amplitude anomaly corresponds to a seismically resolvable hard kick created by the acoustic impedance contrast between the igneous intrusion and the surrounding EVCM sedimentary rocks (coals, siltstones and sandstones). Post drill evaluation of both wells reveals that the source rocks within Pipipa-1 are immature, and therefore the gas shows logged were likely a product of the localised heating of coals by the intrusion encountered in Flinders-1 (Trigg et al. 2003). Had Pipipa-1 drilled 147 m deeper, it would likely have encountered the Flinders-1 intrusion.

6. Discussion

6.1. Why have igneous rocks within the Bass Basin been so poorly predicted?

6.1.1. Data quality and availability

In each case study discussed in the previous section of this paper, the wells were drilled based on sparse 2D seismic reflection data. The quality of the seismic data these wells were drilled on clearly would have been of a lower quality than the modern 2D and 3D seismic displayed in this study (Fig. 15). Furthermore, in a number of instances where the presence of igneous rocks was not predicted prior to drilling a lack of reliable well control appears to be a common factor. With regards to the Bass-1 well, the nearest offset wells were located in the Gippsland Basin, 200 km to the northeast. Consultation of these Gippsland Basin wells would have favoured a carbonate reef genesis, as opposed to an extrusive volcanic origin (Fig. 11), given the occurrence of limestone within the Miocene of the Gippsland Basin. In terms of the Tasmanian Devil-1 well, however, Cenozoic basaltic lavas outcrop ~50 km away in northwest Tasmania (Meeuws et al. 2016). This outcrop is broadly equidistant with the nearest offset well at the time (Pipipa-1, located 53 km away to the northwest of Tasmanian Devil-1) (Fig. 1). A pre-drill seismic interpretation is not included within the Tasmanian Devil-1 end of well report, though based on the predicted lithologies, one can be broadly reconstructed (Fig. 13b). In modern seismic data (Fig. 13) a number of igneous intrusions are clearly identifiable close to the Tasmanian Devil horst, including a dyke propagating along the north-eastern bounding fault and a saucer-shaped intrusion present to the southwest of the horst. While it is unclear how the available seismic data prior to drilling was interpreted by explorationists, consideration of the proximal volcanic rocks onshore Tasmania, and in-turn the recognition of igneous intrusions off the structure may have changed the stratigraphic prediction and therefore altered pre-drill risking of the prospect.

6.1.2. Cyclical nature of exploration and knowledge sharing

A notable feature of exploration within the Bass Basin is that it has been focused in distinct cycles through time (exploration timeline depicted in Fig. 10). There is a clear trend of companies drilling a series of wells, then leaving the basin (often after sub-economic discoveries), followed later by a new company entering the basin and the cycle starting anew. In terms of the wells where igneous rocks were encountered but not predicted prior to drilling in the context of these cycles (visually depicted in Fig. 10), the majority (7/13 wells, 53.8%) were operated by companies that were new to the basin (i.e. part of their first drilling campaign). Therefore, an important aspect of the failure to predict igneous rocks pre-drill is arguably the lack of knowledge transfer between companies leaving and entering the basin. Equally, knowledge sharing appears not to have effectively taken place between different basins across Southern Australia. For example, the Sailfish-1 well, drilled in the contiguous Gippsland Basin in 1971 by NWS Oil & Gas, had a remarkably similar Carbonate reef pre-drill interpretation to the Bass-1 prospect. Sailfish-1 ultimately drilled a submarine volcano instead of a postulated carbonate reef, precisely as the Bass-1 well had done 6 years earlier in the Bass Basin.

6.1.3. Anomalously low acoustic impedance rocks

A number of the igneous units that were unexpectedly encountered in the Bass Basin are nevertheless clearly identifiable in modern seismic datasets, particularly the submarine volcanoes present within the Torquay Group. The only instances where these submarine volcanoes were not predicted pre-drill appear to be Bass-1 and Tasmanian Devil-1, where, as discussed earlier, there was limited prior well control. All the other instances of unexpectedly encountered igneous rocks within the Bass Basin are either igneous intrusions or terrestrial extrusive lava flows.

In terms of understanding why igneous intrusions within the Bass Basin have been poorly predicted, an instructive comparison can be made with intrusions of a broadly similar geometry and composition within the Faroe–Shetland Basin (Northwest European Atlantic continental margin). Specifically, the modelled synthetic seismic response of the Flinders-1 intrusion can be compared with an intrusion examined by Mark et al. (2018) (Fig. 16). The intrusion from the Faroe-Shetland Basin is 47 m thick, hosted within relatively homogenous marine claystone, and appears as a bright, seismically resolvable hard kick. The Flinders-1 intrusion is 64 m thick, hosted within heterogeneous non-marine sediments, and also images as a seismically resolvable hard kick. However, despite the fact that the Flinders-1 intrusion is ~1.1 km shallower and present within a higher frequency domain than the Faroe-Shetland Basin intrusion, it appears significantly dimmer. There appear to be three key contrasting features between the two examples which can help explain observed differences in acoustic impedance. Firstly, the Flinders-1 intrusion has the notable occurrence of a raft of less dense silicic intrusive material, which is also observed in other intrusions within the Bass Basin, which may also account for the slightly undulating profile of the modelled peak seismic wavelet. The Faroe-Shetland Basin intrusion in contrast is characterised by uniformly high density dolerite. Secondly, the relatively homogenous claystone host rock surrounding the Faroe-Shetland Basin intrusion is likely more favourable for generating high acoustic impedance, in comparison to the highly interbedded non-marine strata (e.g. sandstone, siltstone and coal) which hosts the Flinders-1 intrusion. A final important feature to note is the presence and abundance of coals within the Upper EVCM in the strata above the Flinders-1 intrusion. These coals do not affect the modelled synthetic seismic response, through their high impedance nature (a high reflection coefficient) means they likely act as a transmission filter due to large amounts of seismic energy being reflected as opposed to being transmitted (low transmission coefficient) (Coulombe & Bird 1996). Ultimately, the coals within the Bass Basin are known to mask imaging of the strata below, including any intrusions or lava flows (Blevin 2003).

Finally, in terms of the subaerial volcanic rocks (e.g. lava flows) within the Bass Basin informative comparisons can be made with the top of the extrusive lava pile within the Faroe-Shetland Basin. The extrusive lavas within the Faroe-Shetland Basin constitute Palaeocene-Eocene continental flood basalts, are present between 2-3 km depth below the seabed and represent the shallowest extrusive volcanics within the basin. The observed seismic amplitude character of the top of the extrusive pile in the Yolla-1 well can be compared with top extrusive volcanics in the Tobermory well in the Faroe-Shetland Basin (Fig. 17). Both Yolla-1 and Tobermory have around ~3 km of sediment overlying the top of the extrusive volcanic pile and both encountered gas-bearing sandstones in the overlying sedimentary succession. The Tobermory example is typical of the top of the extrusive volcanic pile along the North Atlantic continental margin, which are generally associated with a very bright, hard kick. In contrast, in Yolla within the Bass Basin the top of the volcanics is a relatively dim hard kick. There are two significant features of contrast between Yolla and Tobermory. Firstly, there is an abundance of high-impedance EVCM coals in the strata overlying the Yolla subaerial volcanic rocks which, as already noted, also likely affects transmission of seismic energy and this imaging of the igneous intrusions within the Bass Basin. High impedance coals are not present in the strata at Tobermory. Secondly, the average sonic velocity of the sediments overlying the extrusive volcanics in Yolla is markedly higher (3975 m/s; 77 ms ft^{-1}) than comparative sediments in Tobermory (3031 m/s; 101 ms ft^{-1}). This significantly means the acoustic impedance contrast between the subaerial extrusive volcanics and the overlying sedimentary rocks within the Bass Basin is not as high as the extrusive volcanics within the Faroe-Shetland Basin. Ultimately a relatively dim hard kick could easily be misinterpreted as a subtle increase in acoustic impedance between two different lithostratigraphic successions (e.g. between Middle and Lower EVCM in the case of the Bass Basin).

6.2. Implications for exploration in other sedimentary basins affected by volcanism

Based on our analysis of well and seismic data in the Bass Basin, we highlight three key factors that have generic implications for exploration of other sedimentary basins affected by magmatism:

1. ***Importance of understanding the geophysical properties of igneous rocks as well as sedimentary host rock properties.*** The igneous intrusions within the Bass Basin are hosted within predominantly terrestrial sediments such as siltstone, coals and sandstones, in contrast to the relatively homogenous marine claystones typical of the North Atlantic Margin (e.g. Faroe-Shetland Basin). Consequently, the acoustic impedance of the Bass Basin intrusions is markedly lower than often associated with intrusions in basins such as the Faroe-Shetland basin. The presence of high impedance/low transmission coals, in particular, makes imaging of the underlying igneous intrusions and extrusive terrestrial lava facies more challenging. The variability in acoustic impedance of igneous rocks is an important factor to consider in basins where igneous material may be present in multiple sequences, such as the syn-rift lacustrine and post-rift marine strata of the Santos Basin, South Atlantic continental margin (Moreira et al. 2007).

2. ***Integration of outcrop in the absence of nearby offset wells***. The Tasmanian Devil-1 well provides an illustrative example of how the examination of the nearest outcrop (extrusive volcanic in character) can help inform pre-drill seismic interpretation. This is an important aspect for exploration of basins where there may be little, if any, well control though outcrop is present, for instance within the flexural margins of half grabens along the East African Rift (Davison & Steel 2018).
3. ***Knowledge transfer***. The Bass Basin shares similarities to the Rockall Trough, located along the North Atlantic continental margin, in that both basins have been affected by volcanism and exploration within them has occurred in distinct cycles (Schofield et al. 2017). Clearly a detailed audit, including forensic examination of geological end of well reports and pre-drill stratigraphic predictions, is important when exploring in basins impacted by magmatism to ensure accurate pre-drill interpretation of igneous units.

7. Conclusions

A consistent factor in the five decade-history of petroleum exploration in the Bass Basin, Australia, is the poor track record of explorers in predicting the presence of igneous rocks prior to drilling; of the 20 exploration wells where igneous rocks were intersected, in 13 instances those igneous rocks were not anticipated pre-drill (65%). This study has specifically investigated several of these exploration wells throughout the Bass Basin, where the unanticipated presence of igneous rocks had profound implications for hydrocarbon prospectivity. In four instances (e.g. Tasmanian Devil-1), the prognosed primary reservoir target was found to be high-amplitude igneous rocks instead of clastic hydrocarbon-bearing reservoirs.

Through holistic examination of these wells, there appears to be three important factors contributing to poor pre-drill prediction of igneous rocks: (1) data quality and availability, (2) transfer of knowledge, and (3) the unique geology of the Bass Basin. Early on in the basin exploration history explorers were hindered by a lack of well control, and prospects were mapped on sparse, low quality 2D seismic lines. Nevertheless, even in modern seismic data a number of the volcanic units, particularly igneous intrusions, exhibit only moderately high acoustic impedance, compared to the very high acoustic impedance of similar intrusions in other sedimentary basins (e.g. the Faroe Shetland Basin). Generic lessons relevant to other sedimentary basins with volcanic histories include the importance of integrating available outcrop data in the absence of reliable well control, as well as understanding the geophysical properties of both the volcanics and the surrounding sedimentary strata when attempting to predict seismic properties.

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Figure Captions

Fig. 1. **a**) Main structural elements of the Bass Basin, adapted from Lennon et al. (1999) and Cummings et al. (2004), including **b**) the locations of exploration awells within the basin, and the location of figures shown in this study.

Fig. 2. Bass Basin stratigraphic nomenclature adopted in this paper, lithostratigraphy adapted from Lennon et al. 1999 and sequences from Cummings et al. 2004.

Fig. 3. Workflow for investigating micro-scale datasets used in this study, with an example from a core sample from the Aroo-1 well at 3596.2 m MD (11798.59 ft). The thin-section micrograph is courtesy of Geoscience Australia.

Fig. 4. Frankenstein well log demonstrating the log motif of different varieties of igneous lithologies in the subsurface. The log is constructed from real examples, from multiple wells from the North Atlantic Margin (references along the far right hand side). Mafic volcanic rocks generally exhibit low gamma values (**a**), whereas silicic rocks measure markedly higher values (**b**). Crystalline volcanic rocks such as basaltic compound lava flows (**c**), tabular lava flows (**d**) and igneous intrusions (**e**) have relatively high resistivity and low neutron porosity. Volcaniclastic rocks, such as tuffaceous rocks (**f**), intra-lava volcanic claystones (**g**) and hyaloclastite (**h**) demonstrate significantly higher neutron porosity and lower resistivity due to the presence of clay bound waters.

Fig. 5. Generalised igneous lithology seismic stratigraphy within the Bass Basin. The seismic datasets in this study are shown in time with a normal polarity, whereby a

downward increase in acoustic impedance produced a peak (a hard kick). Insets of the three main types of igneous material are displayed, as well as the sea floor for polarity reference. The top of the submarine volcanics is associated with a bright, seismically resolvable hard kick. A number of the igneous intrusions are poorly imaged, in this instance exhibiting a faint seismically identifiable hard (~2 secs TWT). Finally, the top of the subaerial volcanics is generally associated with a moderately bright, seismically resolvable hard.

Fig. 6. Frankenstein log depicting the igneous rocks encountered throughout the Bass Basin. In terms of the submarine volcanic rocks, chiefly hyaloclastite, the log motif is characterised by (**a**) continuously low gamma and (**b**) moderately high resistivity. Whilst no bulk density log has been acquired through these hyaloclastites in any of the wells, a density log can be derived from the sonic log, revealing a relatively low bulk density (**c**). Overall the submarine hyaloclastite packages exhibit a variably fast sonic velocity (**d**). With regards to the igneous intrusions encountered within the Bass Basin, the largely dolerite material exhibits low gamma (**e**) and high resistivity (**f**). The bulk density is generally high (>2.8 g cm^{-3}), except where poor hole conditions lead to anomalously low values (**g**). These igneous intrusions exhibit fast sonic velocity (**h**). However, within several wells a raft of higher gamma/lower density silicic igneous material is recognised (**i**). Finally, in terms of the subaerial volcanic rocks, a characteristic log motif of repeating blocks of low gamma (**j**), high resistivity (**k**), high density/low neutron porosity (**l**) and fast sonic velocity (**m**) are typical of tabular lava flows. Where the bulk density exhibits continuously marginally lower values than the tabular lavas, this likely represents compound lava flows.

Fig. 7. Regional distribution of igneous rocks throughout the Bass Basin, as proven by well penetrations (red outlined text boxes). Submarine volcanic are present within the Angahook Formation within the Torquay Group. Igneous intrusions are hosted predominantly within the Middle EVCM, with one penetration within the Upper EVCM (Tilana-1 well, Dondu Trough). Subaerial volcanic rocks, finally, are present within the Middle EVCM in the Cape Wickham Sub-basin, and in the Durroon Formation within the Duroon Sub-basin (Anderson Trough). Seismic basin fill not penetrated (dashed lines) based on Cummings *et al*. 2005.

Fig. 8. Core from a hyaloclastite succession from the Bass-1 well. Features of note include (**b**) rounded grains denote a degree of sorting; (**c**) Fine-grained tuffaceous and pumice clasts are also visible; (**d**) Normally graded beds.

Fig. 9. Distinct intrusion log profile recognised throughout the Bass Basin, whereby a more silisic raft of intrusive material is present in the upper third of the intrusion body, surrounded by dolerite. This magmatic contrast is supported by XRF geochemistry performed on ditch cuttings in two separate zones within the Seal-1 well (yellow stippled area).

Fig. 10. Bass Basin exploration timeline showing wells where igneous rocks were not predicted pre-drill. A number of the early wells were drilled on spare, 2D seismic lines. Another important feature is the cyclical nature of exploration, where a new company would enter the basin, embark upon a drilling campaign and fail to predict the presence of igneous rocks. Similar unexpectedly encountered igneous were encountered within the contiguous Gippsland Basin (Sailfish-1 & Kipper-1 wells).

Fig. 11. Regional 2D seismic line through the Bass-1 well (offset wells greyed out to reflect they were drilled later). The build of material recognised on seismic was interpreted pre-drill as a carbonate reef, though turned out to be a submarine volcano. The lower images are geoschematic representations modified from the Bass-1 end of well report.

Fig.12. Predicted stratigraphy compared to encountered (actual) stratigraphy and lithologies within the Aroo-1 well.

Fig. 13. A) Tasmanian Devil-1 prospect within a regional 2D seismic context, where broad graben structure recognised. **B & C**) pre and post drill lithology columns, modified from the Tasmanian Devil-1 end of well report. The accompanying interpreted seismic

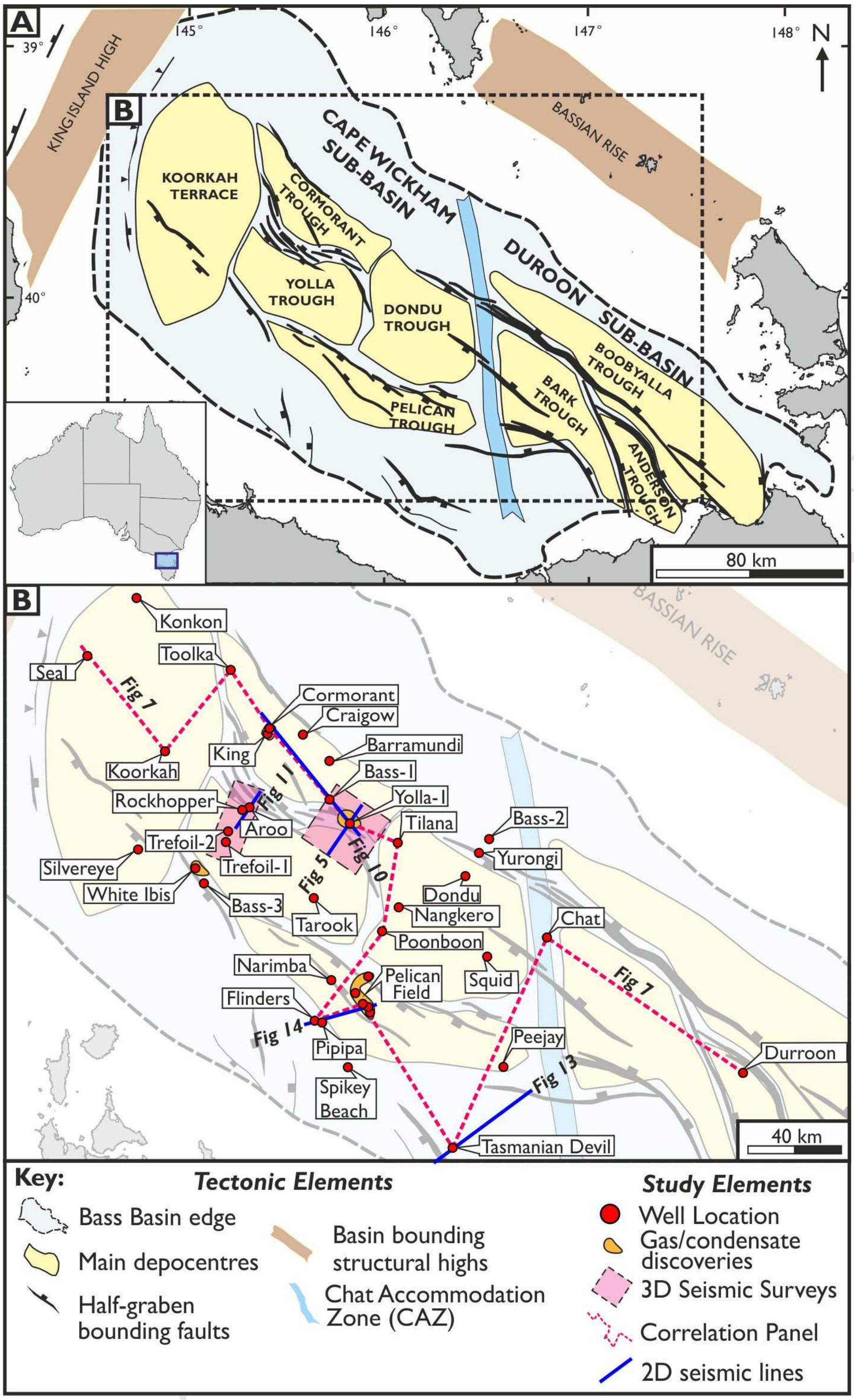
Fig. 14. Flinders-1 uninterpreted and interpreted seismic line (upper section). The pre-drill target was an amplitude anomaly at a slightly deeper level than where the Pipipa-1 offset well terminated. Upon drilling the amplitude anomaly was instead found to be a 64 m thick igneous intrusion, confirmed by modelling the synthetic response (lower section).

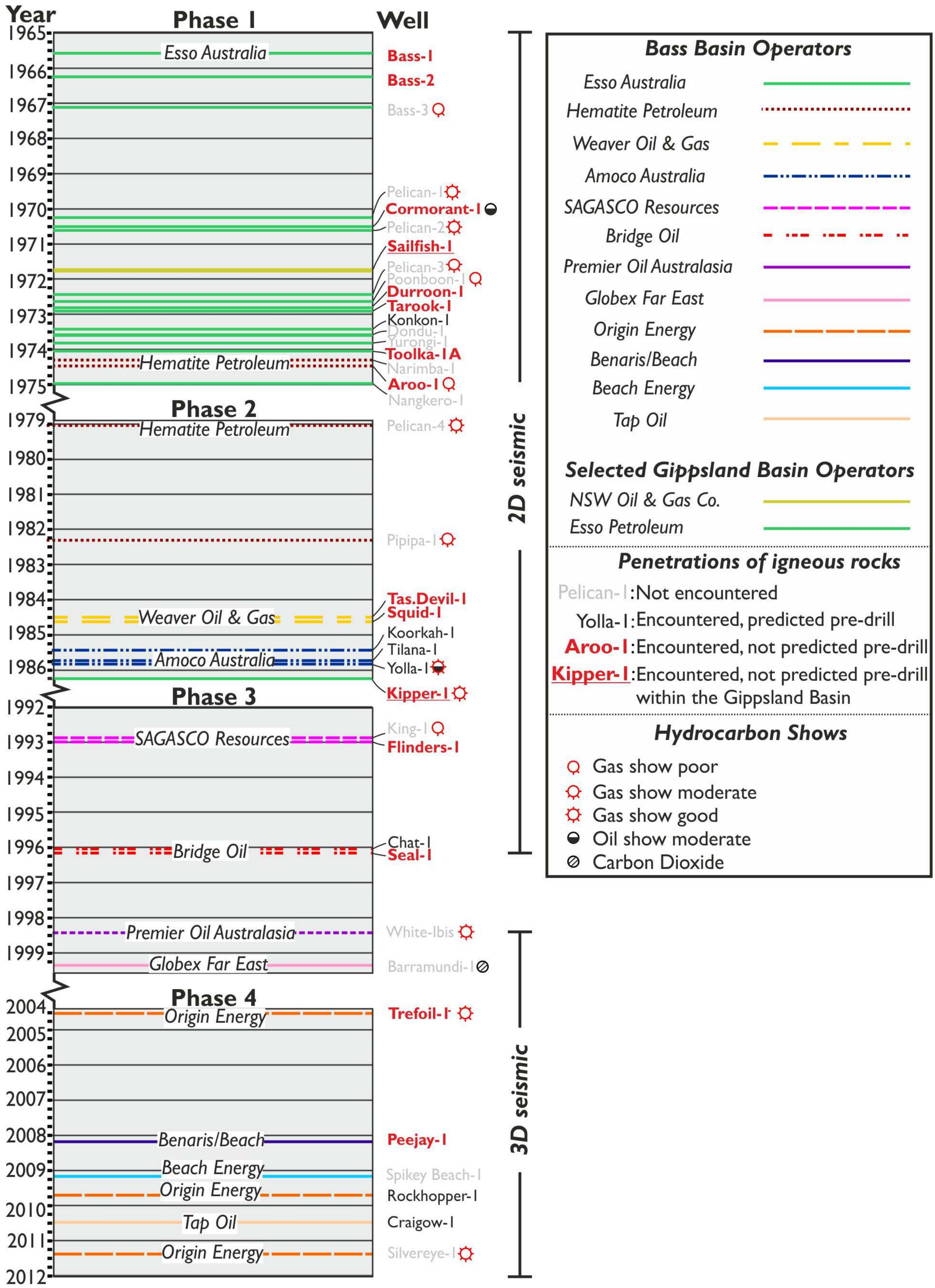
Fig. 15. Comparison between modern seismic data and the black and white seismic data in which the Flinders-1 prospect was interpreted on.

Fig. 16. Synthetic seismic comparison between intrusions from the FSB (from Mark et al. 2018) and the Bass Basin, Flinders-1 example (highlighted by dashed yellow lines on seismic). The FSB intrusion is not as thick and is present within deeper sediments than the Flinders-1 intrusion. However, a denser host rock and the presence of a raft of silicic material associated with the Flinders-1 intrusion combine to produce a

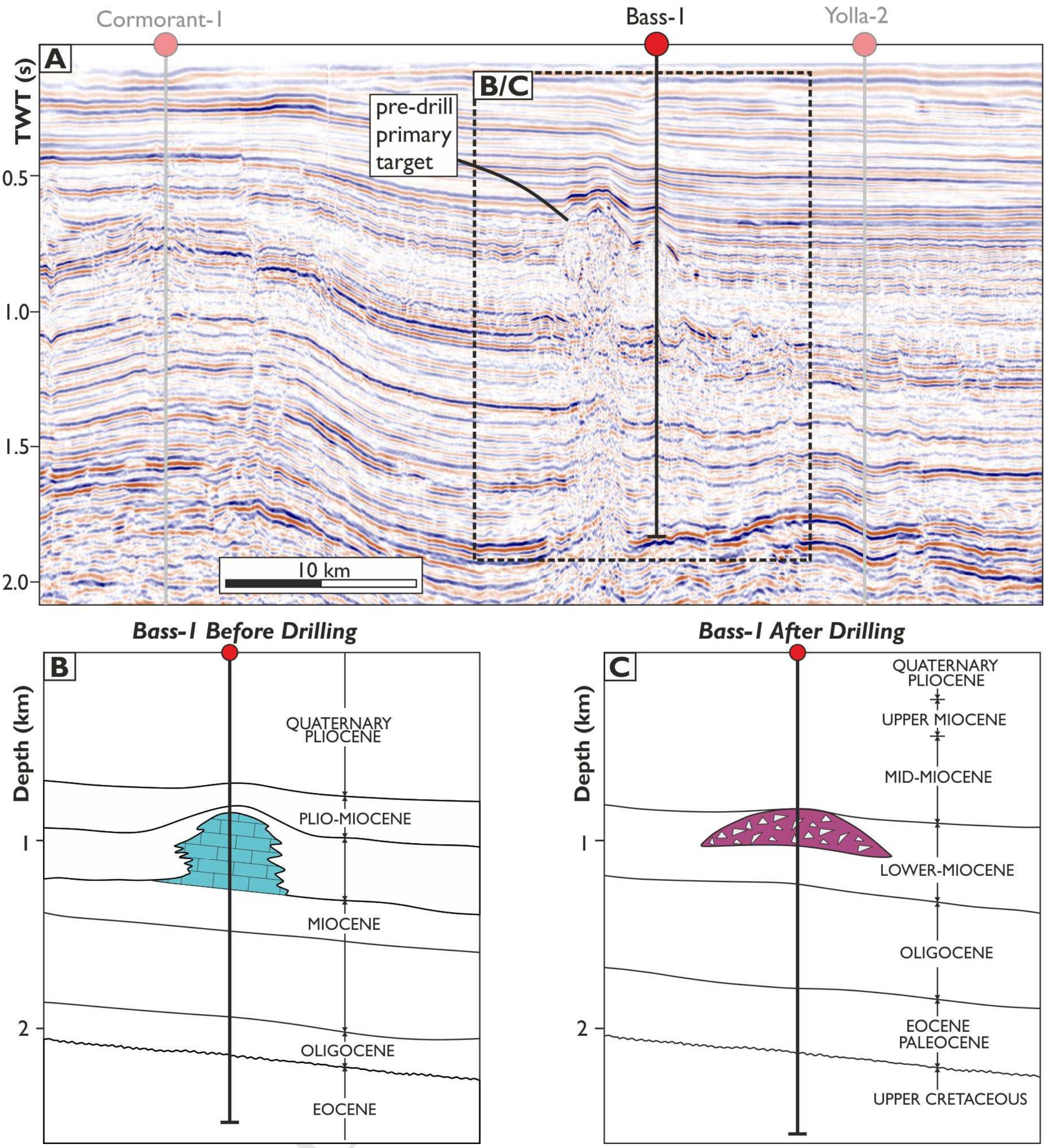
dimmer reflection. The presence of coals within the overburden also likely acts as a transmission filter, hindering imaging of the sediments and the intrusion below.

Fig. 17. Seismic comparison between top extrusive volcanics within the Bass Basin and the Faroe-Shetland Basin, North Atlantic Margin (seismic from the PGS FSB MegaSurvey Plus). The reflection associated with the top of the extrusive volcanics in the Bass Basin appears dimmer than the FSB equivalent due to the presence of high impedance coals acting as a transmission filter, and the overlying sediments being acoustically faster, hence a lower acoustic impedance is generated between the volcanics and the surrounding sedimentary rocks.

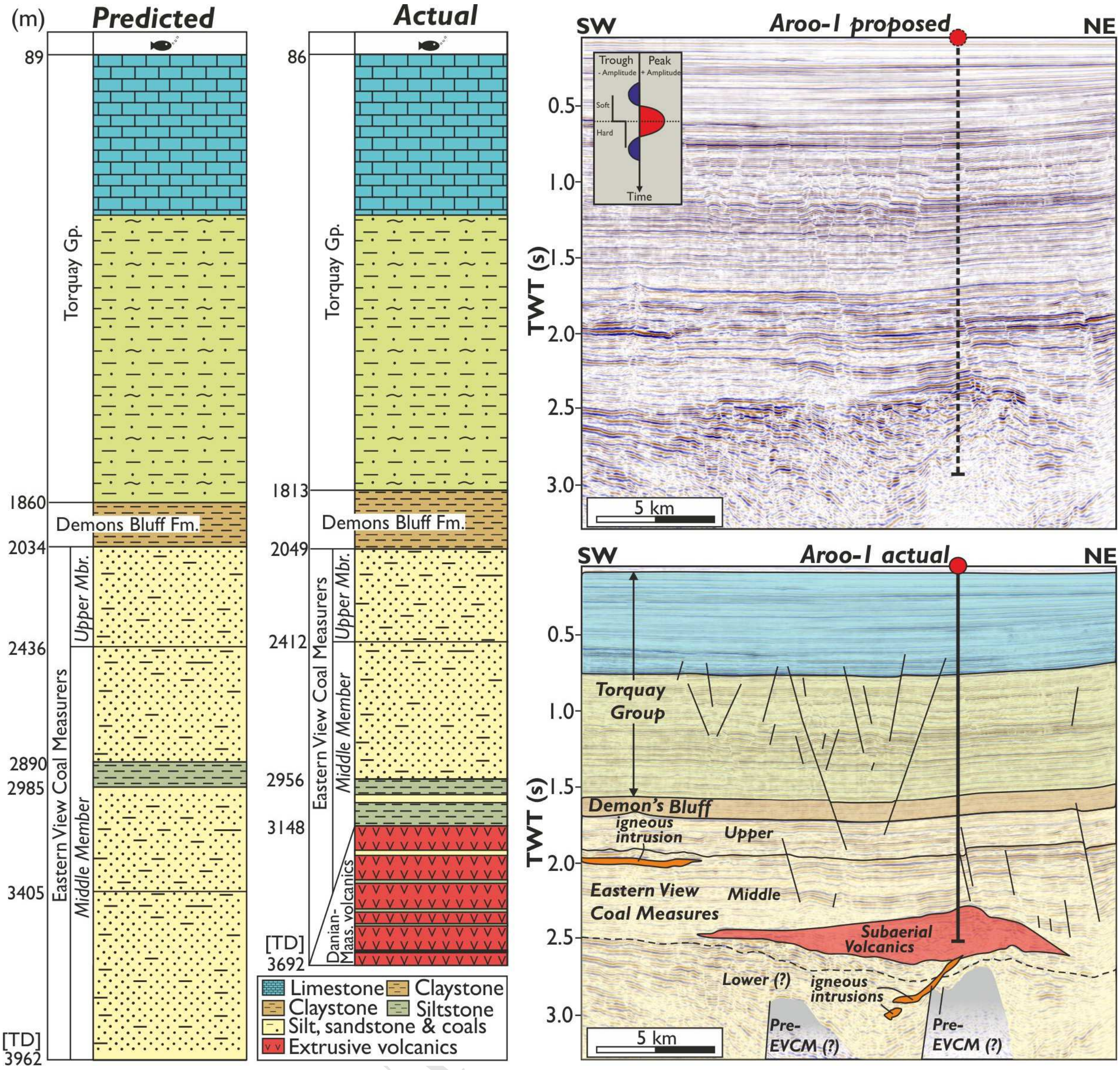

A
B
KING ISLAND HIGH
BASSIAN RISE
KOORKAH TERRACE
CORMORANT TROUGH
CAPE WICKHAM SUB-BASIN
YOLLA TROUGH
DONDU TROUGH
DUROON SUB-BASIN
BOOBYALLA TROUGH
BARK TROUGH
PELICAN TROUGH
ANDERSON TROUGH
80 km
N
Konkon
Toolka
Seal
Fig 7
Cormorant
Craigow
King
Barramundi
Koorkah
Bass-1
Yolla-1
Rockhopper
Fig 11
Aroo
Tilana
Bass-2
Trefoil-2
Trefoil-1
Yurongi
Silvereye
White Ibis
Fig 5
Fig 10
Dondu
Nangkero
Bass-3
Tarook
Chat
Poonboon
Narimba
Pelican Field
Squid
Flinders
Fig 14
Pipipa
Peejay
Durroon
Spikey Beach
Fig 13
Tasmanian Devil
40 km
Key:
Tectonic Elements
Bass Basin edge
Main depocentres
Half-graben bounding faults
Basin bounding structural highs
Chat Accommodation Zone (CAZ)
Study Elements
Well Location
Gas/condensate discoveries
3D Seismic Surveys
Correlation Panel
2D seismic lines



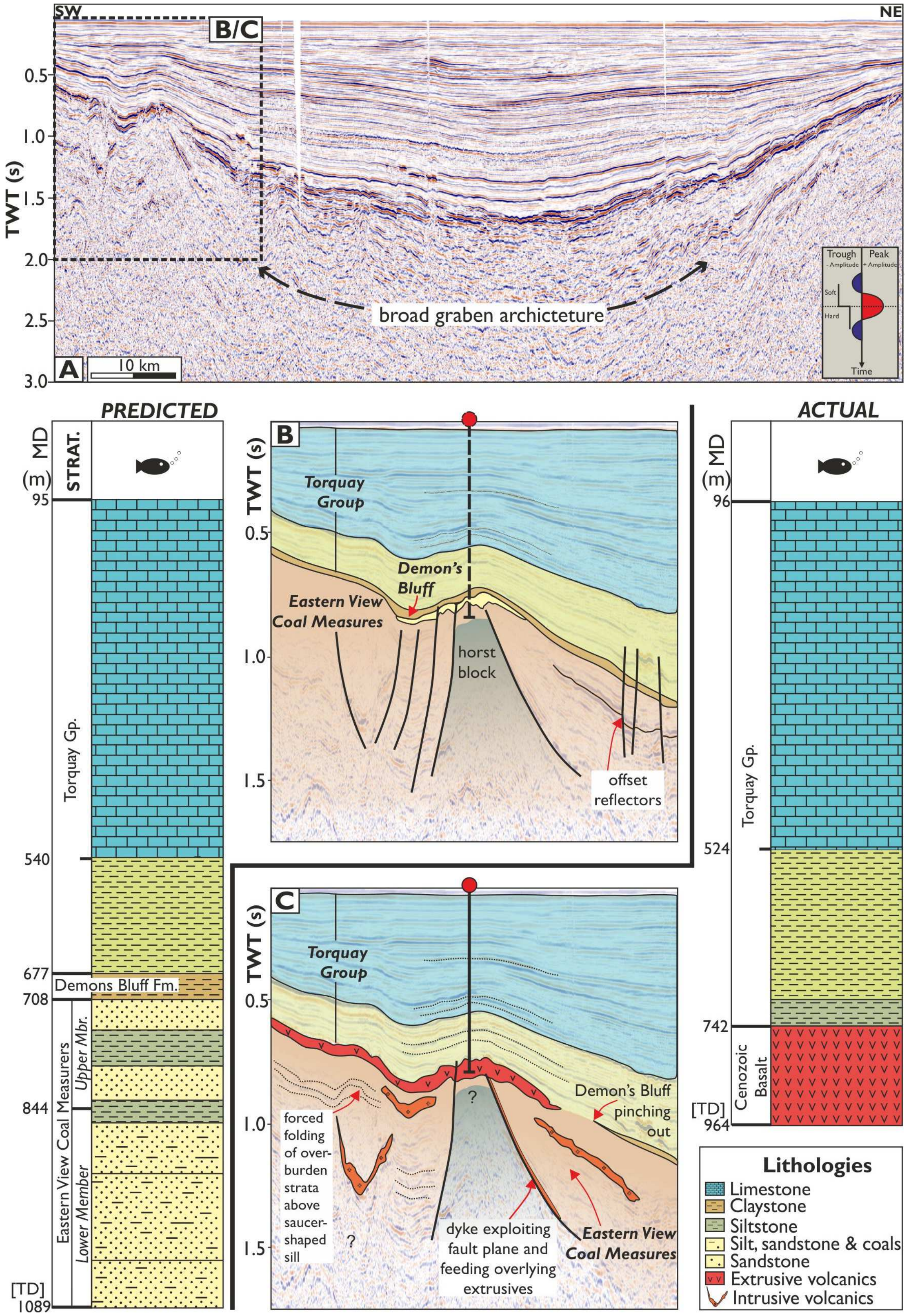
Year
Phase 1
Well
Esso Australia
Hematite Petroleum
Phase 2
Hematite Petroleum
Weaver Oil & Gas
Amoco Australia
Phase 3
SAGASCO Resources
Bridge Oil
Premier Oil Australasia
Globex Far East
Phase 4
Origin Energy
Benaris/Beach
Beach Energy
Origin Energy
Tap Oil
Origin Energy
Bass-1
Bass-2
Bass-3
Pelican-1
Cormorant-1
Pelican-2
Sailfish-1
Pelican-3
Poonboon-1
Durroon-1
Tarook-1
Konkon-1
Dondu-1
Yurongi-1
Toolka-1A
Narimba-1
Aroo-1
Nangkero-1
Pelican-4
Pipipa-1
Tas.Devil-1
Squid-1
Koorkah-1
Tilana-1
Yolla-1
Kipper-1
King-1
Flinders-1
Chat-1
Seal-1
White-Ibis
Barramundi-1
Trefoil-1
Peejay-1
Spikey Beach-1
Rockhopper-1
Craigow-1
Silvereye-1
2D seismic
3D seismic
Bass Basin Operators
Esso Australia
Hematite Petroleum
Weaver Oil & Gas
Amoco Australia
SAGASCO Resources
Bridge Oil
Premier Oil Australasia
Globex Far East
Origin Energy
Benaris/Beach
Beach Energy
Tap Oil
Selected Gippsland Basin Operators
NSW Oil & Gas Co.
Esso Petroleum
Penetrations of igneous rocks
Pelican-1:Not encountered
Yolla-1:Encountered, predicted pre-drill
Aroo-1:Encountered, not predicted pre-drill
Kipper-1:Encountered, not predicted pre-drill within the Gippsland Basin
Hydrocarbon Shows
Gas show poor
Gas show moderate
Gas show good
Oil show moderate
Carbon Dioxide



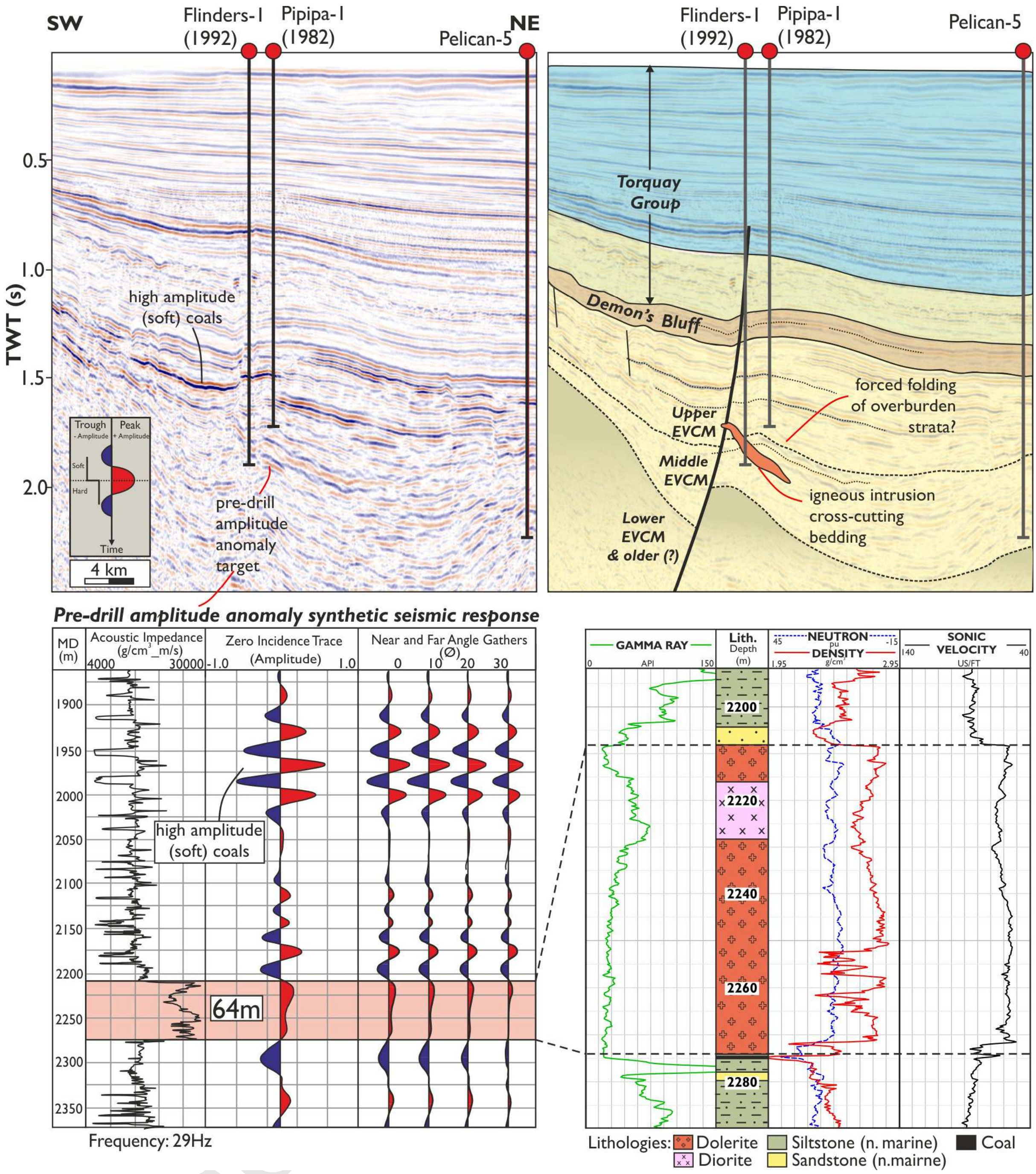
Cormorant-1
Bass-1
Yolla-2
A
B/C
TWT (s)
pre-drill primary target
0.5
1.0
1.5
2.0
10 km
Bass-1 Before Drilling
Bass-1 After Drilling
B
C
Depth (km)
1
2
QUATERNARY PLIOCENE
PLIO-MIOCENE
MIOCENE
OLIGOCENE
EOCENE
QUATERNARY PLIOCENE
UPPER MIOCENE
MID-MIOCENE
LOWER-MIOCENE
OLIGOCENE
EOCENE PALEOCENE
UPPER CRETACEOUS

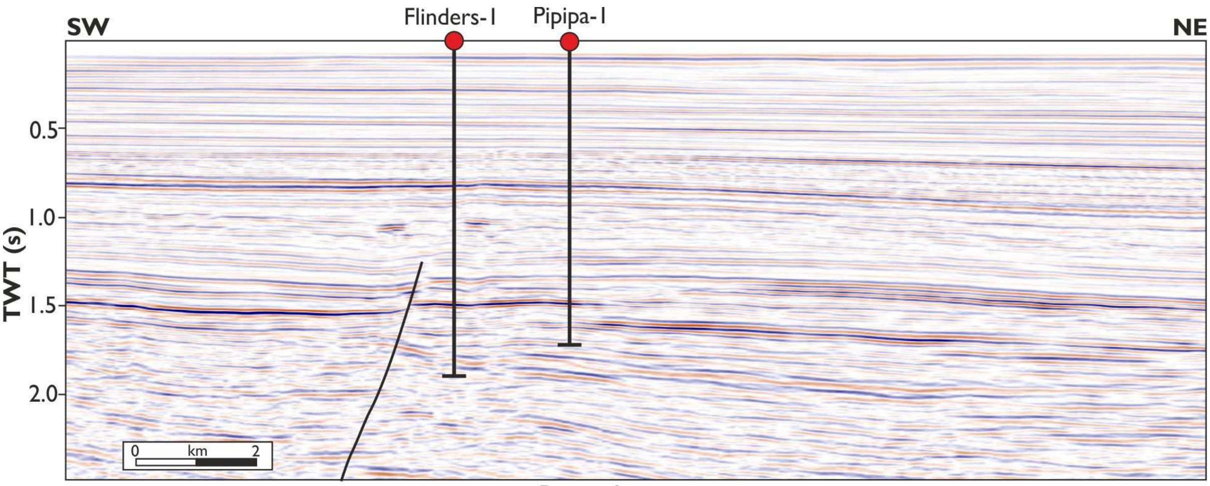


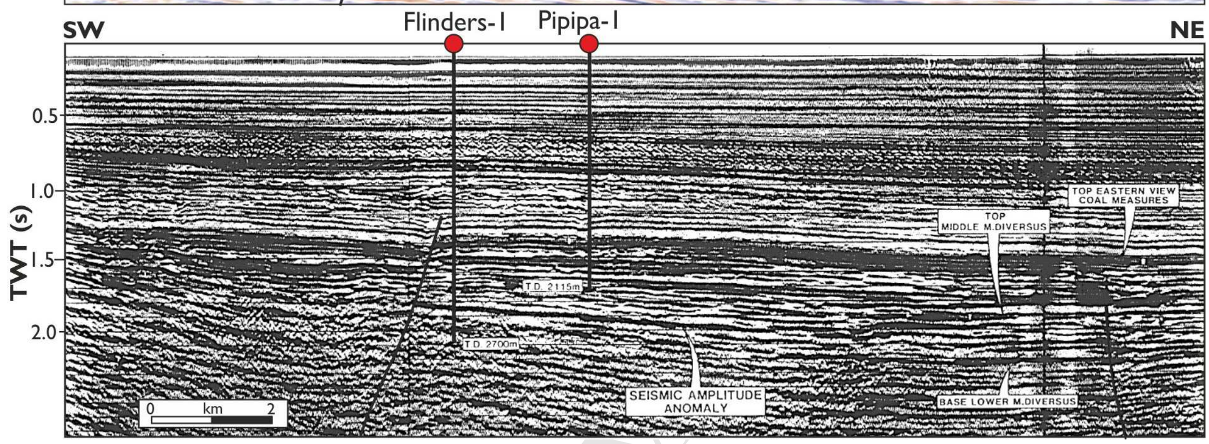
(m)
Predicted
Actual
89
86
Torquay Gp.
1860
1813
Demons Bluff Fm.
2034
2049
Upper Mbr.
2436
2412
Eastern View Coal Measurers
Middle Member
2890
2985
2956
3148
3405
Danian-Maas. volcanics
[TD] 3692
[TD] 3962
Limestone
Claystone
Siltstone
Silt, sandstone & coals
Extrusive volcanics
SW
Aroo-1 proposed
NE
TWT (s)
Trough - Amplitude
Peak + Amplitude
Soft
Hard
Time
5 km
Aroo-1 actual
Torquay Group
Demon's Bluff
igneous intrusion
Upper
Eastern View Coal Measures
Middle
Subaerial Volcanics
Lower (?)
igneous intrusions
Pre-EVCM (?)

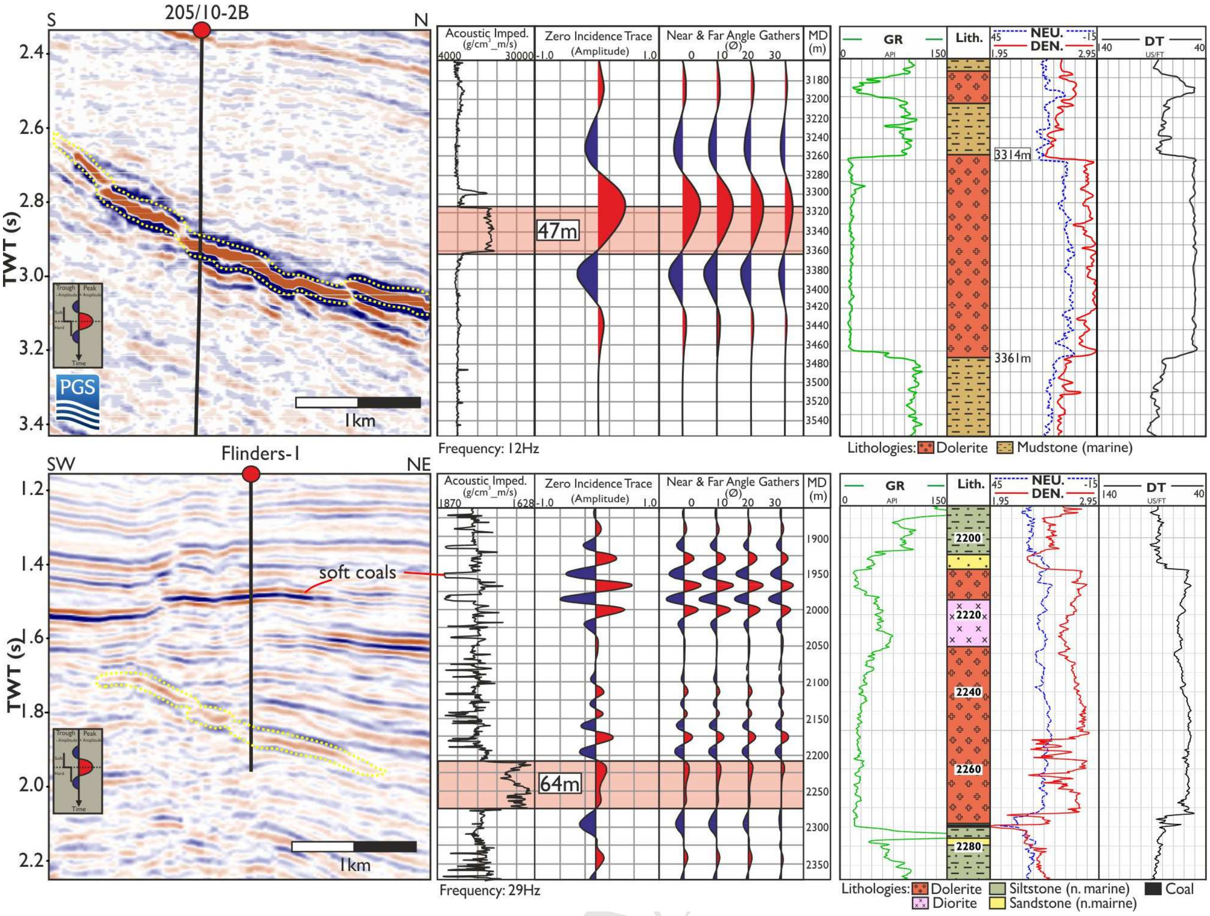


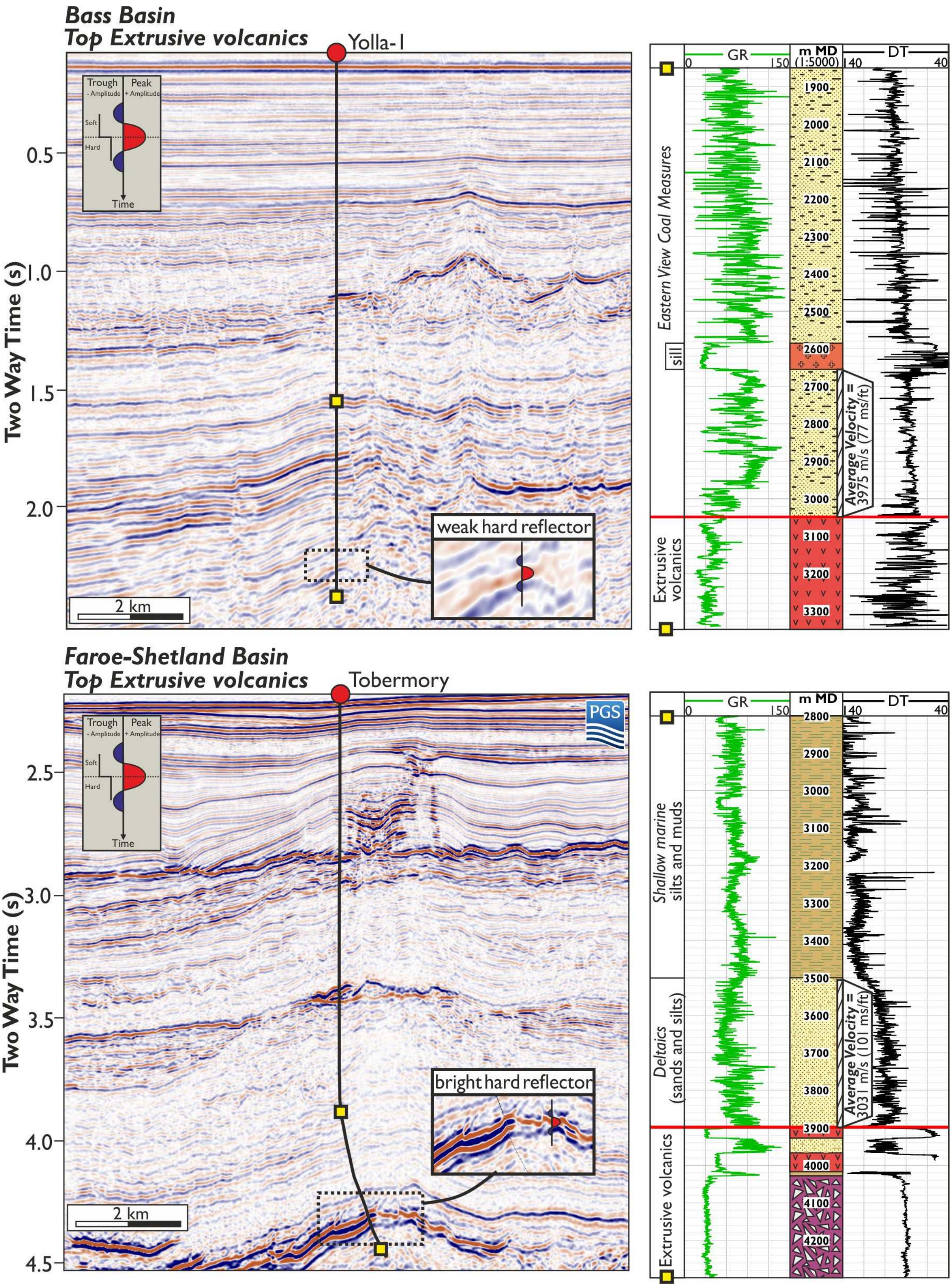
SW
NE
B/C
TWT (s)
broad graben archicteture
A
10 km
Trough
Peak
Soft
Hard
Time
PREDICTED
ACTUAL
MD (m)
STRAT.
95
540
677
708
844
[TD] 1089
Torquay Gp.
Demons Bluff Fm.
Eastern View Coal Measurers
Upper Mbr.
Lower Member
B
Torquay Group
Demon's Bluff
Eastern View Coal Measures
horst block
offset reflectors
C
forced folding of over-burden strata above saucer-shaped sill
dyke exploiting fault plane and feeding overlying extrusives
Demon's Bluff pinching out
96
524
742
[TD] 964
Cenozoic Basalt
Lithologies
Limestone
Claystone
Siltstone
Silt, sandstone & coals
Sandstone
Extrusive volcanics
Intrusive volcanics


SW
Flinders-1 (1992)
Pipipa-1 (1982)
Pelican-5
NE
TWT (s)
0.5
1.0
1.5
2.0
high amplitude (soft) coals
Trough - Amplitude
Peak + Amplitude
Soft
Hard
Time
4 km
pre-drill amplitude anomaly target
Torquay Group
Demon's Bluff
forced folding of overburden strata?
Upper EVCM
Middle EVCM
Lower EVCM & older (?)
igneous intrusion cross-cutting bedding
Pre-drill amplitude anomaly synthetic seismic response
MD (m)
Acoustic Impedance (g/cm³_m/s)
4000
30000
Zero Incidence Trace (Amplitude)
-1.0
1.0
Near and Far Angle Gathers (Ø)
0
10
20
30
1900
1950
2000
2050
2100
2150
2200
2250
2300
2350
high amplitude (soft) coals
64m
Frequency: 29Hz
GAMMA RAY
0
API
150
Lith. Depth (m)
NEUTRON
45
pu
-15
DENSITY
1.95
g/cm³
2.95
SONIC VELOCITY
140
US/FT
40
2200
2220
2240
2260
2280
Lithologies: Dolerite
Diorite
Siltstone (n. marine)
Sandstone (n.mairne)
Coal

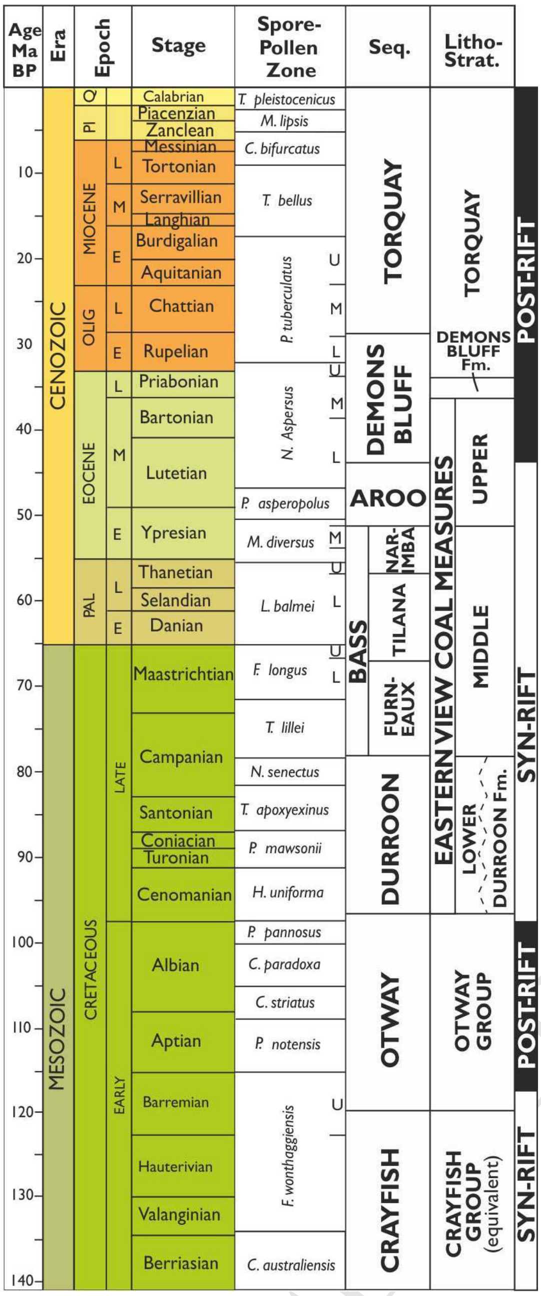

SW
Flinders-1
Pipipa-1
NE
TWT (s)
0.5
1.0
1.5
2.0
0
km
2


SW
Flinders-1
Pipipa-1
NE
TWT (s)
0.5
1.0
1.5
2.0
TOP EASTERN VIEW COAL MEASURES
TOP MIDDLE M.DIVERSUS
T.D. 2115m
T.D. 2700m
SEISMIC AMPLITUDE ANOMALY
BASE LOWER M.DIVERSUS
0
km
2


205/10-2B
S
N
TWT (s)
47m
1km
PGS
Acoustic Imped.
Zero Incidence Trace (Amplitude)
Near & Far Angle Gathers
MD (m)
Frequency: 12Hz
GR
Lith.
NEU.
DEN.
DT
3314m
3361m
Lithologies: Dolerite Mudstone (marine)
Flinders-1
SW
NE
soft coals
64m
Frequency: 29Hz
Lithologies: Dolerite Diorite Siltstone (n. marine) Sandstone (n.mairne) Coal



Bass Basin
Top Extrusive volcanics
Yolla-1
Trough
Peak
- Amplitude
+ Amplitude
Soft
Hard
Time
Two Way Time (s)
0.5
1.0
1.5
2.0
weak hard reflector
2 km
GR
0
150
m MD
(1:5000)
DT
140
40
Eastern View Coal Measures
sill
Extrusive volcanics
Average Velocity = 3975 m/s (77 ms/ft)
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
Faroe-Shetland Basin
Top Extrusive volcanics
Tobermory
PGS
2.5
3.0
3.5
4.0
4.5
bright hard reflector
Shallow marine silts and muds
Deltaics (sands and silts)
Average Velocity = 3031 m/s (101 ms/ft)
2800
3400
3500
3600
3700
3800
3900
4000
4100
4200


Age Ma BP
Era
Epoch
Stage
Spore-Pollen Zone
Seq.
Litho-Strat.
10
20
30
40
50
60
70
80
90
100
110
120
130
140
CENOZOIC
MESOZOIC
Q
Pl
MIOCENE
OLIG
EOCENE
PAL
CRETACEOUS
LATE
EARLY
Calabrian
Piacenzian
Zanclean
Messinian
Tortonian
Serravillian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
T. pleistocenicus
M. lipsis
C. bifurcatus
T. bellus
P. tuberculatus
N. Aspersus
P. asperopolus
M. diversus
L. balmei
F. longus
T. lillei
N. senectus
T. apoxyexinus
P. mawsonii
H. uniforma
P. pannosus
C. paradoxa
C. striatus
P. notensis
F. wonthaggiensis
C. australiensis
TORQUAY
DEMONS BLUFF
AROO
BASS
NAR-IMBA
TILANA
FURN-EAUX
DURROON
OTWAY
CRAYFISH
DEMONS BLUFF Fm.
EASTERN VIEW COAL MEASURES
UPPER
MIDDLE
LOWER
DURROON Fm.
OTWAY GROUP
CRAYFISH GROUP (equivalent)
POST-RIFT
SYN-RIFT

Workflow for investigating volcanic rocks at a micro-scale

Dataset | **Example (from Aroo-1 well)** | **Implication**

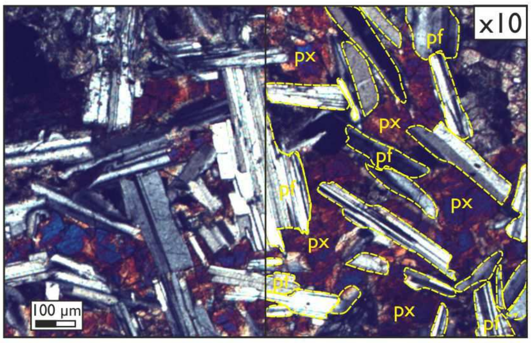
① Well site cuttings descriptions

```
11471 - 11848

VOLCANICS, weathered and unweathered,
dark grey to light green, calcite
amygdules and veinlets.   Weathered
zones are soft, kaolinitic,
calcareous.
```

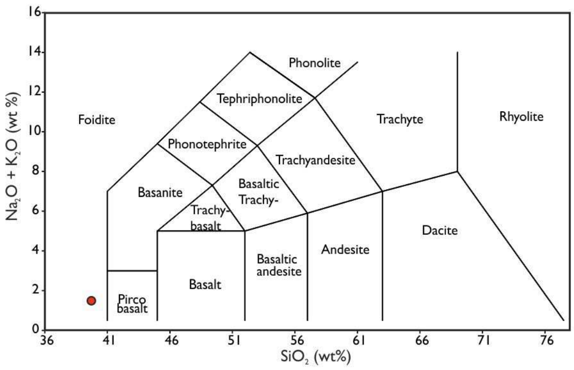
- Volcanic rocks likely present in well
- Note of weathered material and kaolinite suggests a degree of alteration

② Thin-section micrograph from side-wall core



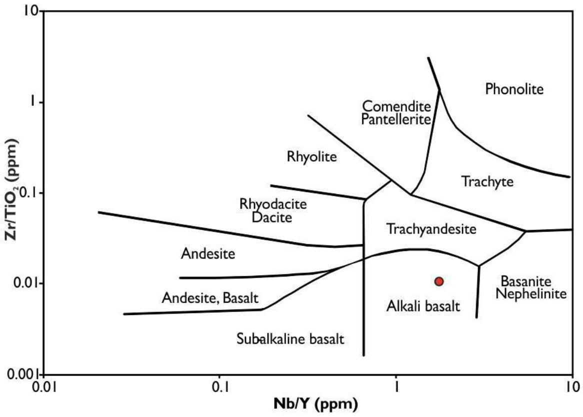
- Confirmation of presence of volcanic material (fine grained crystalline rock)
- Plagioclase feldspar [pf] (multiple twinning) and interstitial pyroxene [px] (two cleavages, second order interference colours)
- mineralogy typical of basaltic material

③ Geochemical plot of major oxides (Total Alkali Silica plot)



- Sample plots in the "foidite" field, not consistent with the mineralogy.
- However, major oxides are readily altered.
- Cuttings descriptions alludes to altered material, suggesting TAS plot not reliable.

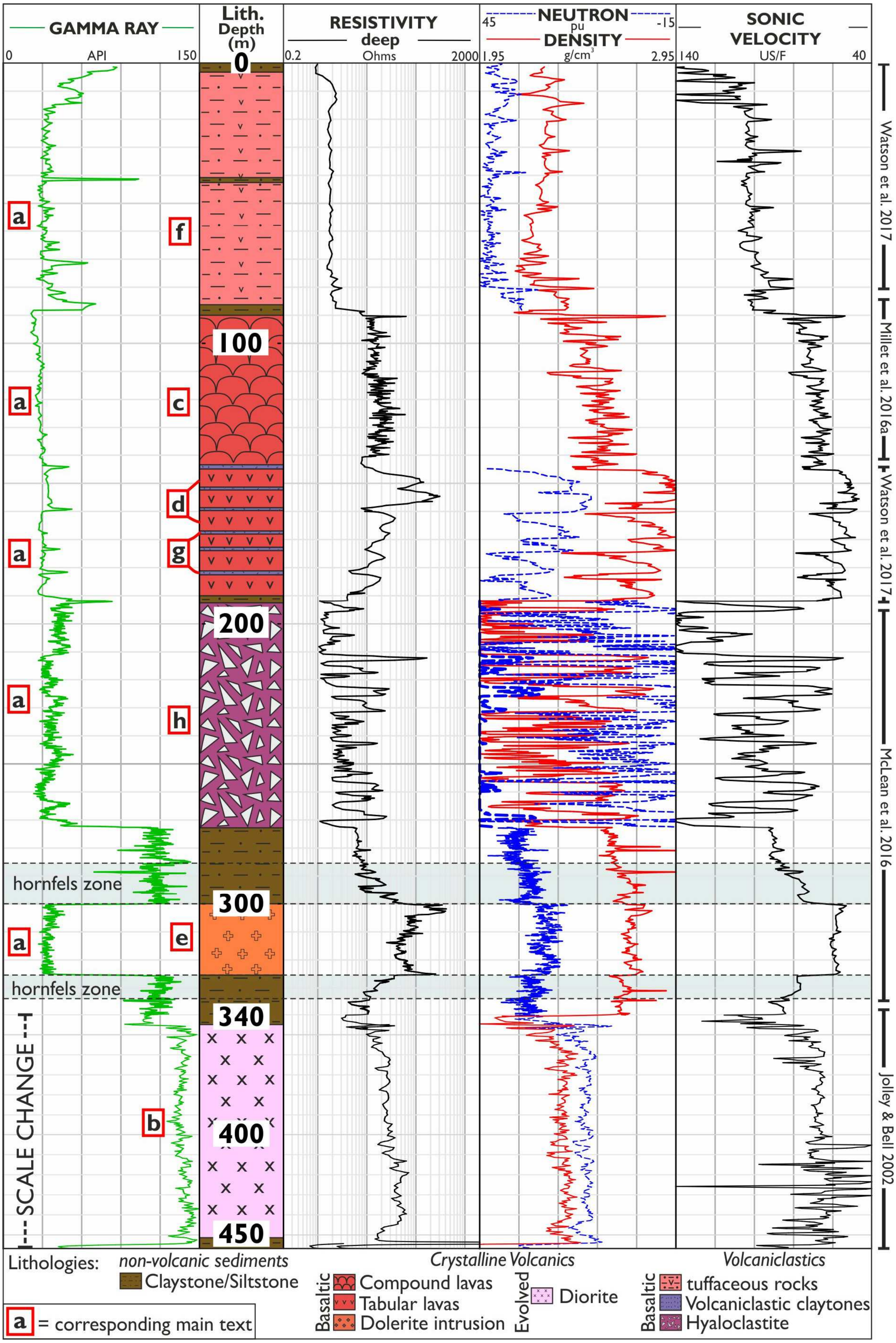
④ Geochemical plot of immobile trace elements (Winchester & Floyd plot)



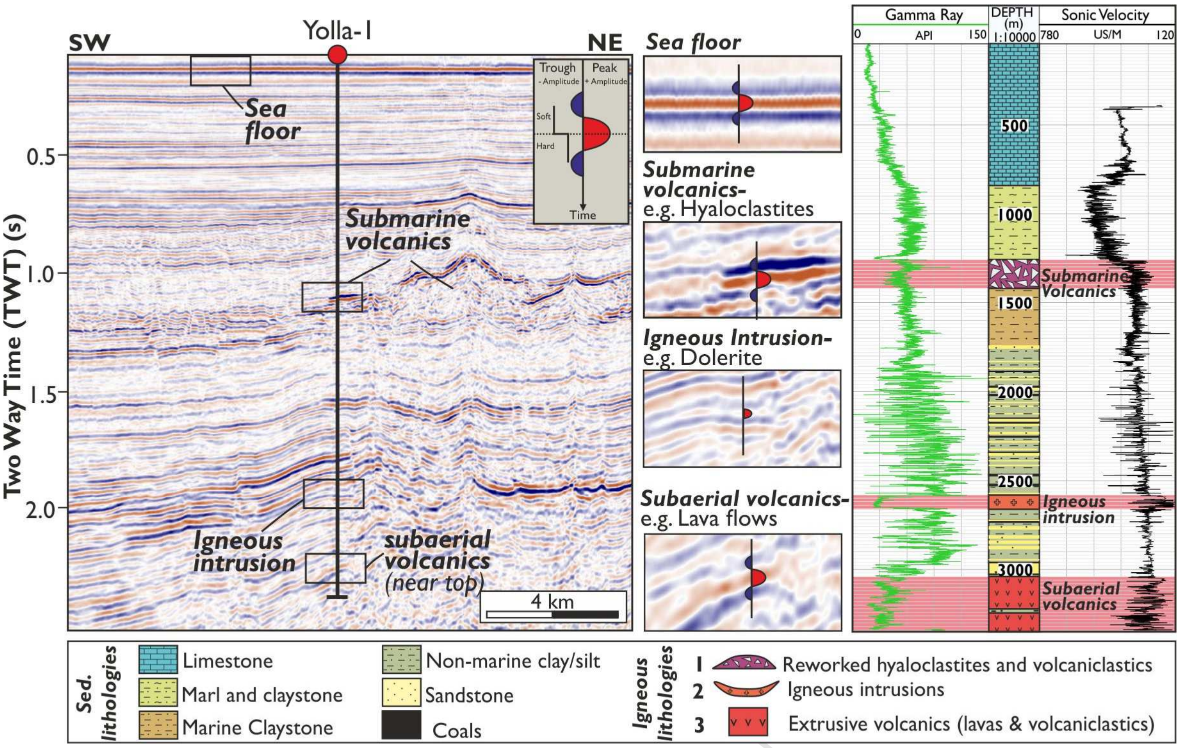
- Sample plots on the "alkali basalt" field
- Consistent with the mineralogy observed in thin-section

Synthesis:

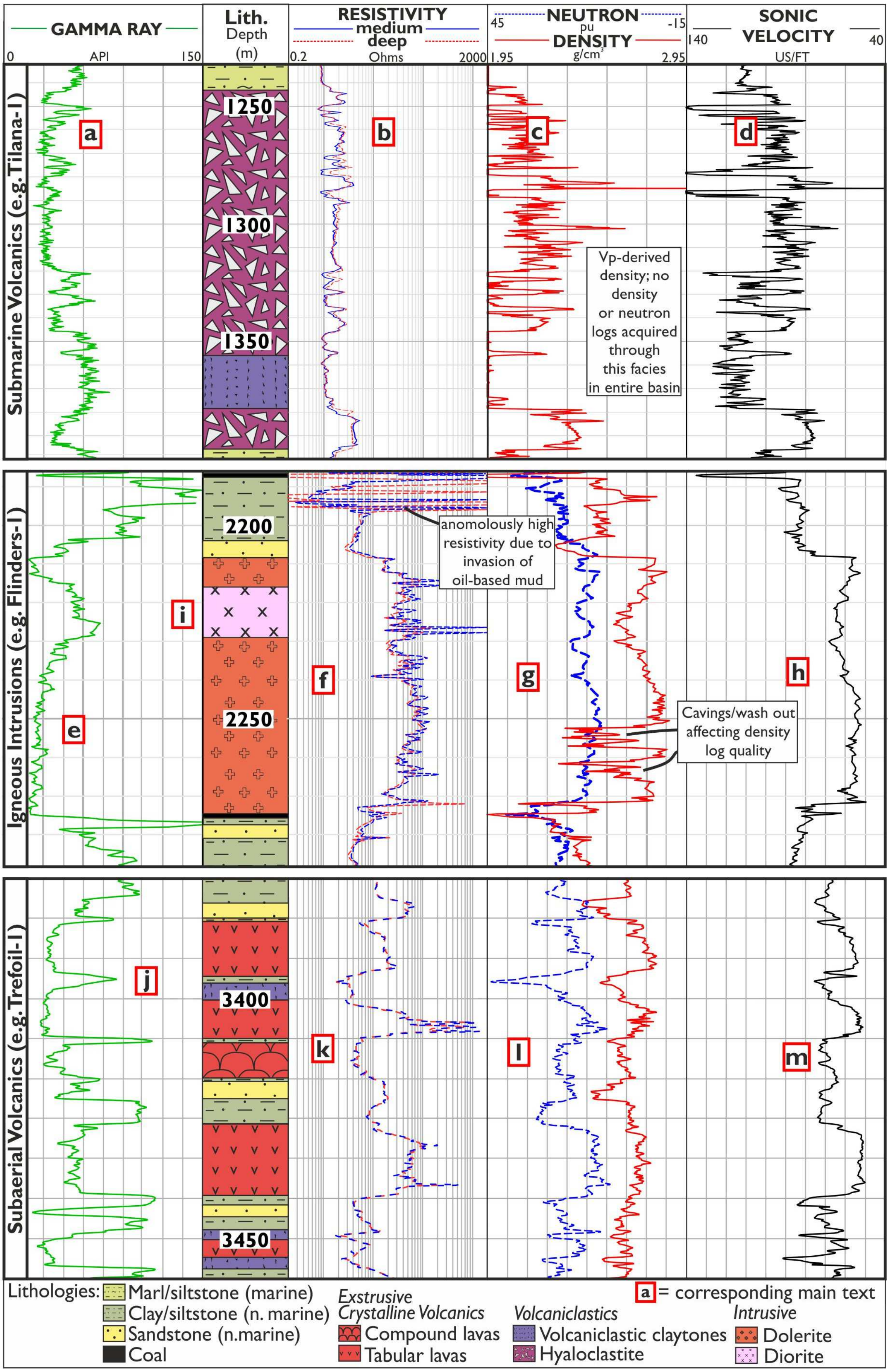
Weathered fine-grained alkali basaltic lava



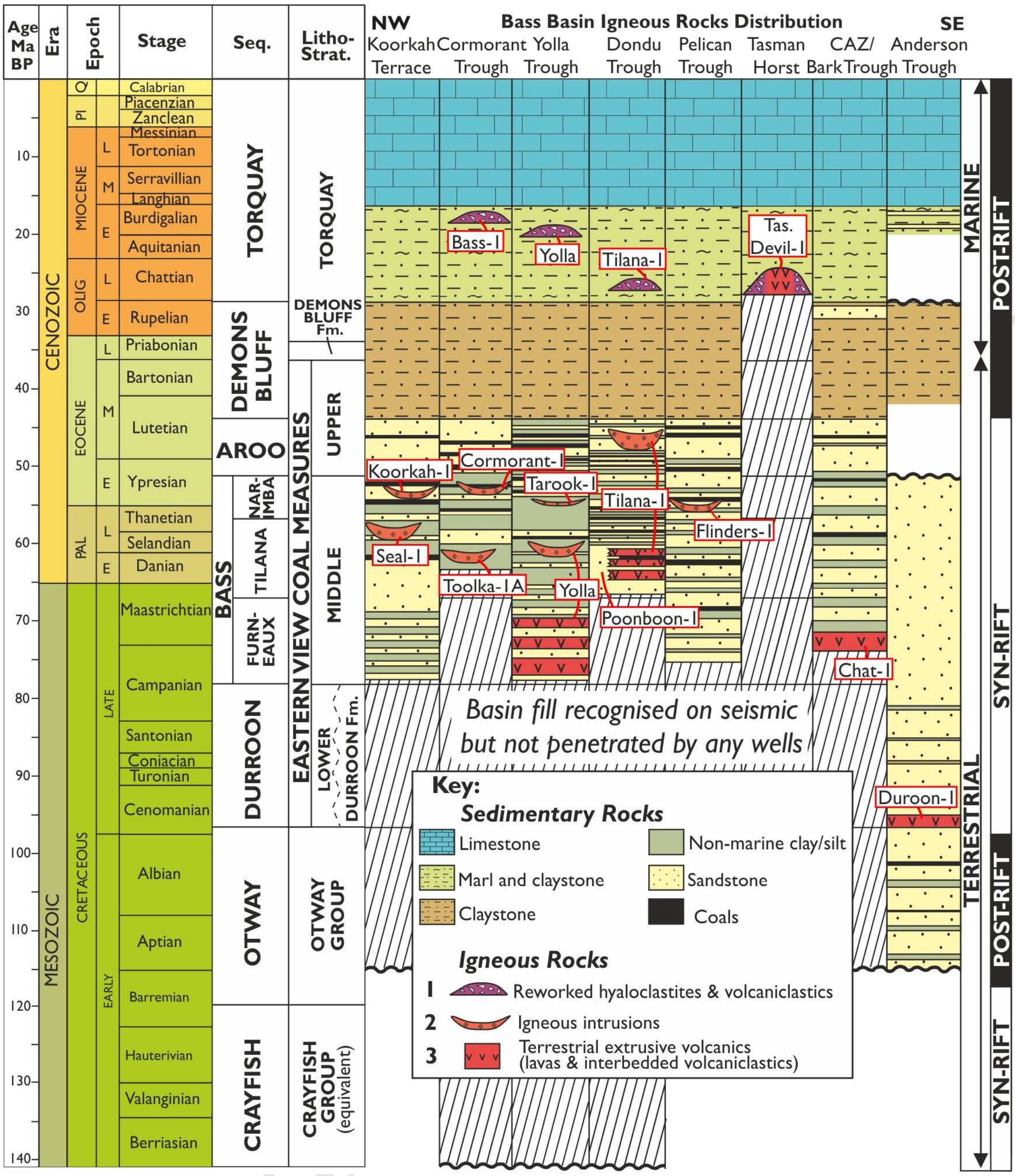
GAMMA RAY
0 API 150
Lith. Depth (m)
RESISTIVITY deep
0.2 Ohms 2000
NEUTRON pu
45 -15
DENSITY g/cm3
1.95 2.95
SONIC VELOCITY
140 US/F 40
0
100
200
300
340
400
450
a
b
c
d
e
f
g
h
hornfels zone
hornfels zone
SCALE CHANGE
Watson et al. 2017
Millet et al. 2016a
Watson et al. 2017
McLean et al. 2016
Jolley & Bell 2002
Lithologies:
non-volcanic sediments
Claystone/Siltstone
Crystalline Volcanics
Basaltic
Compound lavas
Tabular lavas
Dolerite intrusion
Evolved
Diorite
Volcaniclastics
Basaltic
tuffaceous rocks
Volcaniclastic claytones
Hyaloclastite
a = corresponding main text



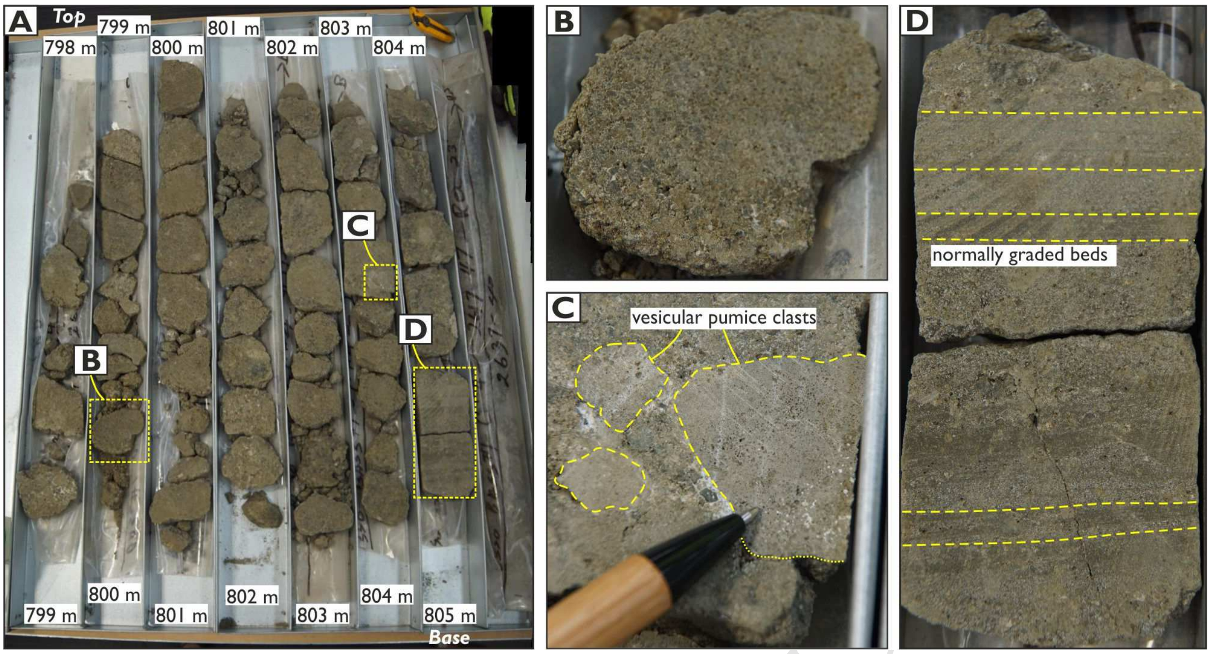
SW
Yolla-1
NE
Sea floor
Submarine volcanics
Igneous intrusion
subaerial volcanics (near top)
4 km
Two Way Time (TWT) (s)
0.5
1.0
1.5
2.0
Trough - Amplitude
Peak + Amplitude
Soft
Hard
Time
Sea floor
Submarine volcanics- e.g. Hyaloclastites
Igneous Intrusion- e.g. Dolerite
Subaerial volcanics- e.g. Lava flows
Gamma Ray
0 API 150
DEPTH (m) 1:10000
Sonic Velocity
780 US/M 120
500
1000
1500
2000
2500
3000
Submarine Volcanics
Igneous intrusion
Subaerial volcanics
Sed. lithologies
Limestone
Marl and claystone
Marine Claystone
Non-marine clay/silt
Sandstone
Coals
Igneous lithologies
1 Reworked hyaloclastites and volcaniclastics
2 Igneous intrusions
3 Extrusive volcanics (lavas & volcaniclastics)

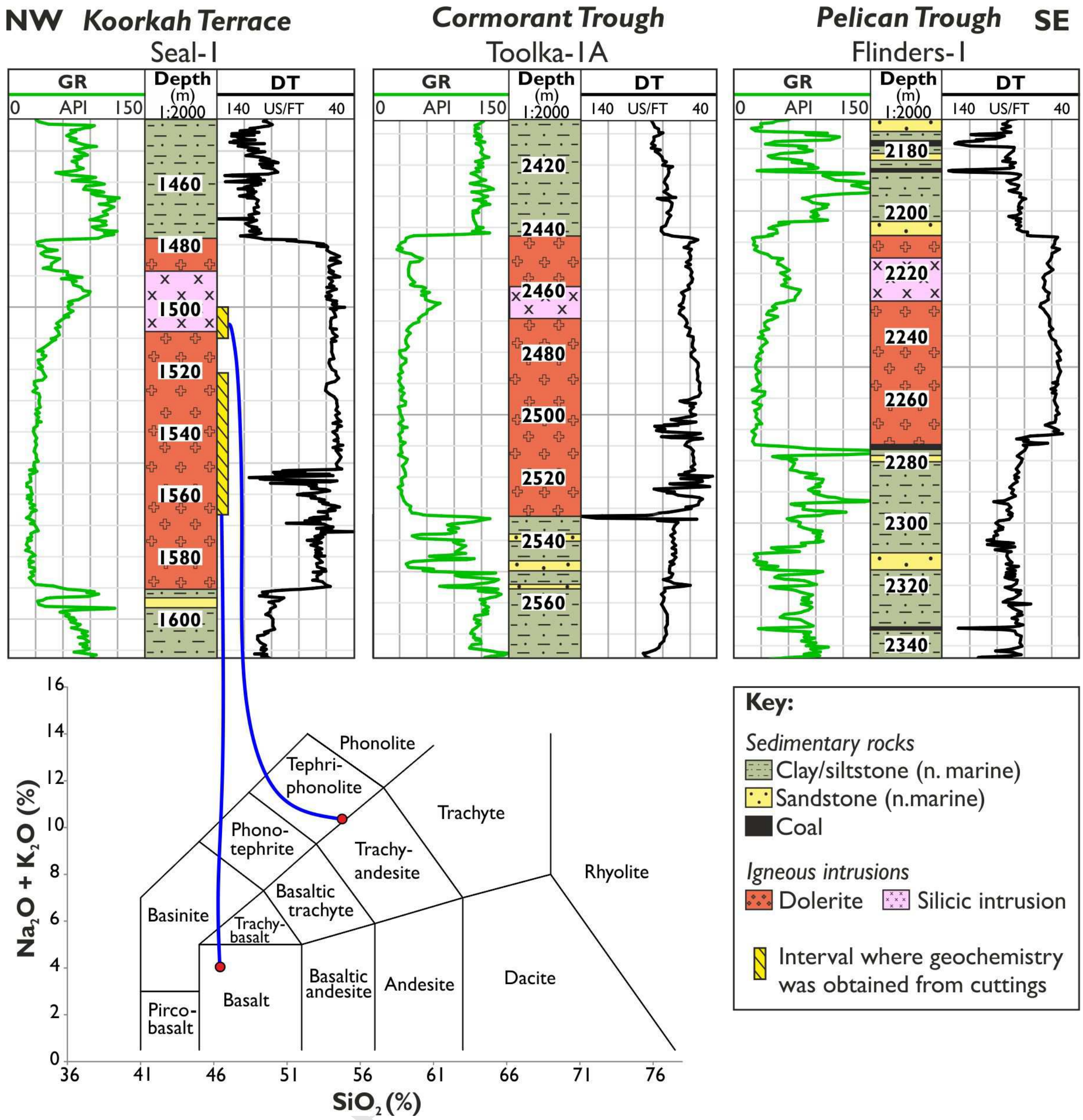


GAMMA RAY
0 API 150
Lith.
Depth (m)
RESISTIVITY
medium
deep
0.2 Ohms 2000
NEUTRON
45 pu -15
DENSITY
1.95 g/cm3 2.95
SONIC VELOCITY
140 US/FT 40
Submarine Volcanics (e.g. Tilana-1)
1250
1300
1350
a
b
c
d
Vp-derived density; no density or neutron logs acquired through this facies in entire basin
Igneous Intrusions (e.g. Flinders-1)
2200
2250
anomolously high resistivity due to invasion of oil-based mud
Cavings/wash out affecting density log quality
e
f
g
h
i
Subaerial Volcanics (e.g. Trefoil-1)
3400
3450
j
k
l
m
Lithologies:
Marl/siltstone (marine)
Clay/siltstone (n. marine)
Sandstone (n.marine)
Coal
Exstrusive
Crystalline Volcanics
Compound lavas
Tabular lavas
Volcaniclastics
Volcaniclastic claytones
Hyaloclastite
a = corresponding main text
Intrusive
Dolerite
Diorite



Age Ma BP
Era
Epoch
Stage
Seq.
Litho-Strat.
NW
Bass Basin Igneous Rocks Distribution
SE
Koorkah Terrace
Cormorant Trough
Yolla Trough
Dondu Trough
Pelican Trough
Tasman Horst
CAZ/ Bark Trough
Anderson Trough
CENOZOIC
MESOZOIC
Q
Pl
MIOCENE
OLIG
EOCENE
PAL
CRETACEOUS
LATE
EARLY
Calabrian
Piacenzian
Zanclean
Messinian
Tortonian
Serravillian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
TORQUAY
DEMONS BLUFF
AROO
BASS
NAR-IMBA
TILANA
FURN-EAUX
DURROON
OTWAY
CRAYFISH
DEMONS BLUFF Fm.
EASTERN VIEW COAL MEASURES
UPPER
MIDDLE
LOWER DURROON Fm.
OTWAY GROUP
CRAYFISH GROUP (equivalent)
Bass-1
Yolla
Tilana-1
Tas. Devil-1
Koorkah-1
Cormorant-1
Tarook-1
Tilana-1
Flinders-1
Seal-1
Toolka-1A
Yolla
Poonboon-1
Chat-1
Duroon-1
Basin fill recognised on seismic but not penetrated by any wells
Key:
Sedimentary Rocks
Limestone
Non-marine clay/silt
Marl and claystone
Sandstone
Claystone
Coals
Igneous Rocks
1 Reworked hyaloclastites & volcaniclastics
2 Igneous intrusions
3 Terrestrial extrusive volcanics (lavas & interbedded volcaniclastics)
MARINE
TERRESTRIAL
POST-RIFT
SYN-RIFT
POST-RIFT
SYN-RIFT


A
Top
798 m
799 m
800 m
801 m
802 m
803 m
804 m
B
C
D
799 m
800 m
801 m
802 m
803 m
804 m
805 m
Base
B
C
vesicular pumice clasts
D
normally graded beds



NW Koorkah Terrace
Seal-1
Cormorant Trough
Toolka-1A
Pelican Trough SE
Flinders-1
GR
0 API 150
Depth (m) 1:2000
DT
140 US/FT 40
1460
1480
1500
1520
1540
1560
1580
1600
2420
2440
2460
2480
2500
2520
2540
2560
2180
2200
2220
2240
2260
2280
2300
2320
2340
Na2O + K2O (%)
SiO2 (%)
Phonolite
Tephri-phonolite
Trachyte
Phono-tephrite
Trachy-andesite
Rhyolite
Basinite
Basaltic trachyte
Trachy-basalt
Picro-basalt
Basalt
Basaltic andesite
Andesite
Dacite
Key:
Sedimentary rocks
Clay/siltstone (n. marine)
Sandstone (n.marine)
Coal
Igneous intrusions
Dolerite
Silicic intrusion
Interval where geochemistry was obtained from cuttings

- The Bass Basin is a Mesozoic-Cenozoic intra-continental rift basin along southern Australian
- Igneous rocks encountered in 20 out of 36 (55.6%) exploration wells drilled within the Bass Basin
- In 13 of 20 exploration wells (65%) the igneous rocks encountered were not predicted pre-drill
- Anomalously low acoustic impedance contrast between igneous rocks and sedimentary sequences in the Bass Basin, relative to other basins notable for magmatism, such as the North Atlantic Margin.