The facies architecture of submarine basaltic volcanoes and their effects on fluid flow

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SUMMARY

Volcanic-affected hydrocarbon basins commonly contain a variety of intrusive and extrusive volcanic rocks. All extrusive facies are ultimately sourced from volcanoes. Importantly, volcanoes link the extrusive components to the underlying magmatic plumbing system; features which may act as subsurface conduits and baffles for fluid flow. Volcanoes also provide insights into the timing of both intrusive and extrusive activity, thus helping constrain hydrothermal and contact metamorphic processes associated with magma intrusion. However, in comparison to the intrusive components of volcanic systems, the criteria for recognising these important features in seismic data are less well known. In addition, the facies of which volcanoes are commonly composed are poorly characterised from well and seismic data.

In this study we use a combination of 3D seismic data, well data and field analogues to detail the architecture of submarine basaltic volcanoes constructed in the Bass Basin, offshore southern Australia. These volcanoes are Miocene in age and were emplaced in a thermally subsiding rift basin. Our studies indicate that the volcanoes are composed of volcaniclastic rock such as hyaloclastite and pyroclasts, produced during effusive activity and magma-water interaction. These facies present a range of drilling complications, and may act as either seals, reservoirs or migration pathways. After their eruption, the volcanoes were encased in a sequence of claystones, and continued to focus subsurface fluid flow and sediment recycling for 20 Myr after their extinction. We conclude that basaltic volcanoes are important components of volcanic-affected basins. This study can be used to help recognise basaltic volcanoes in other data sets, and provide insights into their impacts on petroleum system.

Key words: volcanoes, petroleum, seismic interpretation

INTRODUCTION

Volcanoes link the extrusive and intrusive components of volcanic provinces and in-part determine their architecture (e.g. Valentine and Cortés 2013; Re *et al*., 2015). These components control the development of overlying reservoirs and can compartmentalise and metamorphose host sedimentary rock, as well as focusing fluid flow (e.g. Holford *et al*., 2012; Schofield and Jolley 2013; Rateau *et al*. 2013). Additionally, volcanoes can be used to identify structural trends, stratigraphic relationships and feeder systems that can be difficult to image in seismic data; thus providing insights into the subsurface geology. Volcanoes also have the potential to act as hydrocarbon reservoirs, since the volcaniclastic rocks of which many volcanoes are composed can have high permeabilities and porosities (e.g. Magara 2003). Volcaniclastic rocks also pose a challenge to drilling operations; they represent a potential cause of drilling fluid loss, and can cause drill bit and string sticking, as well as being prone to wash-out (Millett *et al*., in review).

However, the identification of volcanoes from seismic data is often challenging. Previous work has primarily focused on the intrusive components of volcanic systems (e.g. Thomson and Hutton 2004; Schofield *et al*., 2015) since these are easily distinguished from the surrounding sedimentary rocks. Volcanoes can be difficult to identify in regions affected by multiple episodes of volcanic activity (e.g. the Faroe-Shetland Basin), since the quality of seismic data is reduced beneath the uppermost basalt horizon (e.g. Jerram 2002). Furthermore, volcaniclastic rocks can have velocities lower than surrounding lavas (e.g. Planke and Eldholm 1994; Nelson *et al*. 2009). This produces an impedance contrast and causes a loss of seismic energy, making volcanoes difficult to distinguish from background "noise". Additionally, volcanoes display a wide variety of morphologies, some of which may be unresolvable due to their height and basal diameter being below the vertical resolution and line spacing of the seismic survey.

This study uses well and seismic data, in addition to field analogues, to describe the facies architecture of submarine basaltic volcanoes. These volcanoes are free from overlying basalt cover, making them ideal candidates to study. The location of the volcanoes in a thermally subsiding rift basin (the Bass Basin), offshore southern Australia, means that the volcanoes were rapidly buried by sediments and are preserved in a near pristine state. The volcanoes were drilled by the Bass and Yolla-1 wells, which were originally intended to test the hydrocarbon potential of a Miocene "reef complex" at a depth of 790 m. This reef complex was proven to be a volcano, as the Bass-1 well intersected a 185 m-thick sequence of volcanic rocks. The Yolla-1 well also intersected volcanic rock at a depth of 1237 m. This 68 m-thick sequence was interpreted to represent highly altered pyroclastics (Wheeler and Kjellgren 1986). We provide insights into how these volcanoes were constructed, their diagnostic seismic facies and show that the volcanoes focused subsurface fluid flow and sediment recycling for 20 Myr after their extinction.

METHOD

This study utilises 3D seismic data from the Yolla and Labatt surveys which were acquired in 1994 and 2008 respectively. The 525 km^2 Labatt survey has a bin size of 25 × 12.5 m (Tap Oil Ltd. 2008). The Yolla survey is smaller, covering 260 km^2 with a 12.5 × 25 m bin size (Boral Energy Resources Ltd. 1998).

The internal velocity of the volcanoes was calculated either from the thickness of pull ups beneath the edifices (see Magee *et al.*, 2013) or from Yolla-1 well data where pull ups were absent. Petrophysical data from the Yolla-1 and Cormorant-1 wells has been used to constrain seismic events. The Top Volcanic (TV) and Base Volcanic (BV) horizons were picked in the Labatt and Yolla surveys to allow investigation of the volcanoes.

RESULTS

The TV surface defines a series of volcanoes (Figure. 1) with volumes of ≤1.15 km^3. All volcanoes are roughly symmetrical in plan view and have flat-lying, concordant basal surfaces. They have heights of 0.12–0.50 km and diameters of 1.08–4.85 km. The volcanoes have craters ~380□950 m in diameter. Pull-ups beneath the volcanoes are typical of volcanic rocks within a sedimentary sequence (Jackson 2012; Magee *et al.* 2013). Using the thickness of the pull-ups, we show that the volcanoes have velocities that range between 2090–4025 m s^{-1}. These values are higher than that of sediments (commonly <3000 m s^{-1}; see Holford *et al.*, 2012), yet lower than that of lava flows (commonly 3300–6000 m s^{-1}; see Planke and Eldholm, 1994). This suggests that the volcanic material is dominantly fragmental (e.g. pyroclasts and hyaloclastite), consistent with cuttings descriptions from exploration wells (Wheeler and Kjellgren, 1986).

The seismic characteristics of the volcanoes are also typical of volcanic lithologies; they have high amplitude top reflections and reduce the quality of imaging beneath them (see Planke *et al*. 2000; Jerram 2002; Schofield and Jolley 2013). These volcanoes were emplaced in a shallow marine environment, as indicated by the transgressive sequence within which the edifices are found, and by biostratigraphic data.

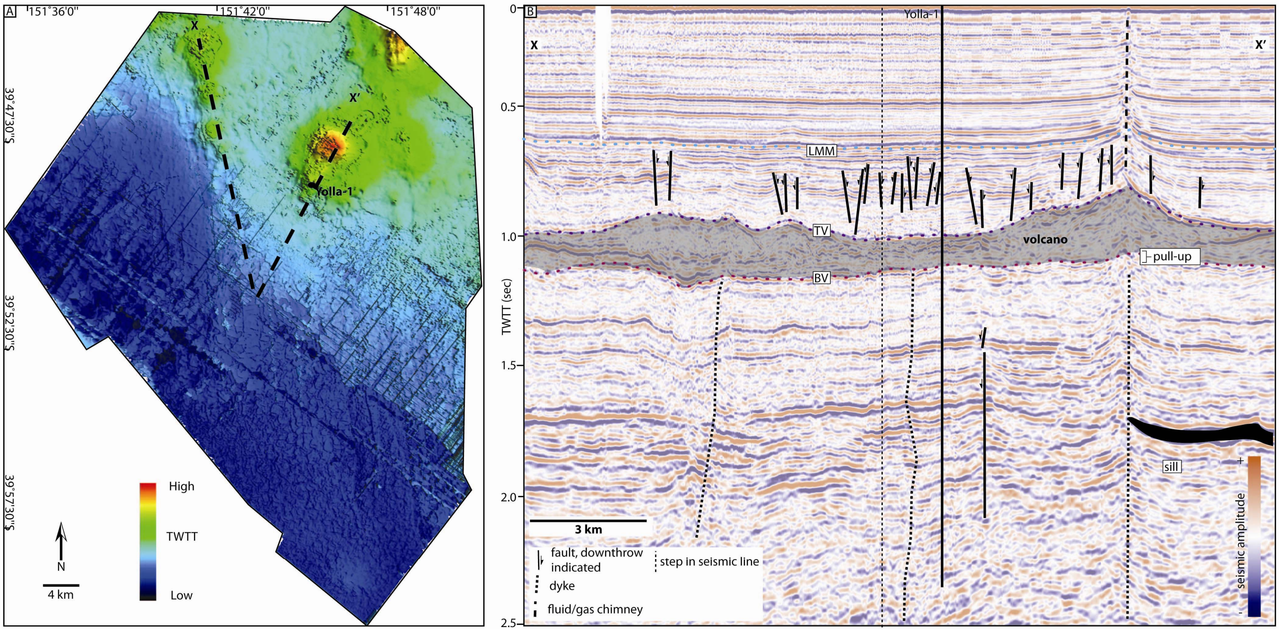

Figure 1. Time map (A) and seismic cross section (B) in the Yolla survey showing the volcanoes. LMM= Lower Mid Miocene, TV=Top Volcanic, BV=Base Volcanic.

Seismic facies

Three key seismic facies are identified within the volcanoes. These include hummocky, chaotic and planar reflections. The hummocky facies forms wedge-shaped bodies and are found within the flanks of the volcanoes. The reflections are moderate to low amplitude and vary from semi-continuous to continuous. They lap-out and are not truncated. We infer this facies represents low velocity, fragmental igneous rocks such as pillow lavas, hyaloclastite and/or pyroclastic rocks, which are common products of shallow submarine eruptions (e.g. Moore 1985). Similar volcanic facies are reported in basins elsewhere (e.g. Jerram *et al*., 2009). These reflections emanate from a source within the BV and grade outwards from a plug-like zone of chaotic facies. This facies is composed of low amplitude, discontinuous reflections. This plug-like zone is interpreted to contain numerous dykes intruded into the edifices (e.g. Moore, 1985), creating high velocity contrasts between fragmental and coherent igneous material.

The planar reflections are moderate to high amplitude with a sheet-like morphology. These are interpreted as high velocity, dominantly coherent submarine lava flows (Jerram *et al*., 2009) with a significant component of hyaloclastite. Hyaloclastite commonly has very variable grain size and vesicularity (e.g. Watton *et al*., 2013) resulting in variable amplitudes. The sheet-like morphology of the high and moderate amplitude planar facies may result from higher effusion rates relative to the hummocky facies (Batiza and White, 2000).

Interpretation of the volcanoes

The volcanoes are interpreted as monogenetic tuff cones (Reynolds *et al*., in review; see Figure 2) on the basis of their similar size and similar crater dimensions (White and Ross, 2011). Tuff cones are also composed of fragmental volcanic rock (e.g. tephra and hyaloclastite), consistent with the seismic facies and data from Yolla-1 which penetrated the flank of a volcano. Tuff cone-forming eruptions may effuse lava in the later stages (e.g. Moore, 1985) and the upper planar, high amplitude facies that typifies the volcanoes are interpreted as a carapace of lavas.

The volcanoes are distinguished from submarine hydrothermal vents based on their higher seismic velocities (2090–4025 m s^{-1} compared to 1800 m s^{-1} for hydrothermal vents; see Svensen *et al*., 2003); their lithology and seismic facies (cf. Planke *et al*. 2005).

Figure 2. Photograph of Surtsey erupting in 1963. This volcano is analogous to the tuff cones found in the Bass Basin. Notice the lavas in the foreground, which are inferred to have formed a protective carapace in our study. The emergent part of Surtsey is ~1.3 km in width. Photo credit: Garðar Pálsson.

Influence of the volcanoes petroleum systems

Volcaniclastic rocks such as those documented herein can potentially be a major cause of catastrophic drilling fluid loss. They can also cause drill bit and string sticking and are prone to wash-out (Millett *et al*., in review). Furthermore, hyaloclastite (represented by the hummocky and moderate amplitude planar facies) can have permeabilities up $10.13e^3$ Darcies, or can act as a seal if heavily altered (Millett *et al*., in review). Since volcanoes are located above the tips of intrusive systems, which can act as barriers or conduits to fluid flow (e.g. Holford *et al*., 2012; Rateau *et al*., 2013), the volcanoes may act as either an extension of the underlying fluid pathway, or as a seal to upwards-migrating fluids (e.g. Figure. 3).

We also highlight the importance of the volcanoes permeability relative to the sediments which encase it. The Yolla volcanoes are overlain by a sequence of polygonally faulted calcareous claystones that reaches a thickness of ~400 m. Spectral decomposition of the top of the claystone sequence reveals a number of branching lobes, interpreted as the deposits of sedimentary density currents (Holford *et al*., in review). These originate from a subcircular conduit. The conduit and the flows are reminiscent of the mud volcanoes found in the North Sea (Andresen *et al*., 2010). We suggest the mudflows are derived from remobilized claystones, and liquefaction was caused by later release of hydrothermal fluids associated with sill intrusion or by tectonic inversion accompanied by the development of significant fluid overpressures.

Above the mud volcano and Yolla volcano is a ~700 m high, near-vertical zone of disrupted reflections forming a pipe-like structure. A series of amplitude time slices through the mid-Miocene-Recent section confirm this spatial alignment and show that this structure possesses a circular planform (maximum diameter ~625 m) and extends to the sea floor. We speculate that the pipe formed when highly pressured fluids and gases originating from deeper parts of the basin exploited the existing fluid pathway comprising the mud and igneous volcanic complexes (Holford *et al*., in review).

Thus, the claystones overlying the Yolla volcano are interpreted to have acted as a low-permeability sealing sequence, forming a barrier to the vertical migration of pressured fluids and/or gases expelled from deeper levels within the basin during mid-Miocene magmatism or inversion. Although this claystone sequence contains a pervasive network of polygonal faults, such faults are commonly found in high-quality sealing sequences with extremely low permeabilities (i.e. $<10^{-17}$ m^{-1}; Cartwright *et al*., 2007). This implies that the pressured fluids and gases are likely to have preferentially exploited and been focused by internal fractures or permeable pathways within the Yolla volcano, or along its margins by lateral pressure transfer (e.g. Figure. 3).

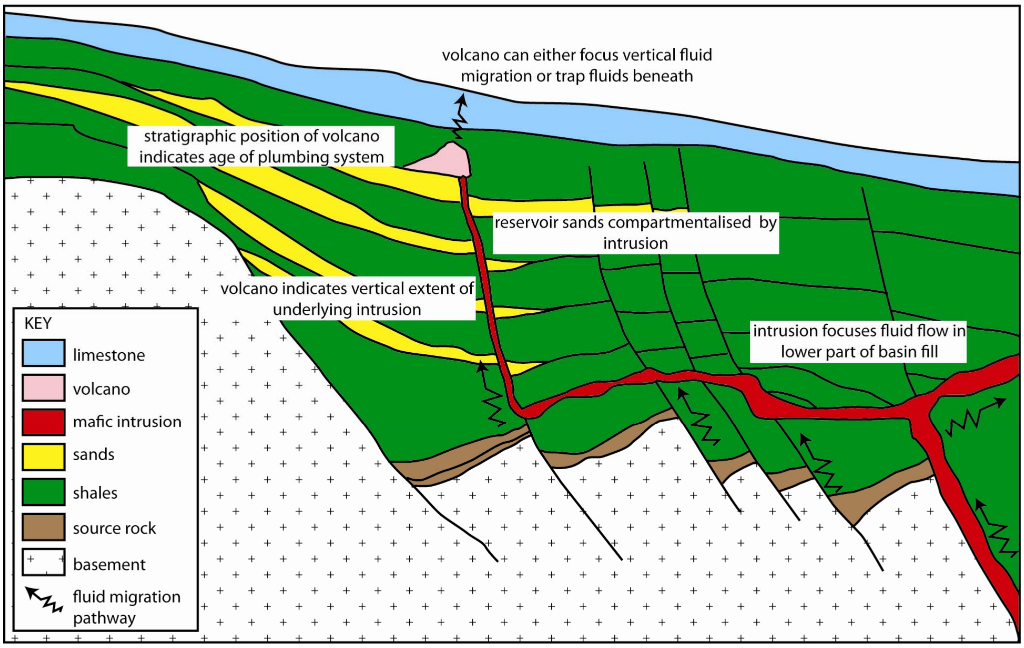

Figure 3. Schematic diagram showing the importance of volcanoes in hydrocarbon basins. The volcanoes indicate underlying intrusive complexes, which compartmentalise the basin. The volcanoes may serve as an extension of the fluid flow system, either facilitating upwards movement of fluid through permeable pore networks and fractures, or retarding fluid flow when the component volcaniclastic rocks are heavily altered. The scale of the intrusion and volcano are schematic. Adapted from Holford *et al*., 2012.

CONCLUSIONS

Volcanoes are important components of volcanic provinces and pose a range of challenges to petroleum explorers. This study has provided insights into the architecture of submarine basaltic volcanoes found offshore southern Australia. The volcaniclastic rocks of which they are composed have very variable petrophysical properties, suggesting the volcanoes can act as either permeable pathways, seals or reservoirs within hydrocarbon systems. Since the volcanoes overly the magmatic plumbing system, the volcanoes may act as an extension to underlying fluid pathways, or else as a seal to upwards migrating fluids. We also highlight that volcanoes can effect fluid flow and sediment recycling in sedimentary basins long after their burial. This study can be used to help recognize basaltic volcanoes in other data sets, and assess the impacts of volcanism on hydrocarbon systems.

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