Tectono-magmatic evolution of the Browse Basin, North West Shelf: Insights for hydrocarbon exploration in igneous provinces

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SUMMARY

Continental margins often undergo complex geological histories, including multiple rift phases, igneous activity, and drastic changes in their sedimentary environments. To succeed in hydrocarbon exploration in such areas, it is necessary to conduct integrated geological investigations to deeper understand their tectonic, magmatic, and sedimentary evolution.

The focus of this study is the Browse Basin, which is a typical rifted continental margin basin located on the Australian North West Shelf. There is active exploration for Jurassic and Cretaceous sandstone reservoirs in this basin, and over 20 hydrocarbon discoveries have been made in past decades. Although this basin is highly prospective, severely faulted reservoirs and the unpredictable distribution of igneous rocks are recognised as major risks for both exploration and field development in this area.

This study investigates the basin-wide record of Mesozoic tectonism and igneous events by integrating multiple subsurface datasets including regional 2D and 3D seismic surveys, logs from exploration/appraisal wells, and regional gravity and magnetic data. We evaluated basin architecture, the distribution of intrusive and extrusive rocks, the petrological characteristics of igneous and sedimentary rocks, and their correlation to seismic facies. A series of Mesozoic paleo-environmental maps illustrate transitions of tectono-magmatic activities through geological time.

Our evaluation suggests that Early to Middle Jurassic rifting exerted the major control on tectonic and magmatic activity in this basin. This event activated NE-SW trending faults and generated significant volumes of igneous rocks across the basin, in particular along the western outboard area, which influenced the distribution of sandstone reservoirs. During the Lower Cretaceous, the focus of faulting and volcanic activity shifted towards the northern part of the basin, forming a series of submarine volcanoes. The outcomes of this study will contribute to future exploration and field development planning in the Browse Basin.

Key words: igneous rocks, magmatism, tectonics, rifted margins, Browse Basin

INTRODUCTION

The Browse Basin is located in the centre of the Australian North West Shelf, which formed by continental breakup between Australia and Greater India during the Mesozoic (Stephenson and Cadman, 1994; Blevin et al., 1998; Barber 2013). This rift basin is a major exploration target, and a number of significant hydrocarbon discoveries have been made within the Jurassic Plover Formation and the Lower Cretaceous Upper Vulcan Formation in recent decades (Bradshaw et al., 1994; Longley et al., 2002). The development of Cretaceous reservoirs of the Ichthys and Prelude fields have successfully led to production of liquified natural gas (LNG) and condensate from 2018, comprising nearly 15% of the cumulative Australian LNG production in 2019-2020 (Department of Industry, Science and Resources, 2022).

Despite recognised resource potential, the prolific occurrence of igneous rocks has hindered further developments for the Jurassic strata. Many exploration wells, particularly those sited along the western outboard of the basin, failed due to unexpected or thicker than expected igneous rock units, resulting in the absence of anticipated siliciclastic reservoirs. Buffon-1/ST1, drilled by Woodside in 1980, encountered nearly 500 m of altered basalt overlying 193 m of volcaniclastics (Symonds et al., 1998). Argus-1 and Maginnis-1/1A, both drilled by BHP in 2000 and 2002, did not intersect the siliciclastic reservoir of the Plover Formation but instead confirmed 178 m and 483 m of volcanic sequences respectively (Locke, 2001; Locke, 2003). More recently, Karoon Gas penetrated over 1,100 m of Middle Jurassic volcanic lithologies with minor interbedded siltstone in the Grace-1exploration well in 2013, failing to reach the primary objective (Steel and O'Neil, 2015).

In addition to exploration failure, it has been suspected that igneous rock units may inhibit fluid flow, which is critical during hydrocarbon production (Rateau et al., 2013). The pressure transient analyses of the Ichthys wells indicate the presence of multiple flow barriers near to wellbores. Whilst the Jurassic strata are intruded by an abundance of dykes and sills (Symonds et al., 1998; Holford et al 2013), there is a high chance of igneous bodies acting to cause reservoir compartmentalisation (Yamamoto et al., 2020). Given these intrusive rock units are relatively thin and steeply-dipping, this poses difficulties for seismic imaging and interpretation, resulting in large uncertainties for field development planning in this basin.

Many publications have reported on the occurrence of igneous rocks in the Browse Basin (Blevin et al., 1997; Struckmeyer et al., 1998; Symonds et al., 1998; Holford et al., 2013; Tovaglieri et al., 2013; Rollet et al., 2016). However, to date the evaluation of rock types (e.g. intrusive, extrusive, volcaniclastic), their basin-wide distribution and their relationship to the tectono-stratigraphy of the basin have not been systematically addressed. The aim of this study therefore, is to place the Mesozoic magmatic evolution of the Browse Basin in a tectonic context by integrating available subsurface datasets to, in turn, suggest new implications for both exploration and field development.

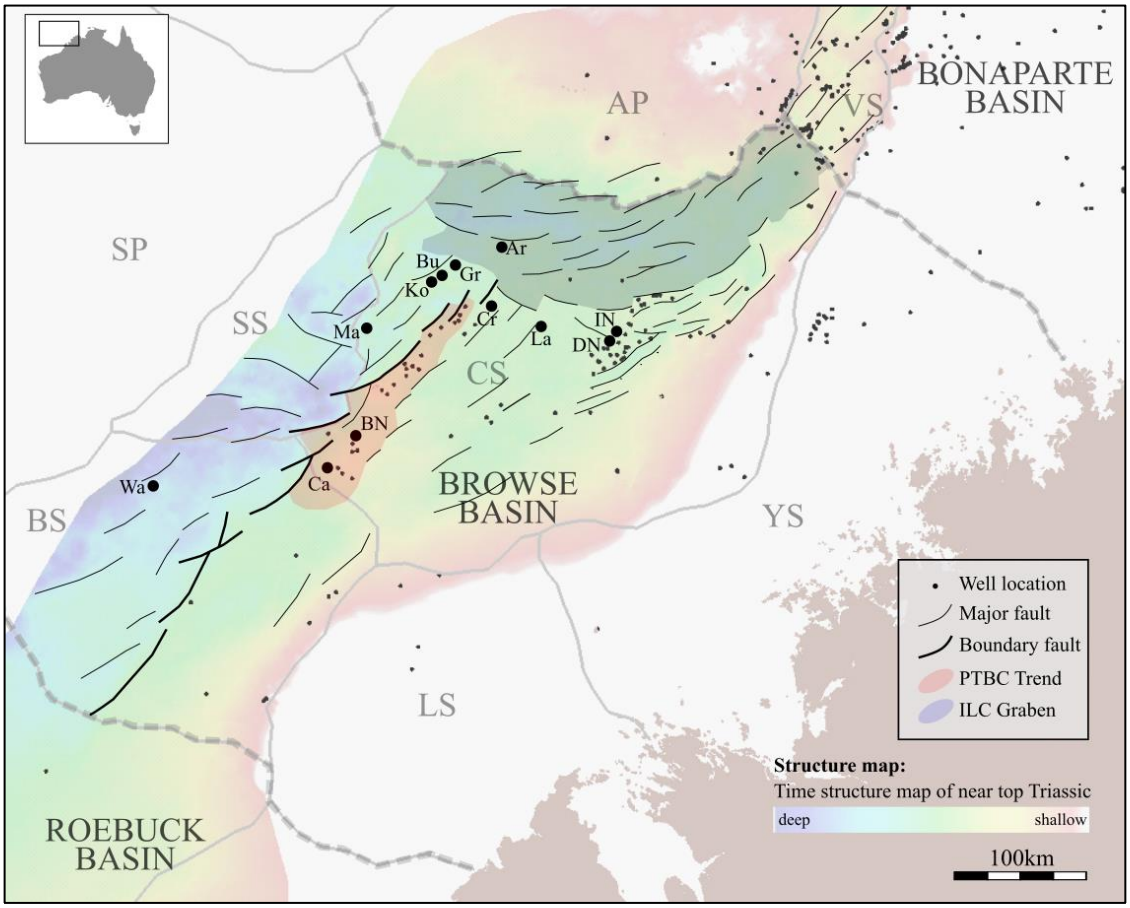

Figure 1. Location map of the study area. AP – Ashmore Platform; BS – Barcoo Sub-basin; CS – Caswell Sub-basin; LS – Leveque Shelf; SP – Scott Plateau; SS – Seringapatam Sub-basin; VS – Vulcan Sub-basin; YS – Yampi Shelf; Ar – Argus-1; BN – Brecknock-4; Bu – Buffon-1; Ca – Calliance-3; Cr – Crown-1; DN – Dinichthys North-1; Gr – Grace-1; IN – Ichthys North-1; Ko – Kontiki-1; La – Lasseter-1; Ma – Maginnis-1; Wa – Warrabkook-1.

STRUCTURAL FRAMEWORK AND CHARACTERISATION OF IGNEOUS ROCKS

In order to investigate structural evolution during Mesozoic rifting and the relationship with magmatic activity, the regional tectonic framework of the Browse Basin was examined using 2D/3D seismic data, and regional gravity and magnetic survey data. We interpreted six horizons in the seismic time domain that range in age from the Upper Triassic to the Late Cretaceous, as well as regional faults present throughout the Browse Basin, partially extending to the northern part of the Roebuck Basin. Thickness maps of each geological interval were mapped to observe fault growth history. Our interpretation reveals that extensional episodes during the Late Triassic to the Middle Jurassic activated a series of NE-SW trending regional faults and grabens along the North West Shelf. This tectonic event triggered the development of a boundary fault between the basin centre (the Caswell Sub-basin) and the outboard part of the basin (the Seringapatam and the outer Barcoo Sub-basin). This separated the structural high trend of the Poseidon, Torosa, Brecknock and Calliance fields (PTBC Trend) and created an elongated accommodation space along the western side of the basin where sedimentary and igneous rocks deposited or emplaced during the Early to Middle Jurassic. The maximum thickness accommodated possibly reaches five kilometres near the Warrabkook-1 well, as this package exceeds two seconds in two-way-time in seismic data. Previous studies suggest this regional tectonism resumed in the latest Triassic (Rhaetian) and continued until the Early Cretaceous, leading to successive breakup of the Lhasa block, Argoland, and Greater India (Longley et al., 2002; Gibbons et al., 2012; Barber 2013; Gartrell et al., 2022). Our study also indicates that the locus of deformation initiated in the southern part of the study area (the Roebuck Basin to the Barcoo Sub-basin) in Late Triassic-Early Jurassic, propagating towards the north (Seringapatam Sub-basin and the Ashmore platform) in later Jurassic times. Interestingly, a discrete active fault pattern was observed in the Lower Cretaceous interval thickness map, which indicates development of east-west trending grabens, extending from north of the Ichthys Field towards the Lasseter and Crown fields (ILC Graben), raising the possibility of a distinct rifting stage with a different stress regime from the Jurassic time.

In order to evaluate the igneous rocks in the region, we reviewed well completion reports, observed seismic facies, and interpreted paleo-environmental maps over the basin. Although we find that magmatic activity continued sporadically throughout the Mesozoic, the Lower to Middle Jurassic interval hosts the main pulse of igneous lithologies of various rock types: intrusive, extrusive, and volcaniclastic. We undertook detailed interpretations for several key wells to classify igneous facies and petrophysical properties using conventional wireline log and FMI data.

In the outboard region of the basin, the Lower to the Middle Jurassic interval is characterised by thick volcanic sequences (e.g. >447 m in Warrabkook-1, >320 m in Kontiki-1, and >1,177 m in Grace-1), mainly consisting of accumulations of tabular or compound basaltic lava flows interbedded with thin shale layers, and often accompanied by pillow lavas and hyaloclastites which can be identified from FMI logs. The lava layers have velocities in the range of 4.0-6.5 km s^{-1} and densities of 2600-3000 kg m^{-3}, and are characterised by chaotic and rather ‘transparent’ (low primary signal) seismic facies in the intervals corresponding to stacked lava flows but are associated with series of strong reflectors once interbedded with parallel shaly beds (<3.5 km s^{-1} and <2700 kg m^{-3}). Although the seismic facies of these igneous intervals are highly heterogeneous spatially, the overall Jurassic interval appears as a large package with the geometry of a clinoform dipping towards west from the central Seringapatam Sub-basin (near Maginnis-1), thickening towards the Barcoo Sub-basin (Warrabkook-1 area) and extending down to the northern Roebuck basin. Our evaluation of igneous and seismic facies designates that the western boundary fault of the PTBC Trend played a major role in the Early to Middle Jurassic rifting where dynamic tectonic, magmatic, and depositional processes occurred under a marine influenced environment.

In contrast, igneous rocks in the central part of the basin (the Caswell Sub-basin) are commonly found within more terrigenous sedimentary facies (e.g. coal beds). They often occur as strongly altered volcaniclastic sediments, which are observed in cores such as the Calliance-3, Brecknock-4, Dinichythys North-1, where it is rare to observe stacks of unaltered lava flows. These weathered and redeposited igneous rocks have a wide range of acoustic velocity and density values (3.0-5.0 km s^{-1} and 2200-2700 kg m^{-3}), which overlaps with the properties of the hosting sedimentary rocks, therefore making it extremely difficult to distinguish them on seismic data.

While Jurassic magmatism is extensive and complex, activity during the Lower Cretaceous seems to have been more spatially restricted. Weathered basalts have been confirmed in Ichthys North-1 (100 m), Minuet-1 (78 m), Ichthys Deep-1 (8.5 m) and Torosa-1 (7 m), concentrated along the ILC Graben and the PTBC Trend. A series of buried volcano-like structures can also be found at the northern part of the basin. Palynological data from Ichthys North-1, which penetrates one of these mound structures, indicate that the altered volcanic rocks occur within a marine shale deposit under a shelfal to slope environment, implicating the volcanic activity occurred as submarine eruptions.

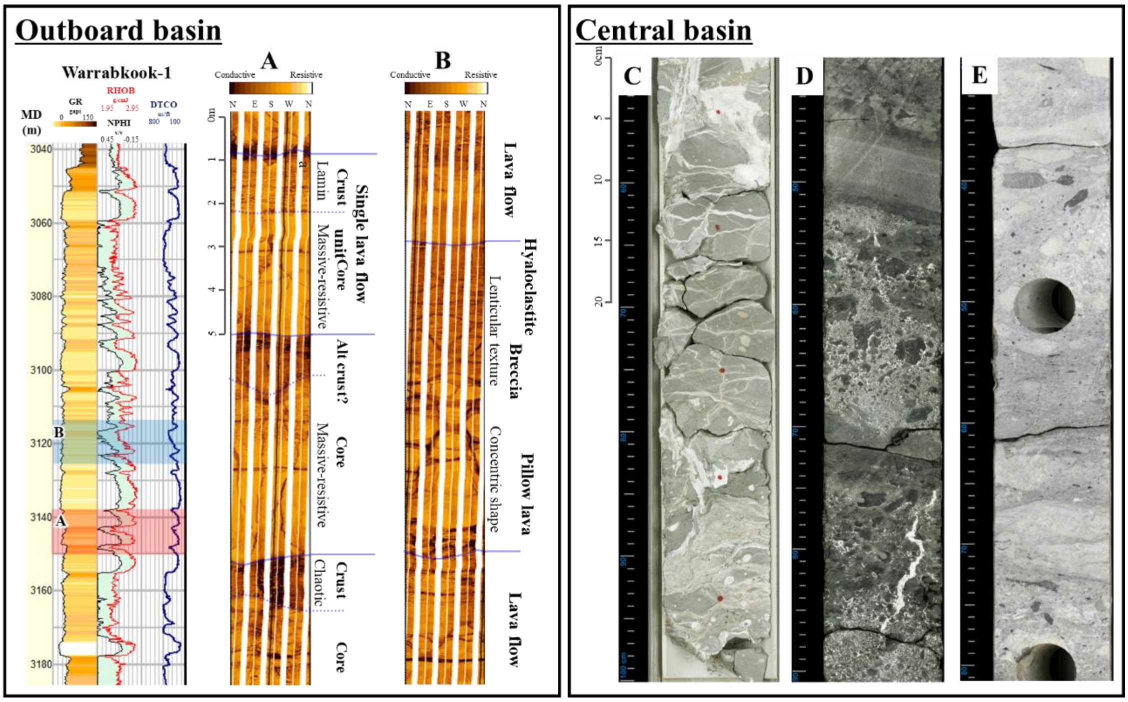

Figure 2. Typical igneous rock facies of the outboard basin and central basin areas. A – FMI image of tabular lava flow from Warrabkook-1 (3138-3150m); B – FMI image of pillow lava and hyaloclastite from Warrabkook-1 (3114-3120m); C – Core photo of altered volcaniclastics with flow structure and vesicles (Calliance-3, 4003.5-4004.0m); D – Core photo of brecciated volcanics overlain by fine grained basalt (Brecknock-4, 34904.4-3903.9m); E – Core photo of volcaniclastic debris with tuffaceous matrix (Dinichthys North-1, 4518.3-4518.8m).

IMPLICATIONS FOR EXPLORATION, DEVELOPMENT AND THE FEASIBILITY OF CCS

Our study provides a basin-wide framework of Mesozoic magmatism in the Browse Basin within a tectono-stratigraphic context. These new insights into the tempo, distribution and nature of the magmatic systems in this area will be beneficial for future exploration, field development and the assessment of CCS feasibility within the basin. For instance, when investigating the prospectivity of Jurassic sequences, NE-SW trending faults should be carefully examined. They represent syn-depositional faults that influence reservoir distribution, and moreover, might have provided pathways for intrusions that may cause reservoir compartmentalisation or degradation. There are many undrilled structures within the thick Jurassic interval in the outboard basin, however the thick sequences of igneous rocks introduced into this region during the Early to the Middle Jurassic represent a major risk to the presence and integrity of conventional reservoir rock. Our study also emphasises the importance of understanding the petrophysical and seismic properties of subsurface igneous rocks. Recognition of the occurrence of igneous rock types (e.g. lava flow, intrusive dykes, volcaniclastics), coupled with their likely degree of alteration and their rock physical characteristics, can help to improve subsurface interpretations that enhance the efficiency of identification of igneous intervals that are otherwise often overlooked in well log and seismic datasets. Major challenges still remain for identifying sub-seismic-scale igneous bodies and near-vertical dykes. However, the risks associated with them can be mitigated by integrated studies that highlight their occurrence and therefore identify the prospective and risky provinces within a basin.

CONCLUSION

The Browse Basin underwent a series of rift episodes during the Mesozoic in response to continental breakup between Australia and Greater India. During the Early to Middle Jurassic, the Australian North West Shelf was subject to extensional deformation, which created a series of NE-SW trending normal faults within the Browse Basin. This episode triggered movement of a boundary fault along the PTBC Trend where extrusive and intrusive igneous rocks were introduced along the outboard basin. Igneous activity was also intense in the basin centre, however, most of the extrusive rocks were weathered, redeposited or eroded under a terrestrial environment resulting as localised distributions. In the Lower Cretaceous, change in the regional stress regime deformed the northern part of the sedimentary basin, displacing the ILC Graben and extending it towards the Vulcan Sub-basin. In response to this extensional event, submarine eruptions occurred in the northern part of the basin (e.g. in Ichthys North-1 area). Our study provides deeper understanding of both regional structure and magma dynamics that will enhance the delineation of prospective fairways and mitigate unexpected risks for future exploration and production activities within the Browse Basin.

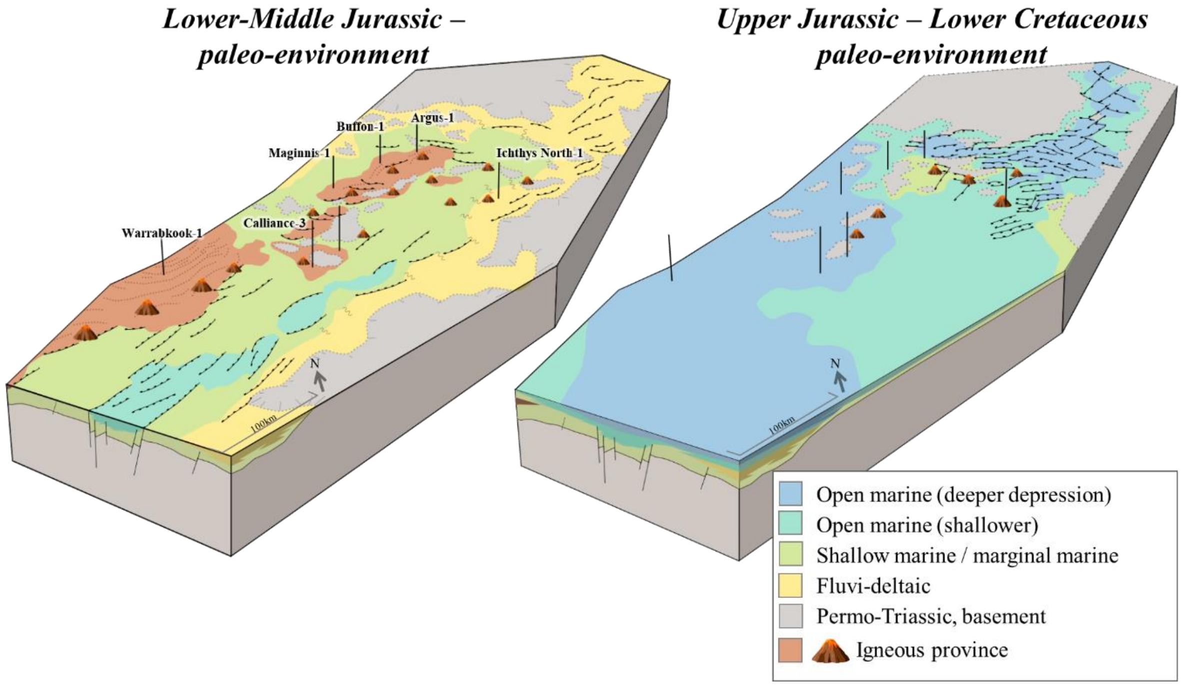

Figure 3. Interpreted paleo-environment and volcanic provinces of the Browse Basin

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