The spatial distribution of igneous intrusions in the Exmouth Plateau and Exmouth Sub Basin, North West Shelf, Western Australia.

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SUMMARY

The North West Shelf of Australia is a volcanic rifted margin. Jurassic-Cretaceous breakup of Gondwana resulted in the intrusion of significant volumes of igneous material into sediments of the Northern Carnarvon Basin. The last major review of the regional distribution of this intrusive material was published over 20 years ago. Since, there have been major advances in the understanding of intrusions in sedimentary basins, and step changes in the quality of 3D and reprocessed 2D seismic data available in Northern Carnarvon basin.

We present preliminary findings of a new study building on these advances that investigates the regional spatial and temporal distribution of intrusions in the basin and the impact of this magmatism on petroleum systems. In this paper, we have mapped plumbing systems of intruded igneous complexes, interpreted on 3D surveys within the Exmouth Sub-basin, and on the Exmouth Plateau.

Within the study area we see (1) typical 'saucer shaped', and 'stepped' intrusion geometries; (2) intrusions exploiting faults and cross cutting stratigraphy as they rise to the surface; (3) interconnected intrusions, forming continuous magmatic plumbing systems >50km in length; (4) intrusions mainly present within in the Triassic Mungaroo Formation, and (5) intrusions possibly sourced from a hotspot that was located beneath the current Cape Range Fracture Zone during breakup.

Key words: Intrusions, Northern Carnarvon Basin, Petroleum Systems, Seismic.

INTRODUCTION

The rifted NW continental margin of Australia formed as a result of Gondwanan breakup between Greater India and Australia during the Jurassic-Cretaceous. Continental breakup initiated along the Argo Margin c. 155 Ma (Oxfordian), then later progressed westwards and then southwards along the Gascoyne, Cuvier and Perth margins from c. 131-136 Ma (Valanginian) (Fullerton et al., 1989, Veevers et al., 1991, Müller et al., 1998). The North West Shelf of Australia is often cited as a 'classic' volcanic rifted margin, as defined by White and McKenzie (1989). Thick igneous sequences are present in sedimentary basins throughout the margin. In the Roebuck Basin, recent wells Hannover South 1 and Anhalt 1 in the Roebuck Basin penetrated extensive thickness of extrusive volcanics. The Jurassic Plover formation in the Browse Basin contains lava flows and tuff deposits proximal to the Ichthys Field gas reservoirs, whilst Buffon 1 intersected 489m of lava flows above 193 m volcaniclastic material (Symonds et al., 1998).

There is much evidence for breakup-related intrusive and extrusive magmatism in the southern part of the North West Shelf. In the Exmouth Sub-basin of the Northern Carnarvon Basin, Yardie East 1 encountered over 20 intrusions ranging in thickness from 3 to 10 m in Late Triassic and Jurassic sediments. Palta 1 intersected a 95 m thick weathered intrusion intruded into Late Jurassic sediments. Toro 1 intersected c. 190 m of volcaniclastic rock from depths below 2625 m. Other wells including Stybarrow 2, Enfield 3 & 4, and ODP Site 763 (on the adjacent Exmouth Plateau) intersect weathered clays interpreted as tuffaceous ashfall deposits. The locations of these wells are shown on Figure 1.

On the Exmouth Plateau and within the Exmouth Sub-basin, Frey et al. (1998), Symonds et al. (1998) and Rey et al. (2008) interpreted regional 2D seismic reflection data, defining broad geographic domains of rift related igneous rocks. The intrusion outlines of Frey et al. (1998), highlighted on Figure 1, form the basis of the current understanding of the distribution of igneous intrusions on the Exmouth Plateau and in the Exmouth Sub-basin.

There has been little subsequent work in further regional-scale definition of intrusions in the basin over the past 20 years, despite:

- Considerable conceptual advances in the understanding of emplacement mechanisms, intrusion morphologies, and the impact of igneous intrusions in sedimentary basins, primarily driven by recent research in the Faroe Shetland Basin, offshore Scotland (e.g. Smallwood and Maresh, 2002, Hansen et al., 2011, Grove, 2013, Schofield et al., 2017, Mark et al., 2018).

- The availability of modern high resolution 3D and re-processed 2D seismic reflection data covering the intruded domains of the Exmouth Sub-basin and Exmouth Plateau.

These advances now allow for the igneous intrusions to be accurately mapped in three dimensions. Work that has been completed more recently (e.g. Magee et al., 2013a, Magee et al., 2013b, McClay et al., 2013, Magee et al., 2017) has focussed mainly on the emplacement dynamics and structures associated with individual intrusions. Hence, we have commenced a new study investigating the regional spatial and temporal distribution of intrusive magmatic activity in the Northern Carnarvon Basin. The focus of this presentation is on the initial results of this study, which document the distribution and morphologies of igneous intrusive plumbing systems within several 3D seismic datasets across the Exmouth Sub-basin and western Exmouth Plateau.

Knowledge of the spatial and temporal distribution of igneous intrusions is important for companies exploring for hydrocarbons in the Northern Carnarvon Basin, as their presence can have a significant impact on the development of petroleum systems. The maturation history of source rocks can be affected (Monreal et al., 2009, Aarnes et al., 2015), reservoir rocks compartmentalised (Holford et al., 2013), and seals breached (Senger et al., 2013). In addition, fractured intrusions can act as a conduit for the transfer of overpressure from deeper to shallower horizons, presenting a significant drilling hazard (Mark et al., 2018).

METHOD AND RESULTS

The data for this study predominantly comprises 3D seismic reflection surveys accessed through the National Offshore Petroleum Information Management System (NOPIMS), whose spatial distribution corresponds with the extent of igneous intrusions as defined by Frey et al. (1998). We undertook seismic interpretation in Petrel. We applied the concepts of seismic facies analysis (Vail and Mitchum Jr, 1977) to identify discrete, mappable groups of seismic reflections representing intrusions. We identified reflections as intrusions in the manner of Planke et al. (2005), noting their characteristic high amplitude, their transgression of stratigraphy, their stepped and saucer shape, and their abrupt termination; the cumulative recognition of each of these characteristics increasing the probability of the reflection representing an intrusion. We interpreted the intrusions as horizons using a combination of manual picking, 2D autotracking and 3D autotracking. We interpreted each survey systematically, firstly interpreting intrusions, then key stratigraphic units (constrained with biostratigraphic information from wells), and then faults. We generated 3D surfaces, which were plotted on a map.

The preliminary results of this study from the analysis of intrusions observed in regional 2D seismic reflection lines and the Coverack, Charon, Bonaventure and Scarborough 3D seismic reflection surveys are:

- Magmatic plumbing systems are present as interconnected systems of intrusions (e.g. Figure 2). The system in the Bonaventure 3D Survey is 50 km in length, and continues beyond the survey bounds.
- It appears that magma that was transported through the intrusions is predominantly sourced from the West on the Exmouth Plateau, and from the North and West in the Exmouth Sub-basin.
- Intrusions have various morphologies: e.g. classic ‘saucer’ shaped, stepped (rising through, and cross cutting stratigraphy), and are often interconnected and interacting with one another.
- Intrusions interact with geological structure, often progressing sub-vertically along normal faults, and exploiting bedding planes. Fault exploitation is especially apparent in the Coverack 3D Survey.
- The path of intrusions is also influenced by lithology. They are emplaced along the path of least resistance. They are more likely to intrude along softer rock types (e.g. sands, fractured coals) than those that are very dense (e.g. shale).
- Most intrusions in the study have been are emplaced within the Triassic Mungaroo Formation.

For example, Figure 2 shows a magma plumbing system we interpreted in the Charon Survey, on the Exmouth Plateau. There are two interconnected intrusions, (A) and (B), present over c. 25 km^2. Intrusions (A) and (B) share the same plumbing system, which is likely sourced from the South West. The magma cross-cut stratigraphy as it rose vertically. Intrusion A is a typical saucer shaped intrusion, relatively flat in its centre, with magma fanning out upwards in all directions prior to termination.

CONCLUSIONS

From these preliminary results we can infer:

- Through the Early Cretaceous, a significant volume of igneous material was injected into the upper crust during continental rifting and subsequent breakup along the volcanic Gascoyne margin.
- The direction of magma transport is consistent with magma being sourced from partial melting induced by a hot spot present at the time of breakup, located in the vicinity of the Cape Range Fracture Zone as proposed by (Rohrman, 2013). This supports the hot spot theory initially put forth by White and McKenzie (1989), further supported by Rohrman (2015).
- The mechanisms of emplacement and resulting morphologies of intrusions are similar to those imaged on other volcanic rifted margins around the world, e.g. the Faroe Shetland Basin (Hansen et al., 2011, Schofield et al., 2017), and the South China Sea (Sun et al., 2014).

The results presented here are the first stage of an integrated basin-wide study that will pave the way for a regional understanding of the spatial and temporal distribution of magmatism, and of the basin-scale impacts this significant volume of emplaced igneous material has had on the evolution of petroleum systems in the North Carnarvon Basin.

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REFERENCES

Aarnes, I., Planke, S., Trulsvik, M. & Svensen, H. 2015. Contact metamorphism and thermogenic gas generation in the Vøring and Møre basins, offshore Norway, during the Paleocene–Eocene thermal maximum. Journal of the Geological Society, 172, 588-598.

Frey, Ø., Planke, S., Symonds, P. A. & Heeremans, M. 1998. Deep crustal structure and rheology of the Gascoyne volcanic margin, Western Australia. Marine Geophysical Researches, 20, 293-311.

Fullerton, L. G., Sager, W. W. & Handschumacher, D. W. 1989. Late Jurassic-Early Cretaceous evolution of the eastern Indian Ocean adjacent to northwest Australia. Journal of Geophysical Research: Solid Earth, 94, 2937-2953.

Grove, C. 2013. Submarine hydrothermal vent complexes in the Paleocene of the Faroe-Shetland Basin: Insights from three-dimensional seismic and petrographical data. Geology, 41, 71-74.

Hansen, J., Jerram, D. A., Mccaffrey, K. & Passey, S. R. 2011. Early Cenozoic saucer-shaped sills of the Faroe Islands: an example of intrusive styles in basaltic lava piles. Journal of the Geological Society, 168, 159-178.

Holford, S., Schofield, N., Jackson, C.-L., Magee, C., Green, P. & Duddy, I. 2013. Impacts of igneous intrusions on source reservoir potential in prospective sedimentary basins along the western Australian continental margin.

Magee, C., Briggs, F. & Jackson, C. A. L. 2013a. Lithological controls on igneous intrusion-induced ground deformation. Journal of the Geological Society, 170, 853-856.

Magee, C., Jackson, C. A. L., Hardman, J. P. & Reeve, M. T. 2017. Decoding sill emplacement and forced fold growth in the Exmouth Sub-basin, offshore northwest Australia: Implications for hydrocarbon exploration. Interpretation, 5, SK11-SK22.

Magee, C., Jackson, C. A. L. & Schofield, N. 2013b. The influence of normal fault geometry on igneous sill emplacement and morphology. Geology, 41, 407-410.

Mark, N. J., Schofield, N., Pugliese, S., Watson, D., Holford, S., Muirhead, D., BROWN, R. & HEALY, D. 2018. Igneous intrusions in the Faroe Shetland basin and their implications for hydrocarbon exploration; new insights from well and seismic data. Marine and Petroleum Geology, 92, 733-753.

Mcclay, K., Scarselli, N. & Jitmahantakul, S. 2013. Igneous Intrusions in the Carnarvon Basin, NW Shelf, Australia. West Astralian Basins Symmposium.

Monreal, F. R., Villar, H., Baudino, R., Delpino, D. & Zencich, S. 2009. Modeling an atypical petroleum system: A case study of hydrocarbon generation, migration and accumulation related to igneous intrusions in the Neuquen Basin, Argentina. Marine and Petroleum Geology, 26, 590-605.

Müller, R. D., Mihut, D. & Baldwin, S. 1998. A new kinematic model for the formation and evolution of the west and northwest Australian margin. The sedimentary basins of Western Australia, 2, 55-72.

Planke, S., Rasmussen, T., Rey, S. S. & Myklebust, R. Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. Geological Society, London, Petroleum Geology Conference series, 2005. Geological Society of London, 833-844.

Rey, S. S., Planke, S., Symonds, P. A. & Faleide, J. I. 2008. Seismic volcanostratigraphy of the Gascoyne margin, Western Australia. Journal of Volcanology and Geothermal Research, 172, 112-131.

Rohrman, M. 2013. Intrusive large igneous provinces below sedimentary basins: An example from the Exmouth Plateau (NW Australia). Journal of Geophysical Research: Solid Earth, 118, 4477-4487.

Rohrman, M. 2015. Delineating the Exmouth mantle plume (NW Australia) from denudation and magmatic addition estimates. Lithosphere, 7, 589-600.

Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., Passey, S. R., Muirhead, D., Grove, C., Magee, C., Murray, J., Hole, M., Jackson, C. A. L. & Stevenson, C. 2017. Regional magma plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within sedimentary basins. Basin Research, 29, 41-63.

Senger, K., Roy, S., Braathen, A., Buckley, S. J., Bælum, K., Gernigon, L., Mjelde, R., Noormets, R., Ogata, K. & Olaussen, S. 2013. Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO2 sequestration. Norwegian Journal of Geology, 93, 143-166.

Smallwood, J. R. & Maresh, J. 2002. The properties, morphology and distribution of igneous sills: modelling, borehole data and 3D seismic from the Faroe-Shetland area. Geological Society, London, Special Publications, 197, 271-306.

Sun, Q., Wu, S., Cartwright, J., Wang, S., Lu, Y., Chen, D. & Dong, D. 2014. Neogene igneous intrusions in the northern South China Sea: Evidence from high-resolution three dimensional seismic data. Marine and Petroleum Geology, 54, 83-95.

Symonds, P., Planke, S., Frey, O. & Skogseid, J. 1998. Volcanic Evolution of the Western Australian Continental Margin and its Implications for Basin Development. In: PURCELL, P. P., RR; (ed.) The Sedimentary Basins of West Australia 2. Perth: West Australin Basins Symposium.

Vail, P. & Mitchum Jr, R. 1977. Seismic Stratigraphy and Global Changes of Sea Level: Part 1. Overview. American Association of Petroleum Geologists, 26, 21-52.

VEEVERS, J., POWELL, C. M. & ROOTS, S. 1991. Review of seafloor spreading around Australia. I. Synthesis of the patterns of spreading. Australian journal of earth sciences, 38, 373-389.

White, R. & Mckenzie, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts.

Journal of Geophysical Research: Solid Earth, 94, 7685-7729.

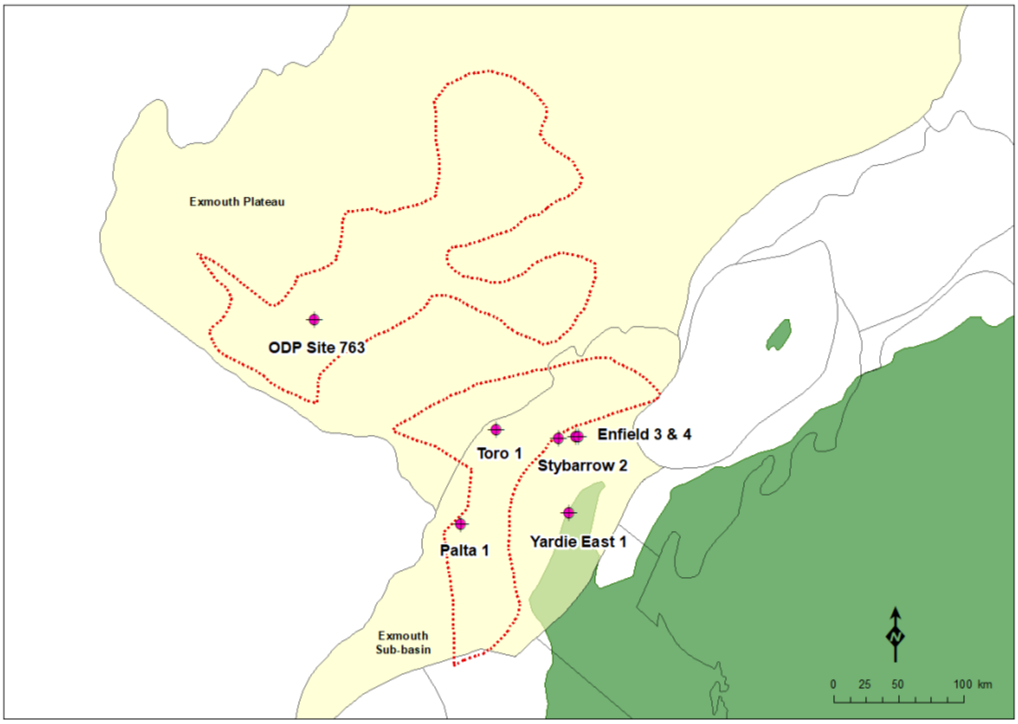

Figure 1. Location map, detailing the locations of intrusions as defined by Frey et al. (1998) and wells penetrating igneous material on the Exmouth Plateau and Exmouth Sub-basin, North Carnarvon Basin, Western Australia.

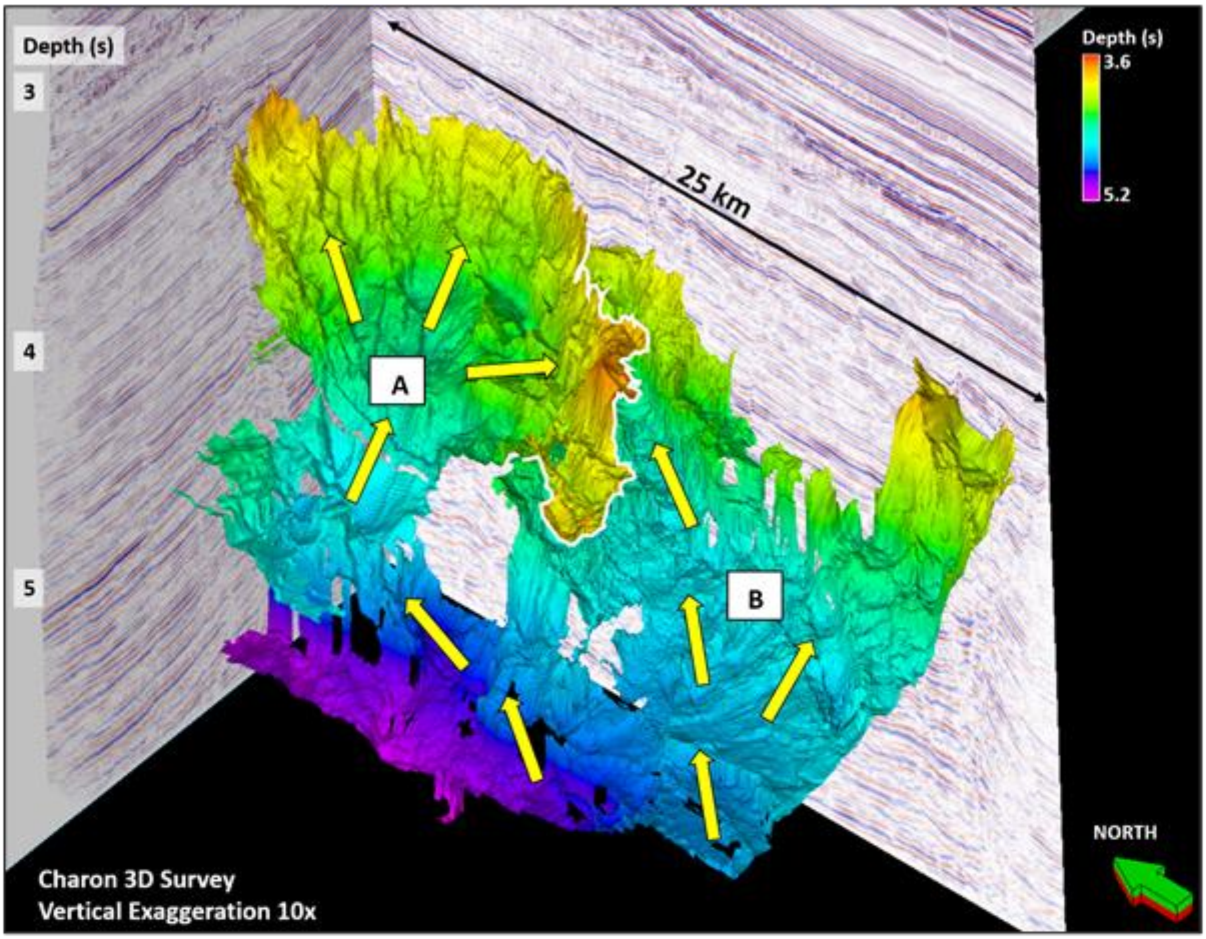

Figure 1. 3D interpretation of a magmatic plumbing system present in the Charon 3D seismic survey. Yellow arrows indicate direction of magma flow during emplacement of the intrusions.