Structural and lithological controls on the geometry and morphology of igneous intrusions: a 3D seismic case study from the Exmouth sub-basin, NW Shelf

Niall Mark
Geology & Petroleum Geology
University of Aberdeen
niall.mark@abdn.ac.uk

Simon Holford
Australian School of Petroleum
University of Adelaide
simon.holford@adelaide.edu.au

Nick Schofield
Geology & Petroleum Geology
University of Aberdeen
n.schofield@abdn.ac.uk

Christian Eide
Department of Earth Science
University of Bergen
christian.eide@uib.no

Stefano Pugliese
Chrysaor
London
stefano.pugliese@chrysaor.com

Douglas Watson
Geology & Petroleum Geology
University of Aberdeen
douglas.watson@abdn.ac.uk

David Muirhead
Geology & Petroleum Geology
University of Aberdeen
dmuirhead@abdn.ac.uk

SUMMARY

Rift-related magmatism resulting in widespread igneous intrusions has been documented in various basins, including the Faroe Shetland Basin (UK), Voring and More Basins (Norway) and the Browse and Carnarvon basins of the NW Shelf of Australia. Seismic mapping, combined with field work, has resulted in greater understanding of subsurface intrusive plumbing systems, but knowledge of emplacement style and the mechanisms by which they propagate is limited. The interpretation of a 3D seismic dataset from the Exmouth sub-basin, NW Shelf Australia, has identified numerous igneous intrusions where a close relationship between intrusions and normal faults is observed. These faults influence intrusion morphology but also form pathways by which intrusions have propagated up through the basin stratigraphy. The steep nature of the faults has resulted in the intrusions exploiting them and thus manifesting as fault-concordant, inclined dykes, whereas in the deeper parts of the basin, intrusions that have not propagated up faults typically have saucer shaped sill morphologies. This transition in the morphology of intrusions related to fault interaction also highlights how dykes observed in outcrop may link with sills in the subsurface. Our interpretation of the seismic data also reveals subsurface examples of bifurcating intrusions with numerous splays, which have previously only been studied in outcrop.

Key words: 3D seismic, igneous intrusions, rifted margins, Carnarvon Basin, Exmouth sub-basin.

INTRODUCTION

Magmatism associated with the break-up of continents to form new ocean basins is a common feature of many rifted margins worldwide (Holford et al., 2013). This magmatism can result in the emplacement of numerous igneous intrusions throughout sedimentary basins and can also cause voluminous extrusive volcanism such as flood basalts. Despite the widespread volcanic and intrusive magmatic activity associated with rifted continental margins, which is often perceived to have negative impacts on petroleum systems, these regions are a focus for hydrocarbon exploration (Schofield et al., 2017). Due to the exploration of many rifted margins for hydrocarbons, widespread 3D seismic reflection coverage has allowed detailed characterisation of igneous intrusion morphology and emplacement.

Previous work examining intrusions in rifted margin settings has highlighted the importance of the host rock lithology for controlling intrusion morphologies and emplacement, with intrusions into predominantly sandy lithologies showing a preference for bifurcated and chaotic morphologies, whereas intrusions into shales have a more uniform morphology (Eide et al. 2017). The interaction of igneous intrusions and faults has also been previously documented in relation to emplacement and morphology, with the intrusions utilising the faulted planes of weakness as an emplacement pathway (McClay et al., 2013; Magee et al., 2013). Despite this, few studies have highlighted both the lithological and structural control on emplacement style and morphology in one setting.

Multiple igneous intrusions are well imaged within 3D seismic data from the Exmouth sub-basin and north of the Gascoyne sub-basin and form the focus of this presentation. Normal faults related to Late Jurassic-Early Cretaceous rifting in the Exmouth sub-basin have been exploited by magma resulting in a complex, interconnected network of igneous intrusions. Observations of igneous intrusions in the study area indicates a preference for fault-controlled emplacement and morphology. The numerous normal faults in the Exmouth sub-basin are the dominant emplacement pathway for igneous intrusions enabling sub-vertical movement of magma through the basin. The intrusions are highly interconnected and also display bifurcating morphologies with multiple splays, which have previously only been studied in detail at outcrop scale (Eide et al. 2017). This work examines how intrusions and their emplacement and resultant morphologies are relevant to ongoing hydrocarbon exploration in the region.

METHOD AND RESULTS

The Coverack 2001/2002 3D seismic reflection dataset covers an area of 878 km² and is located at the transition between the
Exmouth sub-basin to the north and Gascoyne sub-basin to the south. The data was acquired to 6 seconds TWT at 2 milliseconds sample interval, with a crossline and inline spacing of 12.5 and 15 m, respectively (2001/2 Coverack 3D Seismic Interpretation Report). For the seismic data presented here, a downward increase in acoustic impedance is represented as a negative amplitude (hard kick), displayed in blue, therefore the seabed is mapped on a trough. The majority of the intrusions are contained within the strata below the Aptian and Valanginian unconformity. Within this section, the average velocity is 3072 m/s (derived from Herdsman 1) and the dominant frequency is 22 Hz, resulting in a vertical resolution of 34 m (~17.5 m detectability). Within the Coverack 2001/2 3D data, there is one exploration well (Herdsman-1) located in the NE of the survey. The well terminates in the Middle Jurassic Learmonth Formation sandstones. It is possible to make good seismic to well ties in the Cretaceous to Recent section allowing for confident regional mapping. The accompanying Coverack 2001 2D seismic reflection survey provides greater coverage to the west of the 3D survey, though the data quality is generally poorer, decreasing significantly within the deeper Palaeozoic strata. The poor quality of the Coverack 2001 2D makes it difficult to confidently tie the seismic data with the Pendock-1 exploration well.

The Coverack 2001/2 3D was previously the subject of study by McClay et al. (2013), which characterised the igneous features in terms of intrusive or extrusive origin and broadly relating them to the overall evolution of the basin. This study builds on the previous study by McClay et al. (2013) through a more detailed analysis of the igneous intrusions within the survey, which in particular focuses on the relationship between igneous intrusions and faults, and the importance of this relationship as a mechanism for emplacement. Our interpretation of the seismic data has therefore focused on the igneous intrusions and the key horizons that intersect the intrusions.

Across the survey, we mapped four key horizons that can be interpreted with confidence based on the available well data (including composite logs and end of well reports) and the quality of the seismic data. In total, 26 individual igneous intrusions were interpreted along with 15 faults that showed evidence for interaction with intrusions (Figure 1). Interpretative techniques including 3D visualisation, opacity rendering and amplitude extractions were applied to visualise the intrusion-fault interaction. A blue–white-red colour palette was used for interpreting the seismic data, whereby an increase in impedance is expressed by a blue reflector. The igneous intrusions were mapped on a strong negative amplitude, i.e. a prominent blue reflector.

The 26 intrusions mapped have been classified into two categories based on their morphology (Figure 1). Morphology 1 (M1) intrusions are highly interconnected and consist of multiple splay which extends up to 1 km across the basin and crosscut multiple horizons. This morphology is most common in the north-west part of the study area where multiple intrusions are vertically stacked. The M2 intrusions are typically found in the shallower sections of the basin (between 1.5-2.5 s TWT) and appear to be focused within the Upper Jurassic stratigraphy.

**DISCUSSION**

In the Coverack 3D seismic dataset, it is possible to image large intrusions that bifurcate into smaller intrusions, with morphologies similar to those observed at a much smaller scales in field studies (Fig. 10). Examples of this type of morphology in seismic reflection data are limited, with most previous studies of intrusions documenting saucer-shaped morphologies, or fault climbing intrusions. Bifurcating intrusions with numerous splays in the field study area, occur over distances >3 km from the source intrusion. In outcrop, these intrusions have an anastomosing morphology which cross-cuts multiple stratigraphic horizons. The numerous splays can laterally connect to other splays or pinch out. Where the intrusions bifurcate, they can reconnect with the main intrusion body, creating a 3D compartmentalised body of host rock. Similar relationships are observed in Jameson Land, East Greenland and San Rafael Intrusive Complex, SW Utah (Figure 2).

The strong lithological control on emplacement style and resultant morphologies documented from multiple field studies makes it possible to infer the mechanical properties of the host rocks at the time of emplacement. The bifurcating intrusions in outcrop, along with the other intrusions in the Exmouth sub-basin, were emplaced during the late Jurassic to early Cretaceous, mainly into Jurassic and Triassic-age sediments. Lithological constraints from the Herdsman-1 exploration well shows that the Middle Jurassic Learmonth Formation consists of homogenous sandstones, with a net to gross of 86% and average porosities of 26% (Herdsman-1 End of Well Report). The Herdsman-1 exploration well is within 5 km of the pervasive zone of bifurcating intrusion morphologies. We infer that this thick succession of homogenous sandstone, with limited mudstone, has resulted in the development of the complicated bifurcating intrusion morphologies with multiple splays, similar to observations of intrusion emplacement into homogenous sandstones in Jameson Land, East Greenland and the San Rafael Intrusive Complex, SW Utah. Interestingly, despite the high porosities encountered in the Learmonth Formation sandstones, bifurcating morphologies are still present, indicating this morphology is primarily influenced by the lack of mudstone in the host rock.

**CONCLUSIONS**

This study has presented an interpretation of a 3D seismic dataset over the Exmouth sub-basin, Australian NW Shelf, containing multiple intrusions. Our main findings are:

- Intrusions preferentially intrude faults regardless of the host rock lithology.
The main magma propagation direction is from west to east based on kinematic flow indicators indicating a westerly magma source.

Intrusions with a dendritic morphology in seismic can give an indication of the nature of the host rocks. Multiple splays observed in outcrop are a common feature in brittle, homogenous sandstones and similar features have now been identified in seismic.

Intrusions are likely to create complications for hydrocarbon exploration including; compartmentalisation of reservoirs, drilling problems, reduced seismic imaging, impeded migration pathways and thermal alteration of reservoir and source rock intervals.

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REFERENCES


Figure 1. Seismic profiles showing varying intrusion types within the Exmouth sub-basin. Intrusions are defined as follows: 1) intrusions which have saucer shaped sill morphologies and propagate up faults as sub-vertical dykes, 2) intrusions which propagate up faults as dykes also but they have a dendritic morphology and multiple splays. a): all intrusions morphology types displayed in a seismic section, b): M1 morphology (saucer shaped), c): M1 morphology (fault influenced), d): M2 morphology (bifurcating intrusions.)
Figure 2. Bifurcating intrusions with multiple splays in seismic and in the field, demonstrating the scale invariant nature of intrusion morphologies, a): seismic line showing bifurcating intrusions in the Exmouth sub-basin, b): seismic line showing the bifurcating intrusions with a NE-SW orientation, c): bifurcating intrusions in east Greenland, D): bifurcating intrusions in south east Utah.