Recognition of igneous rocks encountered in wells in the Carnarvon Basin, Western Australia: Implications for drilling and petroleum systems.

Michael Curtis
Australian School of Petroleum and Energy Resources
University of Adelaide
Adelaide
South Australia
5005
michael.curtis@adelaide.edu.au

Simon Holford
Australian School of Petroleum and Energy Resources
University of Adelaide
Adelaide
South Australia
5005
simon.holford@adelaide.edu.au

Mark Bunch
Australian School of Petroleum and Energy Resources
University of Adelaide
Adelaide
South Australia
5005
mark.bunch@adelaide.edu.au

Nick Schofield
Department of Geology and Petroleum Geology
University of Aberdeen
Aberdeen
Scotland
AB24 3UE
n.schofield@aberdeen.ac.uk

SUMMARY

The Carnarvon Basin formed during the separation of Greater India and Australia in the Mesozoic. Rifting was associated with the generation of large volumes of melt (possibly related to a hotspot beneath the Cape Range Fracture Zone), which was emplaced into the upper crust of the Exmouth Plateau and Exmouth Sub-basin from the late Jurassic until breakup in the early Cretaceous. Despite the magmatic system spanning 50,000km^2 across the Exmouth Plateau and Exmouth Sub-basin, few wells have intersected igneous rocks. Of those that have, we find that the majority of igneous rock penetrations are unintentional.

In this contribution, we evaluate the impact of igneous rocks on drilling operations, and petroleum systems, for each well known to have passed through igneous rocks in the Carnarvon Basin.

Key words: Petroleum Exploration, Igneous, Intrusions, Volcanoes, Carnarvon Basin, Petroleum Systems, Seismic, Wells.

INTRODUCTION

The Carnarvon Basin, located offshore NW Western Australia, is part of the North West Australian Rifted Margin (NWARM), a series of rift basins formed during Jurassic rifting and Early Cretaceous breakup of Greater India from Australia (Figure 1). The strata of the Northern Carnarvon Basin contain large volumes of igneous rocks associated with this breakup event. Several suites of igneous rocks have been defined, which were emplaced before, during and after breakup (Symonds et al., 1998). It is the syn-rift, pre-breakup igneous rocks that are most spatially associated with petroleum exploration activities in the basin. Igneous rocks emplaced during the Late Jurassic and Early Cretaceous comprise an extensive network of sills and dykes within the Exmouth Sub-Basin (e.g. McClay et al., 2013, Magee et al., 2017) and Exmouth Plateau (e.g. Rohrman, 2013) and several volcanic centres (e.g. Curtis et al., 2021) in the Exmouth Sub-Basin (Black et al., 2017) (Figure 1), possibly sourced from an impinging plume head beneath the intersection of the Cuvier Margin and the Cape Range Fracture Zone (Rohrman, 2015).

Igneous rocks are often considered detrimental to petroleum systems, and a hazard to petroleum drilling operations:

- Intrusions have the potential to compartmentalise hydrocarbon reservoirs (Holford et al., 2013), overcook source rocks (Rohrman, 2007), and break hydrocarbon seals (Schofield et al., 2017).
- Dykes may act as conduits for overpressure, risking blowout if penetrated accidentally during drilling (Schofield et al., 2020).
- Thick accumulations of volcanic ash altered to bentonite can clog and trap the drillstring (Watson et al., 2020).

It is for these reasons that areas of the Carnarvon Basin containing igneous rocks have traditionally been avoided by petroleum explorers. Despite this, syn-rift, pre-breakup igneous rocks have been penetrated inadvertently on several occasions, for example by wells Palta-1, Yardie East-1, Edel-1 and Chester-1, which intersected intrusive sills and dykes; and Stybarrow-2, Enfield-3, Enfield-4 which intersected ashfall deposits.

However, as both seismic imaging capability and our understanding of igneous rocks in sedimentary basins improve, the fear of exploring in affected areas of the Carnarvon Basin is subsiding. For example, in 2014, Woodside discovered gas in a Triassic rotated fault beneath a Late Jurassic volcano with their Toro-1 well in the western Exmouth Sub-Basin (Sturrock, 2014).

As targeted drilling of igneous-associated plays is new in the Carnarvon Basin, we must approach it with all the knowledge we can glean from understanding the impacts of igneous rocks on historic wells in the basin. This contribution summarises lessons learnt from a comprehensive review of wells that have penetrated igneous rocks in the Carnarvon Basin. We have reviewed the wells in terms of the impact the penetrated igneous rocks had on the target petroleum system, and also highlight challenges encountered during drilling operations.

METHOD AND RESULTS

Method

First, wells and boreholes intersecting igneous rocks within the Carnarvon Basin were identified. These include Toro-1, which intersected a volcano; Enfield-3, Enfield-4, Stybarrow-2 and Ocean Drilling Program (ODP) Site 763, which intersected ashfall deposits; and Palta-1, Yardie East-1, Edel-1 and Chester-1, which intersected intrusive sills and dykes (Figure 1).

Available open file data for each well was collected from Australia's National Offshore Petroleum Information Management System (NOPIMS) and the West Australian Petroleum Information Management System (WAPIMS). Open file 2D and 3D seismic reflection and refraction data in the vicinity of each well, and associated interpretation reports, were also accessed. Local scientific literature was also reviewed.

For each well, the impact of the intersected igneous rocks on petroleum exploration was reviewed. In some wells, the impact was most prominent on the target petroleum system (e.g. Yardie East-1, where heating has overcooked source rocks), whereas in others, the igneous rocks were simply a consideration for drilling, and had not interacted with the petroleum system at all (e.g. Toro-1, where altered volcanic clays above the reservoir were thought to be overpressured ahead of drilling). Once the impact of the igneous rocks was established, the key lessons learnt during the drilling of each well were drawn out, and implications for future petroleum exploration considered.

Results

Toro-1 was drilled by Woodside in 2014 in the western Exmouth Sub-basin, and discovered gas in Triassic Mungaroo sands within a rotated fault block (Sturrock, 2014). The well intersects the Late Jurassic Toro Volcanic Centre (TVC). Prior to drilling, low seismic velocities through the TVC were interpreted to represent overpressured formation. Drilling revealed that instead, the low velocities were the result of the TVC having been altered completely to clay at this locality. The lessons here are that the seismic response of volcanic rocks can often be misinterpreted, and that safety procedures during drilling must accommodate the worst outcome.

Enfield-3 and **Enfield-4** were drilled in the central Exmouth Sub-Basin by Woodside in 2000 and 2002 respectively (Willis, 2001, Willis, 2002). **Stybarrow-2** was drilled nearby by BHP in 2003 (Locke, 2004). Each of these wells targeted reservoir sands hosted in the Lower Cretaceous Lower Barrow Group (LBG). The wells intersected volcanic ashfall deposits that have been altered to smectite clay in the LBG and Upper Jurassic Dupuy Formation. **ODP Site 763** is located in the southwest Exmouth Plateau, where similar smectite layers were also observed in Lower Cretaceous strata (von Rad and Thurow, 1992). Drilling operators should use inhibited muds and avoid acid washout to reduce the swelling effects of smectite clay, which can expand in volume by 10 to 15 times if hydrated (Altaner, 1978), damaging formation and clogging the drillbit, forcing POOH for cleaning. The Jurassic ash layer can be correlated westwards to the TVC. Although relatively thin in the wells (several m), these deposits may be much thicker closer to source, where more care should be taken during drilling.

Palta-1 was drilled by Shell in the southern Exmouth Sub-Basin in 2012 and 2013, and targeted reservoirs in the Triassic Mungaroo Formation and Permian Kennedy Group (Gibson, 2014). No igneous rock was observable on seismic pre-drill, or diagnostic igneous rock cuttings observed during drilling. However, post-drill analysis of vitrinite reflectance data, apatite fission track data and subsequent targeted thin sections revealed the presence of intrusive rocks over at least 60 m immediately below the Early Cretaceous KV Unconformity (Duddy, 2013). The reason for the lack of imaging was likely due to extensive carbonate replacement and clay alteration of the mafic intrusion, which was recognised, but logged as carbonate/dolomite by wellsite geologists. Lessons from this well highlight how the presence of igneous rocks is often not predictable prior to drilling, and that they can be missed by first pass logging on the drill floor. Intrusions going unidentified risks losing out on key information regarding the basin's thermal history and subsequent inaccuracy in basin modelling.

Yardie East-1 was drilled by MESA Australia in 1982, onshore on the Exmouth Peninsula NW Western Australia, and targeted an anticline in the Mungaroo Formation (Kjellgren, 1982). Twenty mafic intrusions of 5 m average thickness were intersected in Jurassic and Triassic strata beneath the Callovian Unconformity. When compared to nearby well, Murat-1, Yardie East-1 vitrinite reflectance data shows that the intrusions locally matured source rocks from immature to overmature over an interval of several hundred metres (Figure 2). From this well we learn that collective heating from multiple narrow intrusions may adversely affect source rock maturity over a wide interval, not just in narrow haloes surrounding individual intrusions, as is widely believed.

Edel-1 was drilled in the Gascoyne Sub-Basin, on the Edel Terrace, by Ocean Ventures Pty in 1972 (Ocean Ventures, 1972). The well targeted a magnetic high interpreted pre-drill as a dip closed anticline. The magnetic anomaly was likely the result of over 70 variably altered mafic intrusions ranging in thickness from 3 to 25 m that were encountered beneath the KV Unconformity. What is significant is that this voluminous emplacement of mafic magma into host sandstone was not imaged on seismic collected both before (1972) and after (1978) drilling. Emplacement of these intrusions heavily degraded reservoir characteristics. Over a >1000 m interval, host sandstone was completely compartmentalised, and porosity and permeability significantly reduced by quartz cementation likely the result of intrusion driven hydrothermal alteration. Here, the usefulness of magnetic data in predicting the presence of mafic igneous rocks is highlighted, along with the possible damage to reservoir by both primary and secondary effects of intrusion emplacement.

Chester-1 was drilled by Hess in the central Exmouth Plateau in 2013. The well discovered gas in the Mungaroo Formation in the SW of the Glencoe 3D seismic reflection survey

(Jakymec and Banfield, 2013). Chester-1 penetrated 48 m of mafic igneous rock from 4905 mMD where the well path was dipping 18° from vertical. Magee and Jackson (2020) show that if the intrusion was a horizontal sill, its thickness would be 45.6 m, and would be resolved on the Glencoe survey. The intrusion is not resolved, therefore Magee and Jackson (2020) suggest that the intrusion is more likely a dyke, and forms part of a Late Jurassic dyke swarm radiating from the southwest of the Exmouth Sub-Basin, and extending across much of the western Exmouth Plateau (Figure 1). The presence of such extensive Late Jurassic dykes has significant implications for petroleum exploration in the Carnarvon Basin: These dykes are (1) a new source of heating, affecting source rock maturity across the basin to be incorporated into basin models, and (2) a vertical barrier to lateral hydrocarbon in Triassic and Jurassic reservoirs, compartmentalising large areas of the basin. Furthermore, if fractured, they may (1) transfer overpressure from deep within the crust, becoming a significant drilling hazard, and (2) act as vertical migration pathway for both hydrocarbons, and mineralising hydrothermal fluids.

CONCLUSIONS

From this study of wells that have penetrated igneous rocks in the Carnarvon Basin we can conclude:

- The majority of wells that penetrated igneous rocks in the Carnarvon Basin did so without planning to. This is primarily due to the difficulties associated with imaging both narrow and altered igneous rocks on seismic reflection data: 90% of igneous intrusions are narrower than the vertical resolution (c. 40 m) of seismic datasets (Schofield et al., 2017). This is an issue that will persist into the future. It is only in Toro-1 (where the volcano is several hundred metres thick and clearly imaged on the Eendracht 3D seismic reflection survey) and Edel-1 (where intrusions were associated with a magnetic anomaly) that the presence of igneous rock was at all predictable prior to drilling.

- Low seismic velocities in igneous rocks can reflect both alteration and overpressured formation. Appropriate safety protocols anticipating possible overpressure must be in place prior to drilling through such igneous rocks.

- When drilling in the vicinity of volcanoes, operators should anticipate the possible presence of significant thicknesses of smectite clay – an alteration product of tuffaceous ashfall deposits – and take precautions accordingly. Smectite is a swelling clay that can expand to over 1000% of its original volume, potentially damaging reservoirs, drilling components, and forcing downtime due to drillbit clogging.

- The emplacement of igneous intrusions can adversely affect both reservoir rocks and source rocks. Stacked intrusions as seen in Edel-1 and Yardie-East-1 can locally compartmentalise reservoirs; drive hydrothermal fluid circulation causing precipitation of minerals and reducing porosity and permeability; and drive increases in source rock maturity.

- New research (Magee and Jackson, 2020) suggests the presence of a swarm of vertical dykes across the western Carnarvon Basin. Operators should be mindful of associated exploration considerations (e.g. new heat source, and impacts on regional hydrocarbon migration pathways) and drilling risks (e.g. possible overpressure transfer).

ACKNOWLEDGMENTS

We gratefully acknowledge the Australian School of Petroleum and Energy Resources at the University of Adelaide where this work was completed. This work was funded through a postgraduate scholarship from the University of Adelaide, Faculty of Engineering Computer and Mathematical Sciences, and also by ASEG Research Foundation Grant no. RF19P01.

REFERENCES

ALTANER, S. 1978. Smectite Group. In: MIDDLETON G., CHURCH, M., CONIGLIO, M., HARDIE, L., & LONGSTAFFE, F. (eds). Engyclopedia of Sediments and Sedimentary Rocks. Encyclopedia of Earth Sciences Series. Springer, Dordecht.

BLACK, M., MCCORMACK, K., ELDERS, C. & ROBERTSON, D. 2017. Extensional fault evolution within the Exmouth Sub-basin, North West Shelf, Australia. Marine and Petroleum Geology, 85, 301-315.

CURTIS, M., HOLFORD, S., BUNCH, M., AND SCHOFIELD, N. 2021. Controls on the preservation of Jurassic volcanism in the Northern Carnarvon Basin. The APPEA Journal. *In press.*

DUDDY, I. 2013. Palta-1 and Palta-1 ST1 Final Well Completion Report, Appendix 4: Thermal History Reconstruction in the Palta-1 Well, Exmouth Sub-Basin, offshore Western Australia using AFTA and VR data.

GIBSON, P. 2014. Palta 1 & Palta 1 ST1 Initial Well Completion Report. Shell Development (Australia) Pty Ltd.

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. In: KEEP, M. & MOSS, S. (ed.). The Sedimentary Basins of Western Australia IV, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 18-21 August 2013.

JAKYMEC, M. & BANFIELD, J. 2013, Well Completion Report, Chester-1 & Chester-1 ST1: Interpretive Data. Hess Exploration Australia Pty Ltd.

KJELLGREN, G., HOLLAMS, R., MARKS, T. & WHITE, H. 1982. Yardie East 1, Well Completion Report. Perth, WA: Mesa Australia Limited.

LOCKE, A. 2004. Stybarrow 2: Well Completion Report, Interpretive Volume. Perth: BHP Billiton.

MAGEE, C. & JACKSON, C.-L. 2020. Seismic reflection data reveal the 3D structure of the newly discovered Exmouth Dyke Swarm, offshore NW Australia. Solid Earth, 11, 579-606.

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.

MCCLAY, K., SCARSELLI, N. & JITMAHANTAKUL, S. 2013. Igneous Intrusions in the Carnarvon Basin, NW Shelf, Australia. In: KEEP, M. & MOSS, S. (ed.). The Sedimentary Basins of Western Australia IV, Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, WA, 18-21 August 2013.

OCEAN VENTURES. 1972. Edel-1 Final Well Completion Report. Ocean Ventures Pty Ltd.

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. 2007. Prospectivity of volcanic basins: Trap delineation and acreage de-risking. AAPG Bulletin, 91, 915-939.

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

SCHOFIELD, N., HOLFORD, S., EDWARDS, A., MARK, N. & PUGLIESE, S. 2020. Overpressure transmission through interconnected igneous intrusions. AAPG Bulletin, 104, 285-303.

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.

STURROCK, V. 2014. Toro 1 (WA-430-P, Carnarvon Basin) Initial Well Completion Report. Woodside Energy Ltd.

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.

VON RAD, U. & THUROW, J. 1992. 11. Bentonitic clays as indicators of Early Neocomian post-breakup volcanism off northwest Australia. Proceedings of the Ocean Drilling Program, Scientific Results, 122, 213-232.

WATSON, D., SCHOFIELD, N., MAGUIRE, A., TELFORD, C., MARK, N., ARCHER, S. & HARDMAN, J. 2020. Raiders of the Lost Mud: the geology behind drilling incidents within the Balder Formation around the Corona Ridge, West of Shetland. Petroleum Geoscience, 26, 110-125.

WILLIS, S. 2001. Enfield 3, Well Completion Report, Interpretive Data. Woodside Energy Ltd.

WILLIS, S. 2002. Enfield 4, Well Completion Report, Interpretive Data Woodside Energy Ltd.

FIGURES

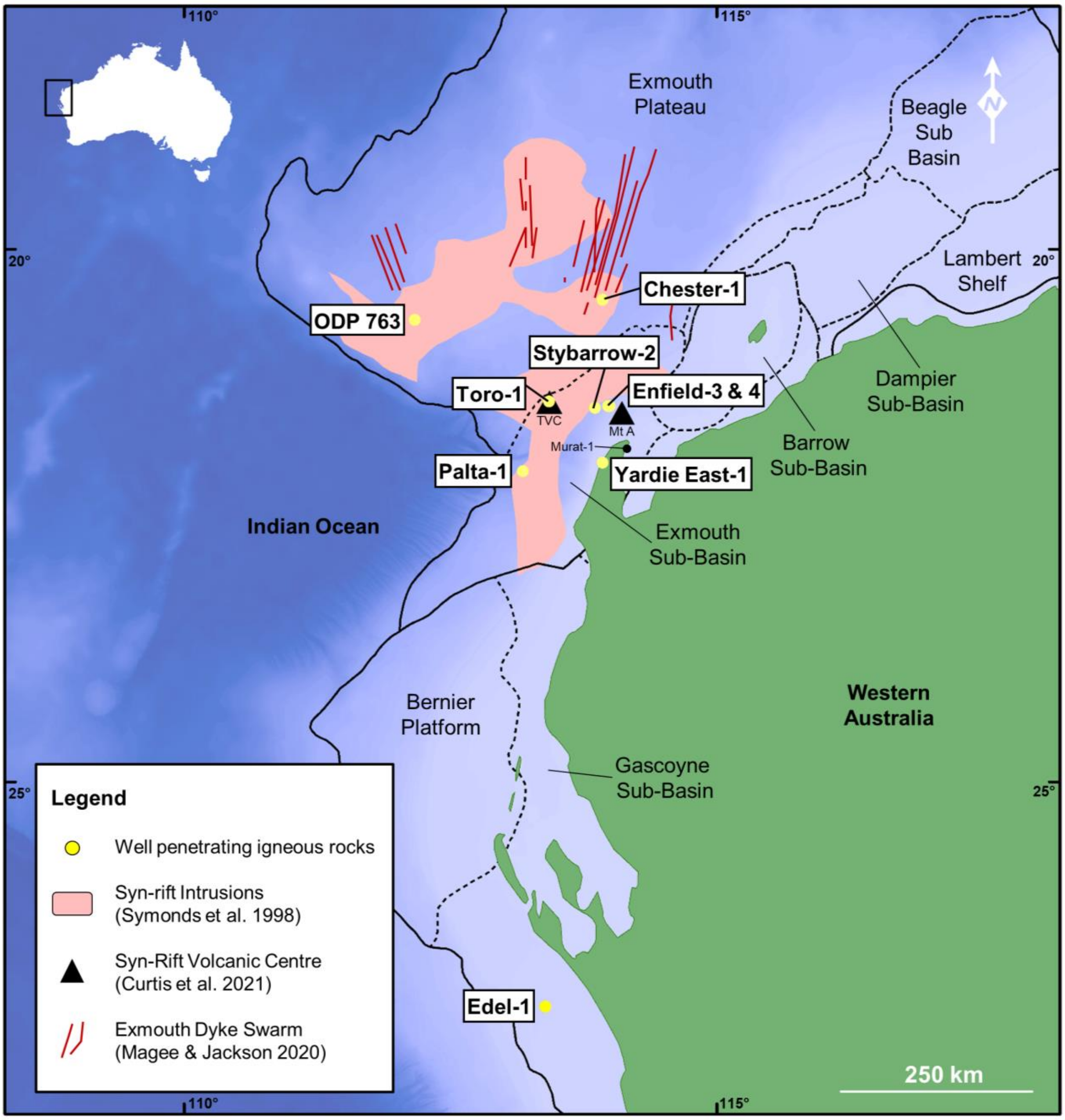

Figure 1. Map of the Carnarvon Basin detailing the locations of wells investigated in this study. Also shown are the locations of syn-rift intrusions (after Symonds et al., 1998, and Magee & Jackson, 2020) and volcanic centres (TVC – Toro Volcanic Centre, Mt A – Mt Aneto; after Curtis et al., 2021).

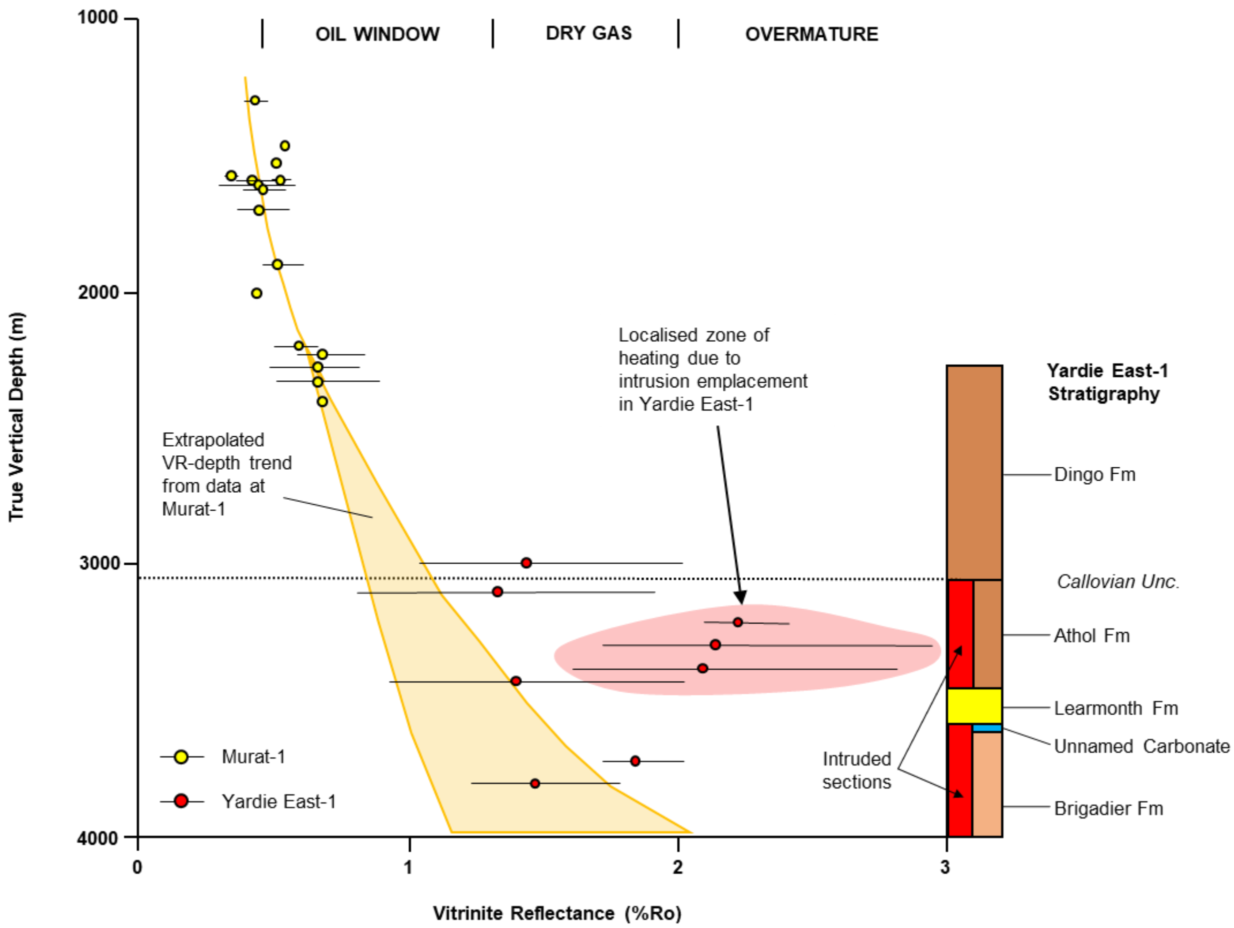

Figure 2. Vitrinite reflectance (VR) vs depth plot for Yardie East-1 (red points) and Murat-1 (yellow points) nearby. This plot shows (1) that the VR vs. depth gradient is higher in Yardie East-1 than in Murat-1, and (2) that there is a localised spike in VR associated with the intruded Athol Formation within Yardie East-1.