Nature and origin of Jurassic volcanism in the Eromanga Basin

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SUMMARY

The Cooper and Eromanga Basins of South Australia and Queensland are the largest onshore hydrocarbon producing region in Australia. Igneous rocks have been documented infrequently within end of well reports over the past 34 years, with a late Triassic to Jurassic age determined rom well data. However, the areal extent and nature of these basaltic rocks were largely unclear. Here, we integrate a variety of subsurface datasets to clarify the nature and origin of igneous rocks preserved within Eromanga Basin sequences overlying the Nappamerri Trough of the Cooper Basin. We recognise mafic monogenetic volcanoes that extend into tabular basalt lava flows, igneous intrusions and, more locally, hydrothermally altered compound lava flows. The volcanic province covers ~7500 km^2 and is proposed to have been active between ~180-160 Ma. We name this Jurassic volcanic province the Warnie Volcanic Province after the Warnie East 1 exploration well, drilled in 1985. The distribution of extrusive and intrusive igneous rocks is primarily controlled by basement structure, with extrusive and intrusive igneous rocks elongate in a NW-SE direction. The magmatism is interpreted as a product of extension and intraplate convective upwelling above the subducting Pacific Slab.

Key words: Intraplate, volcanism, monogenetic, Australia, Jurassic

INTRODUCTION

The Cooper and the overlying Eromanga Basin extend for 130,000 km^2 and 1,000,000 km^2 respectively across central, north and eastern Australia. Together, they represent the largest conventional onshore hydrocarbon-producing region in Australia. The majority of discoveries within the Cooper Basin are situated within structural traps on regional highs, however, a number of companies began to pursue unconventional hydrocarbon plays within the basin during the late 2000s, resulting in an increase in activity within the Nappamerri Trough (Hall *et al.*, 2016). The Nappamerri Trough is the largest and deepest depocentre within the Cooper Basin covering ~10,000 km^2 and reaching present day depths of ~4.5 km. The acquisition of new well and seismic data due to the exploration activities has resulted in the increased recognition of igneous rocks in the Cooper and Eromanga Basins.

Igneous rocks of suspected late Triassic-Jurassic age have been sporadically encountered by drilling during the past 34 years, though there has been no systematic study of the character, origin and significance of these igneous rocks. We have combined a variety of datasets to document the extent and character of Mesozoic volcanics recognised within Eromanga Basin stratigraphy overlying the Nappamerri Trough of Cooper Basin age. The Warnie Volcanic Province (WVP) is the suggested name for this >7500 km^2 suite of volcanics identified within the Jurassic succession of the Eromanga Basin (Figure 1). The province is named after the Warnie East 1 exploration well, which was drilled in 1985 and encountered 65 m of basalt.

METHODS AND RESULTS

The Cooper and Eromanga Basins have been explored extensively over the past 60 years, so are characterised by the largest collection of well and seismic reflection data for any onshore sedimentary basin in Australia. A large database of seismic reflection data was available through Santos Limited and the Queensland Government's Department of Natural Resources and Mines. 3D and 2D seismic reflection surveys throughout the South Australian and Queensland sides of the basin were assessed for the presence of volcanic rocks. Notably, only four surveys available to this study (the Winnie 3D, the Gallus 2D, the Challum 3D and the Snowball 3D survey (provided by Santos)), were interpreted to contain volcanic rocks. Unless stated, seismic data were displayed using normal (American) polarity, whereby a downward increase in acoustic impedance corresponds to a positive (blue) reflection and a downward decrease a negative (red) reflection.

Over 2,000 wells have been drilled in the Cooper and Eromanga Basins. Despite this, of the wells available, only three (Lambda 1, Orientos 2 and Kappa 1) were identified as having intersected extrusive volcanic rocks with only one well (Warnie East 1) encountering an intrusive igneous rock. The Warnie East 1, Lambda 1 and Orientos 2 wells were key in constraining volcanism above the central Nappamerri Trough. To estimate the relative age of the volcanic units, well data were tied, where possible, to the seismic reflection surveys available. For constraining the age of the Eromanga succession within the Central Nappamerri trough, the Halifax, Etty, Padme, Charal and Anakin wells were key.

The main 3D seismic reflection survey discussed here is the Winnie 3D survey. Acquired in 2012 by Drillsearch Energy Ltd, the survey was shot above the eastern Nappamerri Trough in southwest Queensland over an area of 2545 km^2. The main focus when acquiring the survey was on the unconventional targets in the area, typically the extensive Permian coal-rich source rocks (Hillis *et al.*, 2001). The dominant frequency within the Jurassic succession is ~40 Hz, with volcanic rocks in the region having an acoustic velocity of 4 to 6 kms^{-1} (taken from the Lambda-1 exploration well). Using an average velocity of 5 kms^{-1} a vertical resolution of ~30 m and a detection limit of 4 m was calculated.

We identified ~100, <= 4 km^2 cone shaped features that often express an eye-shaped morphology (Figure 2). The cones within the survey are less than 2 km long and 750 m wide, and often elongate in a NW-SE direction. We have interpreted these as monogenetic volcanoes, small cumulative volume volcanic edifices built up by one continuous, or many discontinuous, small eruptions over a short time scale (<= 10 years) (Nemeth and Kereszturi, 2015). Twelve of the volcanoes are linked with what appear to be elongate, NW-SE oriented lava flows that are conformable to stratigraphy and have dimensions of 2-7 km in length and 0.5-2.5 km in width (covering areas of 4-13.5 km^2). The flows appear to be strata-concordant and confined to the Hutton Sandstone or the base of the Birkhead Formation which would place the flows between 160 and 178 Ma (Alexander and Hibburt, 1996).

Igneous intrusions within the Winnie 3D survey are identified as igneous rocks that cross-cut the Triassic to Jurassic strata; notably the Nappamerri, Hutton and Birkhead Formations. We identified and mapped 14 intrusions in the seismic data; these occur ~100–200 ms (~105 – 210 m) below the palaeosurface. Most of the sills identified are of a similar scale to the lava flows in the area (2 – 4.5 km long, 1.2 – 1.7 km wide). The Winnie 3D survey also hosts a spectacular single intrusion, 14 km long and 8 km wide, by far the largest igneous feature in the WVP. Classical intrusion related features such as inflation lobes are observed within spectral decomposition and ~20 vents cross-cut this intrusion, in places leading to extrusive lava flows in the overlying sediments. The presence of the pockmarks on the surface of the intrusion suggests emplacement of the sill predated a later stage of volcanism that occurred towards the top of the Birkhead Formation.

The Lambda 1 well was drilled in 1984 by Delhi Petroleum Pty. Ltd. At a depth of 1571 m, 283 m of igneous rocks were intersected, directly underlying the base of the Birkhead Formation. The upper 33 m of basalt are heavily weathered, fractured and vesicular, as noted in the Lambda well report. The remaining 250 m of basalt is fresh and crystalline. It typically has low gamma ray values, with consistently high density and acoustic velocity. There are localised areas where the density drops drastically, however, these are associated with increases in the caliper and may therefore point to caving of the wellbore when it was drilled or fractures within the basalt, rather than lithological variations. At the base of the basalt ~1.5 m of core was cut, within which the fine grained, crystalline nature of the basalt is apparent. These igneous rocks are interpreted to be extrusive in origin.

K-Ar dating was previously conducted on a bag of drill cuttings from Lambda 1 taken from a depth of 1658 m. Although the samples were too altered to be used for total rock analysis, fresh plagioclase within the cuttings was separated for analysis and used to determine an age of 227 +/- 3 Ma, suggesting emplacement of the basalt during the early Triassic (Murray, 1994). However, in Lambda-1, the basalt is situated between the Jurassic Birkhead Formation and the Triassic Nappamerri Group, supporting a Late Triassic to Jurassic age (Draper, 2002). K-Ar dating of basaltic volcanic rocks is often unreliable due to unquantified argon loss (Schofield *et al.*, 2017) and in combination with the extensive seismic evidence for Middle to Late Jurassic age volcanics, we deem a Jurassic age of eruption most likely.

DISCUSSION

Stratigraphically, all the extrusive igneous rocks analysed within well data are situated between Jurassic sedimentary rocks (the Hutton and Birkhead Formations) and the Triassic Nappamerri Group. which supports a late Triassic to Jurassic age. The corroboration of well data with 3D seismic reflection data has allowed us to define further intrusive and extrusive volcanic events that are strata-concordant with the Birkhead Formation and Hutton Sandstone, placing them between ~178 and 160 Ma. The oldest extrusive volcanics identified using 3D seismic reflection data are vents observed within the northern Challum 3D survey that appear to sit near the top of the Nappamerri Group below the Hutton Sandstone. This could extend the age of the Warnie Volcanic Province into the Triassic which would agree with the K-Ar dating for the Lambda 1 well. Equally, the vents could be interpreted as cross-cutting the Triassic strata which would give them an Early Jurassic age. In the absence of further data, their exact age is unclear. We conclude that the vast majority of igneous rocks identified using 3D seismic reflection data and well data throughout this study have been constrained to a broad age range between ~178 and 160 Ma spanning the Middle Jurassic, however, further work is encouraged to better define their ages.

Our interpretation of seismic data indicates that igneous features in the study area are typically twice as long as they are wide. Furthermore, almost all the igneous rocks are elongated in a NW-SE direction, closely matching the strike of the faults within the Nappamerri Trough. We thus infer that during eruption and emplacement of the igneous rocks, the basin structure exerted a strong control on the morphology of lava flows and igneous intrusions.

We propose a model for the WVP based on current understanding of the lithospheric and geodynamic state of Central Australia in the Middle to Late Jurassic. We propose that asthenospheric shear above the subducting Pacific Plate stimulated mantle flow below Australia. Localisation of mantle flow occurred beneath southwest Queensland because of edge driven convection leading to emplacement of the WVP above the Nappamerri Trough. Despite our proposed model, we strongly believe that more work needs to be conducted on the area before it can be concluded what the source of the WVP is. In the Newer Volcanic Province of southeastern Australia, geochemistry, in particular major and trace element analysis, provided insights into why mantle melting occurred in the absence of extension or a mantle plume (Demidjuk *et al.*, 2007). As such, we would strongly recommend similar studies to be conducted on the geochemical signature of the basalts of the WVP.

CONCLUSIONS

We have integrated a variety of datasets to clarify the extent and character of igneous rocks emplaced above the Nappamerri Trough of the Cooper Basin, within Eromanga Basin seqeunces. Monogenetic volcanoes, igneous intrusions and compound lava flows extending over ~7500 km^2 are proposed to have been active between ~180–160 Ma forming part of the proposed 'Warnie Volcanic Province'. Regionally, the distribution of igneous rocks appears to be controlled by basement structures. On a continental scale, we interpret the

Warnie Volcanic Province to be a product of intraplate convective upwelling above the subducting Pacific slab.

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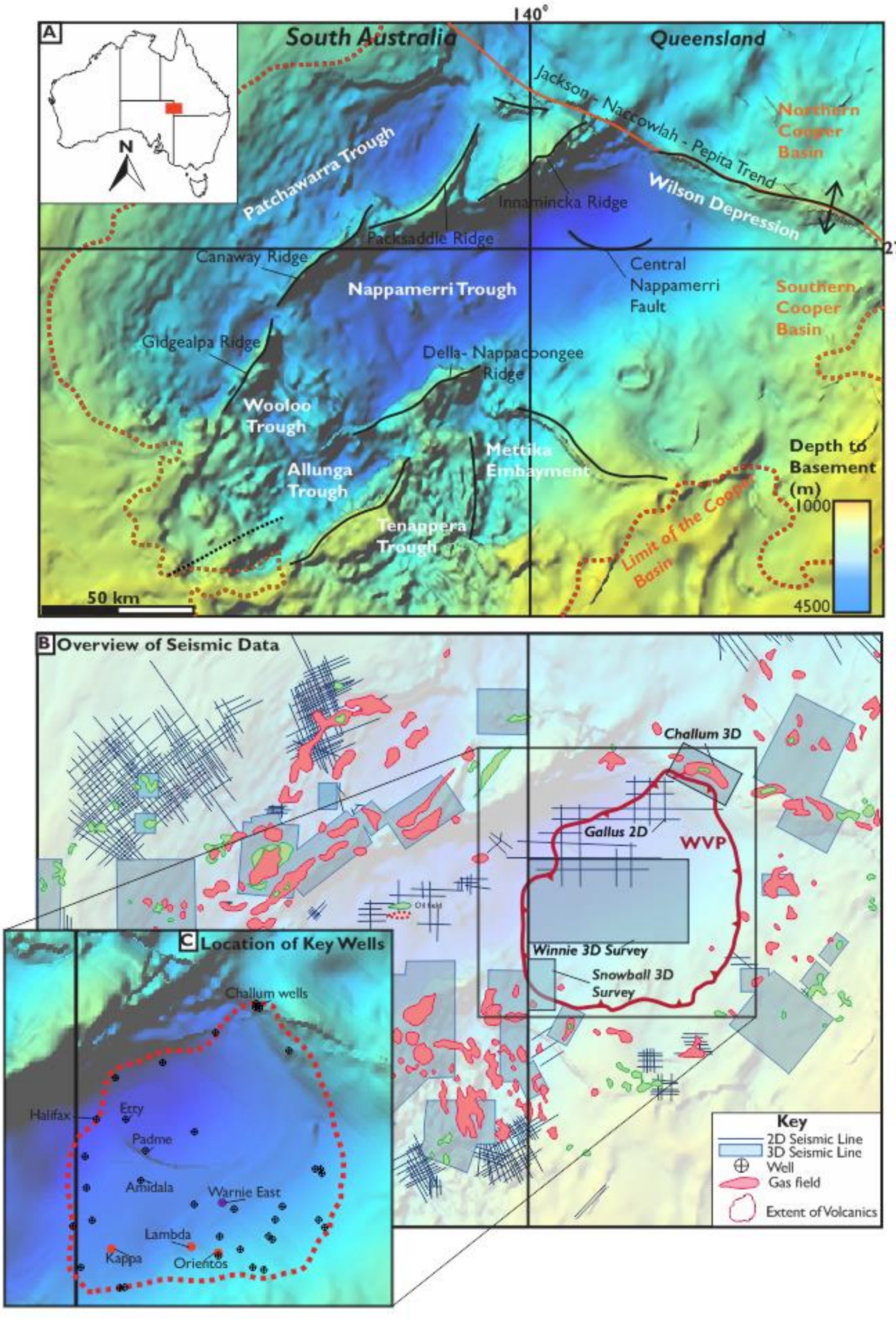

Figure 1. Location of the Warnie Volcanic Province and the data used in this study. (A) Top basement map. Key structures of the southern Cooper Basin highlighted. (B) Top basement map superimposed with the location of 3D and 2D seismic surveys utilised in this study and (C) the location of key exploration wells.

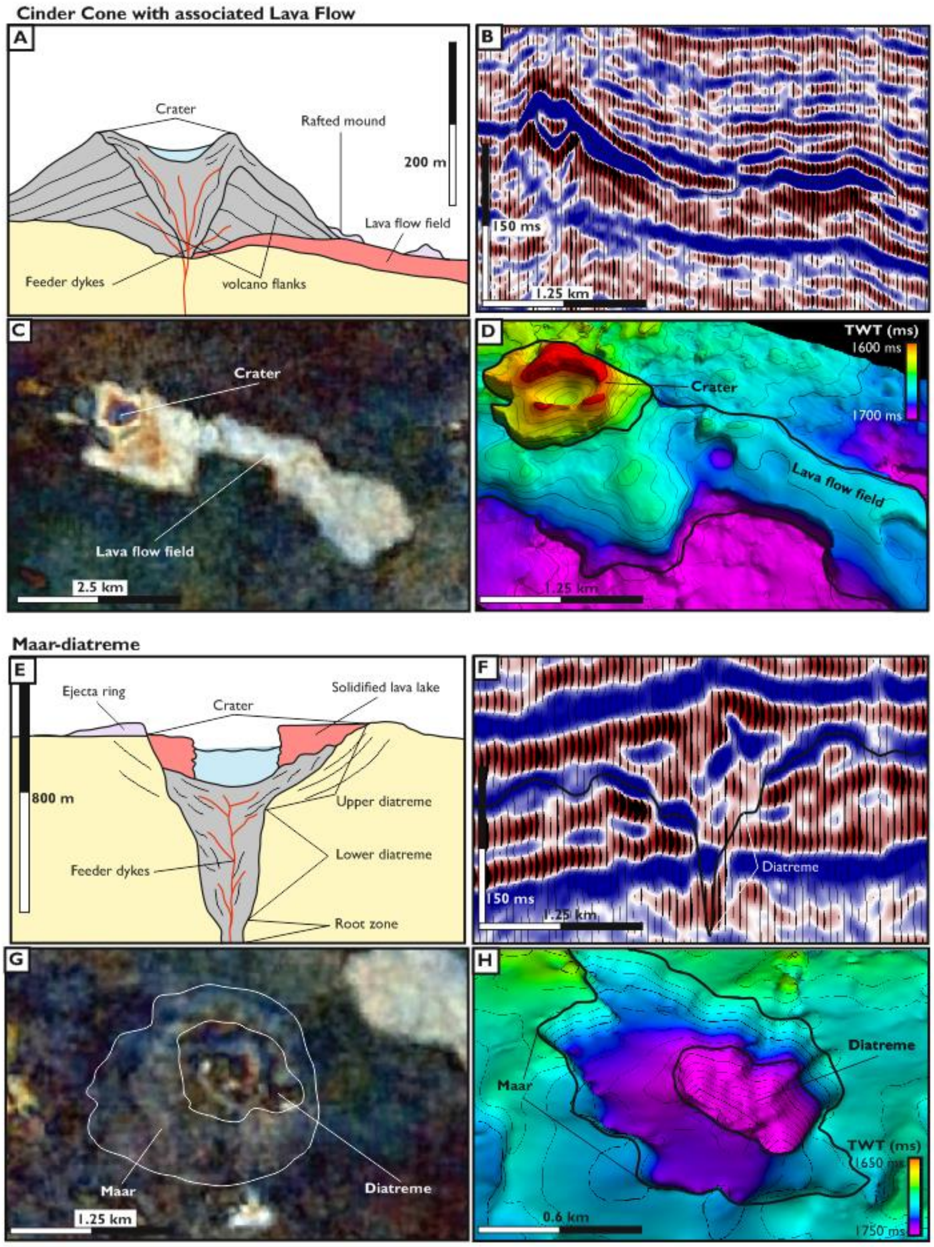

Figure 2. (A) Cross section through a cinder cone, adapted from Nemeth and Kereszturi (2015). (B) Seismic line across a cinder cone and lava flow, taken from the Winnie 3D survey, highlighting the general morphology and seismic response. Note the characteristic eye shape within the centre of the vent. (C) Plan view spectral decomposition of the cinder cone in B highlighting how different it is from the surrounding sediments. (D) Oblique view of the same cinder cone shown in TWT. (E) Cross section through a Maar-diatreme, adapted from Nemeth and Kereszturi (2015). (F) Seismic line across a proposed Maar-diatreme from the Winnie 3D survey. Note how it cuts down into the subsurface with an internally chaotic seismic response. (G) Plan view spectral decomposition of a maar-diatreme. (H) Oblique, TWT view of the proposed maar-diatreme.