

# The Warnie Volcanic Province: A Jurassic Volcanic Province in Central Australia

Jonathon P.A. Hardman<sup>1</sup>, Simon P. Holford<sup>2</sup>, Nick Schofield<sup>1</sup>, Mark Bunch<sup>2</sup> Daniel Gibbins<sup>3</sup>

<sup>1</sup>*Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3FX, UK*

<sup>2</sup>*Australian School of Petroleum, University of Adelaide, Adelaide, SA 5005, Australia*

<sup>3</sup>*Vintage Energy, 58 King William Road, Goodwood SA 5034, Australia*

e-mail: [simon.holford@adelaide.edu.au](mailto:simon.holford@adelaide.edu.au)

## Abstract

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 from well data. However, the areal extent and nature of these basaltic rocks were largely unclear. Here, we integrate seismic, well, gravity and magnetic data to clarify the extent and character of igneous rocks preserved within Eromanga Basin stratigraphy 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<sup>2</sup> and is proposed to have been active between ~180-160 Ma. We deem 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. Finally, we detail how the WVP fits into the record of Jurassic volcanism in eastern Australia. The WVP is interpreted as a product of extension and intraplate convective upwelling above the subducting Pacific Slab. The discovery of the WVP raises the possibility of other, yet unidentified, volcanic provinces worldwide.

## Keywords

Intraplate; volcanism; monogenetic; Australia; Jurassic

## 1. Introduction

The Cooper and the overlying Eromanga Basin extend for 130,000 km<sup>2</sup> and 1,000,000 km<sup>2</sup> respectively across central, north and eastern Australia. Together, they represent the largest conventional onshore hydrocarbon-producing region in Australia (Hall, 2016). The first gas discovery was made in 1963 and since then, over 1,400 producing wells have been drilled, with 190 gas and 115 oil fields discovered throughout both basins (Fig. 1) (Mackie, 2015). 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

33 plays within the basin during the late 2000s, resulting in an increase in activity within the  
34 Nappamerri Trough (Hillis *et al.*, 2001; Pitkin *et al.*, 2012; Khair *et al.*, 2013; Scott *et al.*, 2013;  
35 Hall *et al.*, 2016). The Nappamerri Trough is the largest and deepest depocentre within the  
36 Cooper Basin covering  $\sim 10,000$  km<sup>2</sup> and reaching present day depths of  $\sim 4.5$  km (Fig. 1A).  
37 The acquisition of new well and seismic data due to the exploration activities has resulted in  
38 the increased recognition of igneous rocks in the Cooper and Eromanga Basins.

39 Igneous rocks of suspected late Triassic-Jurassic age have been sporadically  
40 encountered by drilling during the past 34 years (Short, 1984; Boothby, 1986; Bucknill, 1990;  
41 Allen, 1998), though there has been no systematic study of the character, origin and  
42 significance of these igneous rocks. Here, we combine extensive seismic, well and airborne  
43 geophysical data to document the extent and character of Mesozoic volcanics recognised  
44 within Eromanga Basin stratigraphy overlying the Nappamerri Trough of Cooper Basin age.  
45 The Warnie Volcanic Province (WVP) is the suggested name for this  $>7,500$  km<sup>2</sup> suite of  
46 volcanics identified within the Jurassic succession of the Eromanga Basin (Fig. 1B). The  
47 province is named after the Warnie East 1 exploration well, which was drilled in 1985 and  
48 encountered 65 m of basalt. We provide an in-depth study of the regional implications of the  
49 WVP for the Cooper and Eromanga Basins. We find that SE-NW intracratonic sag faulting  
50 (Kulikowski *et al.*, 2015) controlled the morphology of igneous rocks whilst the basin structure  
51 likely controlled the location of igneous rocks.

52 Finally, we discuss the origin of the WVP. Evidence for Triassic to mid-Cretaceous  
53 volcanic activity is pervasive throughout the sedimentary basins of central Australia,  
54 manifested by an influx of volcanic arc-derived sediment into the Eromanga Basin (Boult *et al.*,  
55 1998), silicic tuffs in the Surat Basin (Wainman *et al.*, 2015) and widespread volcanogenic  
56 zircons throughout the Great Artesian Basin (Bryan *et al.*, 1997). However, the origin of  
57 intraplate volcanism is contentious and can be difficult to isolate from tectonic processes  
58 occurring close to the region of volcanism (Conrad *et al.*, 2011; Zhou *et al.*, 2018). The WVP  
59 was located  $>500$  km away from a significant plate boundary during the Jurassic. It is therefore  
60 important to consider the source of this volcanism and the tectonic implications for central  
61 Australia. We theorise that the WVP's geodynamic origin is ultimately linked to subduction  
62 at the eastern margin of Gondwana, through asthenospheric shear  $\sim 1500$  km from the oceanic  
63 trench, however, we also discuss other mechanisms that can produce intraplate volcanism.  
64 Our discovery of a previously undescribed volcanic province in an area that has undergone  
65  $>50$  years of extensive subsurface data collection due to continued hydrocarbon exploration,

66 raises the prospect of other undiscovered intraplate volcanic provinces both in Australia and  
67 in other continental areas worldwide.

## 68 **2. Geological Overview of the Cooper and Eromanga Basins**

69 The geology of southwest Queensland and northeast South Australia, central Australia, is  
70 defined by a series of intracratonic basins stacked on top of each other; the Warburton,  
71 Cooper, Eromanga and Lake Eyre Basins (Fig. 2 & Fig. 3).

72 The Warburton Basin is a lower Palaeozoic sedimentary basin that hosted Silurian to  
73 Carboniferous granite emplacement (Murray 1986; Boucher 1997; Alexander *et al.*, 1998).  
74 The Cooper Basin unconformably overlies the Warburton Basin. The Cooper Basin is a  
75 northeast to southwest trending intracratonic structural depression that accommodated the  
76 deposition of sedimentary rocks from the late Carboniferous to the Middle Triassic (Laws &  
77 Gravestock, 1998). Several tectonic origins for the Cooper Basin have been suggested,  
78 including a mildly compressional structural depression (Apak, 1994 & Sun, 1997), a depression  
79 created through wrenching (Kuang, 1985) and extension during post-compression flexural  
80 relaxation (Kulikowski *et al.*, 2015). Deposition throughout the early Permian was dominated  
81 by highly sinuous fluvial systems situated on a major floodplain with peat rich swamps and  
82 lakes (Abul Khair *et al.*, 2015). Later Triassic deposition took place in a period of tectonic  
83 quiescence (Gravestock *et al.*, 1998).

84 Deposition in the Cooper Basin was terminated by regional uplift, compressional folding and  
85 erosion in the middle Triassic. The Cooper Basin is unconformably overlain by the Eromanga  
86 Basin, which forms part of the Great Artesian Superbasin (GAB), a group of interconnected  
87 basins that cover much of Queensland, South Australia and New South Wales. The Eromanga  
88 Basin is an intracratonic sag basin whose subsidence has been attributed to dynamic  
89 topography induced by subduction of the Pacific plate below Australia (Gallagher & Lambeck,  
90 1989; Russell & Gurnis, 1994; Matthews *et al.*, 2011). Deposition within the Eromanga Basin  
91 was controlled by subsidence rates and tectonic activity on the margins of the Australian Plate  
92 that were attributable to subduction of the Pacific plate beneath the Australian plate  
93 (Alexander *et al.* 1996; Draper, 2002).

### 94 **2.1 The Jurassic Succession of the Eromanga Basin**

95 The Jurassic succession of the Eromanga Basin is of stratigraphic importance as it is where the  
96 extrusive igneous rocks documented within this study are believed to be located. Much of the

97 Jurassic strata in the Eromanga Basin consists of predominantly quartzose fluviatile sandstones  
98 with subordinate shales and some coals (Senior *et al.*, 1978; Exon & Burger, 1981; Draper  
99 2002). Sediments in the Eromanga Basin can be divided into three packages of decreasing age;  
100 lower non-marine, marine and upper non-marine. The focus of this study is the lower non-  
101 marine package that was deposited between the early Jurassic (~206 Ma) and the early  
102 Cretaceous (~119 Ma) (Fig. 2). During this time, large sand-dominated, braided fluvial systems  
103 drained into lowland lakes and swamps. Throughout deposition, it is believed that sediment  
104 supply was a competing product of input from arc volcanism to the east, and sediment sourced  
105 from stable cratonic regions to the south (Boult *et al.*, 1997). In the next part of this paper  
106 we detail the Early to Late Jurassic stratigraphy in order to provide a palaeogeographic  
107 framework for the study. The stratigraphic framework of the Jurassic succession has been  
108 iterated considerably in the last 20 years, evidenced by the progression of Alexander &  
109 Hiburt's stratigraphic ages (1996) to Reid *et al.*'s (2009), to those listed on the Australian  
110 Stratigraphic Units Database (Geoscience Australia, 2017). For each formation we have used  
111 the most up-to-date reference available.

#### 112 2.1.1 Poolowanna Formation, Early Jurassic, ~200–178 Ma

113 In southwest Queensland, the Poolowanna Fm. sits unconformably on top of the Late Triassic  
114 unconformity, which formed as a result of uplifting, tilting and erosion of the Cooper Basin at  
115 the end of the Early to Middle Triassic (Fig. 5). The palaeotopography of this unconformity  
116 strongly controlled deposition of the Poolowanna Formation and the subsequent Hutton  
117 Sandstone (Hall *et al.*, 2015). Lithologies consist of coal and silt deposited in a highly sinuous  
118 fluvial setting with minor coal swamps (Hall, 2015).

#### 119 2.1.2 Hutton Sandstone, Early to Middle Jurassic, ~178–166 Ma

120 The Hutton Sandstone is a high energy braided fluvial Jurassic sandstone that either sits  
121 conformably on top of the Poolowanna Fm. or, where the Poolowanna is not present,  
122 unconformably above Triassic sediments (Kapel, 1966; Watts, 1987). The Hutton Sandstone  
123 is a mineralogically mature fine to coarse-grained sandstone with minor siltstone interbeds  
124 (Hall *et al.*, 2015). Throughout much of the Great Artesian Basin, the Hutton is a regional  
125 aquifer extending over an area of 1.7 million km<sup>2</sup> (Hamilton *et al.* 1998). Similarly, the Hutton  
126 is the main reservoir within the Jurassic succession of the Eromanga Basin.

### 127 2.1.3 Birkhead Formation, Middle to Upper Jurassic, ~ 166–160 Ma

128 The boundary between the Hutton and Birkhead formations is sharp to transitional across  
129 the Eromanga Basin (Lanzilli, 1999) and is associated with a change in the depositional setting  
130 from the high energy, braided fluvial setting of the Hutton Sandstone to a low energy, fluvial-  
131 deltaic to deltaic and lacustrine setting in the Birkhead Formation (Watts, 1987; Lanzilli, 1999).  
132 This decrease in depositional energy is also associated with a change in sediment provenance  
133 from craton-derived sediment to lithic-rich, volcanogenic sediment from a proposed volcanic  
134 arc situated to the east above the subducting Pacific plate (Lanzilli, 1999). The diachronous  
135 influx of volcanogenic sediments can be traced across the Eromanga Basin (Boult, 1997). It is  
136 commonly picked as the top of the porous unit in the Hutton Sandstone (Patton, 1986; Watts,  
137 1987), however, it can also be identified by the influx of lithic rich sandstones (Watts, 1987).  
138 There are several key features associated with the sediments shed from the volcanic arc  
139 (Patton, 1986):

- 140 • 50% quartz with high amounts of potassium and plagioclase feldspar. Trace amounts  
141 of tourmaline, pyroxene, mica and zircon were also noted (Watts, 1987; Alexander  
142 and Sansome, 1996).
- 143 • Lithic fragments mostly consisting of labile minerals.
- 144 • Common altering of the above lithics to kaolinite and chlorite or replacement of  
145 carbonate cements such as siderite or dolomite.
- 146 • Rare glassy fragments.

147 Based on the lithology of the volcanogenic sediments, it has been concluded that the volcanics  
148 that formed them were of acid to intermediate affinity (Patton, 1986). The influx of  
149 volcanogenic sediments is believed to have been controlled by the margin above the  
150 subducting Pacific plate (Boult *et al.*, 1998). During the Jurassic it is suggested that subduction  
151 of the Pacific plate beneath Australia caused extensive arc volcanism (Tucker *et al.*, 2016).  
152 When uplift in this area was greatest, volcanogenic sediments were shed into the Eromanga  
153 Basin (Boult *et al.*, 1997). Volcanogenic sediment in the Birkhead Fm. often forms a weak link  
154 with lower sealing capacity within what is the main sealing lithology for the Hutton Sandstone  
155 (Boult *et al.*, 1997).

#### 156 2.1.4 Adori Sandstone, Upper Jurassic, ~ 160-155 Ma

157 The Birkhead Formation is capped by the Adori Sandstone, marked by a transition to clean,  
158 non-volcanogenic sedimentation. The Adori Sandstone is a well sorted and typically cross  
159 bedded, fine to coarse-grained sandstone (Hibburt, PGSA). It is interpreted to have been  
160 deposited in a low sinuosity fluvial system consisting of channel, point bar and flood plain  
161 deposits in the Central Eromanga Basin (Burger & Senior, 1975; Hibburt, PGSA). Due to the  
162 absence of igneous rocks in the Mesozoic to Cenozoic succession younger than the Adori,  
163 the succession is not discussed in detail here.

#### 164 2.2 Structural Setting of the Study Area

165 Structurally, the Cooper Basin can be divided into southern and northern sections  
166 (Gravestock & Jensen-Schmidt, 1998; Hall, 2016). To the north, depocentres are dominantly  
167 Triassic, with Permian depocentres in the south (Hall *et al.*, 2018). The northern and southern  
168 sections of the Cooper Basin are separated by the Jackson-Naccowlah-Pepita Trend (JNP  
169 trend) (Fig. 1). In the south west, depocentres are generally thicker, reaching a maximum  
170 thickness of 2400 m in the Nappamerri Trough (Hall *et al.*, 2015) and many of these  
171 depocentres have experienced synclinal folding due to differential compaction (Apak, 1997).  
172 The major depocentres are separated by northeast-southwest trending ridges (Gravestock &  
173 Jensen Schmidt, 1998).

174 The area of focus in this study is the eastern Nappamerri Trough of north east South Australia  
175 and south west Queensland. The Nappamerri Trough contains the deepest basement within  
176 the Cooper Basin and hosts the Halifax well that intersected the deepest Permian-age  
177 sedimentary rocks in the basin at 4,209 m (Beach Energy, 2013b). To the north, the  
178 Nappamerri Trough is bounded by the Gidgealpa, Canway, Packsaddle and Innamincka ridges  
179 (Fig. 1A). The southern extent of the Nappamerri Trough is bounded by the Della-  
180 Nappacoongee, Dunoon and Murteree ridges (Fig. 1) (Hall, 2016). The ridges bounding the  
181 northern and southern Nappamerri Trough are cored by deep thrust faults reactivated from  
182 pre-existing structures within the Warburton Basin (Robert *et al.*, 1990). These were believed  
183 to have been reactivated in the Permian and the Cenozoic, when the Cooper and Eromanga  
184 Basins were subject to contractional deformation (Sun, 1997).

### 185 **3. Methodology**

#### 186 **3.1 Identification of Volcanics Using Subsurface Data**

187 A number of volcanic features can be recognised using subsurface data. Here we describe the  
188 main techniques that were used to investigate igneous rocks within the Nappamerri Trough.

##### 189 *3.1.1 Seismic Data*

190 Seismic reflection is a geophysical technique that estimates properties of the earth's  
191 subsurface through the measurement of reflected seismic waves. It can be used to provide an  
192 estimate of the acoustic impedance of the boundaries to layers of rock within the subsurface  
193 (the product of the acoustic velocity and density of a rock). Seismic reflection data have been  
194 shown by numerous studies to be especially effective at imaging igneous rocks due to the high  
195 acoustic impedance of igneous material when compared to surrounding sedimentary rocks,  
196 and the distinctive morphology formed by lava flows and intrusions (Planke *et al.*, 2000). Here  
197 we provide a brief introduction to the different types of igneous rock identified in the  
198 subsurface on seismic reflection data

199 Vents identified within seismic reflection data are typically grouped into either hydrothermal  
200 or volcanic vents (Reynolds *et al.*, 2017). The morphologies of hydrothermal vents and  
201 volcanoes are similar as they both exhibit eye, dome or crater shaped morphologies in seismic  
202 data (Fig. 4B)(Planke *et al.*, 2005; Grove, 2013; Reynolds *et al.*, 2017). This can make  
203 distinguishing hydrothermal vents from volcanoes difficult when seismic reflection data are  
204 the sole data source.

205 Volcanoes can be confidently identified using seismic reflection data where they extend into  
206 lava flows (e.g. Fig. 4A-D). Lava flows are distinguishable as layer-parallel acoustically hard,  
207 bright reflectors within the subsurface (Planke *et al.*, 2000; Schofield & Jolley, 2013; Hardman  
208 *et al.*, 2018A) (Fig. 4B). Extrusive igneous rocks are distinguishable from intrusive igneous  
209 rocks as they do not transect stratigraphy.

210 Igneous intrusions have been studied intensely using 3D seismic data (Bell & Butcher, 2002;  
211 Thomson & Schofield, 2004; Archer *et al.*, 2005; Magee *et al.*, 2014). Igneous intrusions form  
212 acoustically hard, bright reflectors that are layer parallel or transect stratigraphy. In places,  
213 they can produce forced folding of the overburden with onlapping stratigraphy facilitating age-  
214 dating of the intrusion (Trude *et al.*, 2003).

### 215 3.1.2 Seismic Attributes

216 3D seismic reflection data facilitates the analysis of the geophysical properties of igneous rocks  
217 in 3D. Seismic attributes such as RMS amplitude and spectral decomposition have proven to  
218 be effective tools in picking the extent and morphology of lava flows in seismic data (Fig.4C)  
219 (Schofield & Jolley, 2013; Planke *et al.*, 2017; Hardman *et al.*, 2018A; Reynolds *et al.*, 2018).  
220 Spectral decomposition involves filtering 3D seismic reflection wavelets to produce three  
221 amplitude components at distinct frequencies that are displayed as separate colour channels  
222 using the primary colours red, green and blue. These channels are then blended to produce  
223 full colour spectrum images where the igneous rocks appear visibly different to the  
224 surrounding sediments, due to their differing reflectiveness for particular frequencies (they  
225 transmit acoustic energy efficiently at all frequencies). Furthermore, this technique can be  
226 used to investigate the geometries of igneous rocks, and features such as inflation lobes (Fig.  
227 8C) can help with distinguishing igneous intrusions from extrusive igneous rocks.

### 228 3.1.3 Well Data

229 In addition to the use of seismic data, the integrated analysis of borehole data including  
230 wireline log responses, core and cuttings is essential to accurately identifying igneous rocks  
231 within the subsurface (Nelson *et al.*, 2009; Rider & Kennedy, 2011; Watson *et al.*, 2017). The  
232 onshore response of igneous rocks in outcrop has been linked to offshore observations  
233 facilitating the identification of different volcanic facies through petrophysical and petrological  
234 analysis (Nelson *et al.*, 2009; Millet *et al.*, 2016).

235 Here, we use a combination of petrophysical and petrological data in our description of the  
236 WVP. Although cuttings and core were not examined within this study, descriptions were  
237 available within well reports that were integrated with petrophysical data and seismic  
238 reflection data to provide a comprehensive overview of the data available.

## 239 3.2 Description of Dataset

240 The Cooper and Eromanga Basins have been explored extensively over the past 60 years, so  
241 are characterised by the largest collection of well and seismic reflection data for any onshore  
242 sedimentary basin in Australia (Carr *et al.*, 2016). A large database of seismic reflection data  
243 was available through Santos Limited and the Queensland Government's Department of  
244 Natural Resources and Mines. 3D and 2D seismic reflection surveys throughout the South  
245 Australian and Queensland sides of the basin were assessed for the presence of volcanic rocks



246 (the extent of the seismic data examined is visible on Fig. 1B). Notably, only four surveys  
247 available to this study (the Winnie 3D, the Gallus 2D, the Challum 3D and the Snowball 3D  
248 survey (provided by Santos Limited)), were interpreted to contain volcanic rocks. Unless  
249 stated, seismic data were displayed using normal (American) polarity, whereby a downward  
250 increase in acoustic impedance corresponds to a positive (blue) reflection and a downward  
251 decrease a negative (red) reflection.

252 Over 2000 wells have been drilled in the Cooper and Eromanga Basins. Despite this, of the  
253 wells available, only 3 (Lambda 1, Orientos 2 and Kappa 1) were identified as having  
254 intersected extrusive volcanic rocks with only 1 well (Warnie East 1) encountering an  
255 intrusive igneous rock. The Warnie East 1, Lambda 1 and Orientos 2 wells were key in  
256 constraining volcanism above the central Nappamerri Trough (Fig. 1C). The Kappa 1 well was  
257 adjacent to the Snowball 3D survey, aiding interpretation of volcanism in the south west (Fig.  
258 1C). To estimate the relative age of the volcanic units, well data were tied, where possible,  
259 to the seismic reflection surveys available. For constraining the age of the Eromanga  
260 succession within the Central Nappamerri trough, the Halifax, Ety, Padme, Charal and Anakin  
261 wells were key (location on Fig. 1C).

262 Here we present an overview of all the available datasets that constrain the distribution and  
263 age of igneous rocks within the study area. First, we detail the main WVP, within which the  
264 lithology and morphology of the igneous rocks appear broadly similar throughout the eastern  
265 Nappamerri Trough. We then deal with the Snowball 3D survey and the Kappa 1 well that  
266 image volcanic rocks that have a markedly different petrological and geophysical character  
267 when compared to the rest of the WVP. It is important we recognise that whilst this is the  
268 extent of the data that was available during this study, the authors are aware of other seismic  
269 reflection surveys within the Nappamerri Trough that were not available to download digitally  
270 and were not possible to acquire within the period of time during which this study was  
271 conducted. These surveys may also image igneous rocks that could fuel further work on the  
272 area.

## 273 **4. Description of Igneous Rocks in Seismic Data within the eastern Nappamerri** 274 **Trough**

### 275 **4.1 Winnie 3D**

276 The main 3D seismic reflection survey utilised within this study is the Winnie 3D survey.  
277 Acquired in 2012 by Drillsearch Energy Ltd. The survey was shot above the eastern  
278 Nappamerri Trough in southwest Queensland over an area of 2545 km<sup>2</sup> (Fig. 1). The main  
279 focus when acquiring the survey was on the unconventional targets in the area, typically the  
280 extensive Permian coal-rich source rocks (Hillis *et al.*, 2001; Schmidt, 2013). The dominant  
281 frequency within the Jurassic succession is ~40 Hz, with volcanic rocks in the region having  
282 an acoustic velocity of 4 to 6 kms<sup>-1</sup> (taken from the Lambda-1 exploration well). Using an  
283 average velocity of 5 kms<sup>-1</sup> a vertical resolution of ~30 m and a detection limit of 4 m was  
284 calculated.

#### 285 **4.1.1 Extrusive Igneous Rocks**

286 We identified ~100, <= 4 km<sup>2</sup> cone shaped features that often express an eye-shaped  
287 morphology (Fig. 2B). The cones within the survey are less than 2 km long and 750 m wide,  
288 and often elongate in a NW-SE direction. We have interpreted these as monogenetic  
289 volcanoes, small cumulative volume volcanic edifices built up by one continuous, or many  
290 discontinuous, small eruptions over a short time scale (<= 10 years) (Nemeth & Kereszturi,  
291 2015).

292 Twelve of the volcanoes are linked with what appear to be elongate, NW-SE oriented  
293 lava flows that are conformable to stratigraphy and have dimensions of 2-7 km in length and  
294 0.5-2.5 km in width (covering areas of 4-13.5 km<sup>2</sup>) (e.g. Fig. 6 & 7). The flows appear to be  
295 strata-concordant and confined to the Hutton Sandstone or the base of the Birkhead  
296 Formation which would place the flows between 160 and 178 Ma (Alexander & Hibburt, 1996)  
297 (Fig. 7).

298 We have also interpreted one feature within the survey as a diatreme. Maar-diatreme  
299 volcanism can occur where a volcanic pipe forms through gaseous explosions that cut into  
300 the country rock (Fig. 4 E-H)(White & Ross, 2011). These explosions form a maar (the crater  
301 and associated ejecta ring) and a diatreme (the root to the maar), consisting of a steep-sided  
302 cone shaped structure filled with pyroclastic, volcanic and country rocks)(White & Ross,

2011). Unlike vents and associated lava flows, they consist of downward dipping reflectors that truncate the underlying stratigraphy with typically chaotic internal reflectors (Fig. 4F). Spectral decomposition proved to be the most powerful tool for identifying maar-diatremes above the Nappamerri Trough, as the circular crater morphology stood out against the surrounding sediments (Fig. 4G). One feature interpreted to be a diatreme was identified within the survey, displayed in detail in (Fig. 4). It is  $\sim 2.25 \text{ km}^2$  and  $\sim 120 \text{ m}$  deep (150 ms, TWT) and is found in the west of the Winnie 3D survey (Fig. 6).

#### 4.1.2 Intrusive Igneous Rocks

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 Fms (e.g. Fig. 8A). We identified and mapped 14 intrusions in the seismic data; these occur  $\sim 100$ – $200 \text{ ms}$  ( $\sim 105$  –  $210 \text{ m}$ ) 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 (Fig. 8A & B). Classical intrusion related features such as inflation lobes are observed within spectral decomposition (Fig. 8C).  $\sim 20$  vents cross-cut this intrusion (see pockmarks on Fig. 8C), in places leading to extrusive lava flows in the overlying sediments (see surface flows on Top Birkhead overlying the intrusion in Fig. 8B). The presence of the pockmarks on the surface of the intrusion suggest emplacement of the sill predated a later stage of volcanism that occurred towards the top of the Birkhead Fm.

#### 4.1.3 Timing of Volcanism and Intrusion

The timing of igneous activity within the Winnie 3D survey was constrained by the stratigraphic relationship between igneous activity and the Triassic to Jurassic stratigraphy in the study area. In places, intrusions are observed to have caused forced folding of the overburden, as evidenced by onlap of Birkhead Fm. sediments onto the deformed overburden overlying the intrusions (Fig. 8B). Onlap of sedimentary rocks onto these forced folds was used to age constrain the intrusion (Trude *et al.*, 2003), whilst the strata-concordant surface flows were assigned an approximate age based on their stratigraphic level that was tied to known stratigraphy within the wells. We estimate that volcanism lasted throughout deposition of the Hutton and Birkhead formations between  $\sim 178$  and  $160 \text{ Ma}$ , with the youngest

334 volcanics identified as surface flows emplaced on the top Birkhead marker horizon (Alexander  
335 & Hibburt, 1996).

#### 336 *4.1.4 Basement Structure and Igneous Rock Distribution*

337 The basin structure of the eastern Nappamerri Trough is largely obscured by the thick  
338 Cooper and Eromanga Basin fill (the deepest Permian-age sedimentary rocks drilled in the  
339 basin are 4,209 m deep (Beach Energy, 2013b)) and the highly reflective coals of the Permian  
340 Toolachee and Patchawarra Fms that make imaging of deeper sediments difficult. Of all the  
341 3D seismic reflection surveys available for this study, only the Winnie 3D survey imaged  
342 reflections ~2800 ms deep within the Nappamerri Trough (approximately 4.3 km subsurface  
343 depth based on the Charal-I time-depth relationship). Notably, the exact lithology of this  
344 reflection is unclear, largely due to the lack of any intersections in the Central Nappamerri  
345 wells. Unlike the flat-lying Cooper and Eromanga stratigraphy, these deep reflections were  
346 often inclined at an angle of  $\sim 10^\circ$  (taken with the scale set so that 1s TWT depth = 1 km  
347 distance laterally). Although not confidently picked throughout the whole of the Winnie 3D  
348 survey, the reflections can be mapped over an area of  $\sim 600 \text{ km}^2$  (Fig. 9C). We interpret these  
349 to represent the top Basement in the Nappamerri Trough.

350 In places, the reflections are visibly offset on the order of  $\sim 100$  ms (Fig. 9A). When mapped  
351 and in plan view, it is clear that the most major offset (a  $\sim 400$  ms step in the data visible in  
352 Fig. 9A) trends  $\sim 15$  km NW-SE across the Winnie 3D survey (Fig. 9C). The same 400 ms step  
353 has been noted by previous mapping (NGMA, 2003) where it is visible on a top basement  
354 map in the eastern Nappamerri Trough. We interpret offset of the top basement as faulting  
355 and, so that it may be easily referred to throughout the text, name the major 400 ms offset  
356 the Central Nappamerri Fault.

357 Beneath the vents and volcanoes of the Winnie 3D survey, the seismic reflection data  
358 exhibited a velocity pull-up effect, where reflection events directly beneath the vents were  
359 pulled up in two-way time relative to the surrounding area (Fig. 9A). This could either  
360 represent shallow high velocity material (i.e., the vents or volcanoes themselves) or a high  
361 velocity feeder zone representing a vertical column of igneous rock or hydrothermally altered  
362 host rock. This effect was particularly obvious on the well-imaged Toolachee Fm. and, hence,  
363 the Toolachee Fm. was mapped in order to better constrain the distribution of the pull-up  
364 effects throughout the area (Fig. 9C). Here, the distorted zones are imaged as dark patches  
365 that are clearly distinguished from the fluvial channels that make up the Toolachee Fm. (Fig.

366 9C). We have interpreted these as vents that are either hydrothermal vents or basaltic dykes.  
367 The position of these vents was highlighted and superimposed on top of an image of the  
368 basement reflections (Fig. 9C). The vents broadly fall into two groups, one to the SW of the  
369 Central Nappamerri Fault and one to the NE of the Central Nappamerri Fault. These groups  
370 fall adjacent to the Top Basement reflections or directly above visible offset in the basement,  
371 strongly implying a pervasive structural control on the location of vents in the Winnie 3D  
372 survey.

#### 373 **4.2 Gallus 2D**

374 The Gallus 2D seismic reflection dataset was shot in 2013 by Beach Energy. The survey covers  
375 420 km<sup>2</sup> of the Nappamerri Trough, to the north of the Winnie 3D survey (Fig. 11). It was  
376 used to constrain the northern extent of the WVP. Although a dominant frequency of ~35  
377 Hz and average velocity of 5 kms<sup>-1</sup> for the igneous rocks in the area suggests a vertical  
378 resolution of ~40 m and a detection limit of 5.5 m, imaging was generally poorer than that of  
379 the Winnie 3D survey. This was probably due to the inferior signal-to-noise ratio of stacked  
380 2D seismic reflection data by comparison with that of an equivalent section line extracted  
381 from stacked 3D data. In particular, the 2D nature of the survey and, hence, the inability to  
382 conduct attribute analysis made the mapping of igneous rocks difficult.

383 A northwards continuation of the monogenetic vents, flows and intrusions that were detailed  
384 in the Winnie 3D survey is imaged within the Gallus 2D survey (Fig. 11A-C). In order to  
385 better constrain the distribution of the volcanics in the Gallus 2D survey, the top and bottom  
386 of the igneous rocks were mapped. From these, we calculated the isochron thickness of the  
387 igneous rocks in the area (Fig. 11A). Like the Winnie 3D survey, volcanism was more pervasive  
388 towards the east, with the thickest volcanics (~300 ms, approximately 163 m) located at the  
389 eastern edge of the survey. Whilst none of the volcanics were intersected by any wells, the  
390 approximate stratigraphic age was constrained by the nearby Halifax and Ety wells (Fig. 11C),  
391 placing the volcanics within the Hutton and Birkhead formations, as found for the Winnie 3D  
392 survey.

#### 393 **4.3 Madigan 3D**

394 The Madigan 3D seismic reflection survey was shot in 1996 by Santos Ltd. The Madigan 3D  
395 survey covers an area of 584 km<sup>2</sup> over the Challum Field, which consists of gas reserves  
396 hosted within the Toolachee Formation and pre-Permian carbonates (Yew & Mills, 1989)(Fig.

397 10). The survey is situated across the very north eastern edge of the Nappamerri Trough,  
398 above the JNP trend, adjacent to the confluence point of the JNP trend and the Innamincka  
399 Ridge. The dominant frequency within the Jurassic succession was  $\sim 35$  Hz, and using an  
400 average velocity of  $5 \text{ km s}^{-1}$  a vertical resolution of  $\sim 35$  m and a detection limit of 5 m was  
401 calculated.

402 Two vents were identified within the seismic data that consisted of a single positive amplitude  
403 reflection (Fig. 10). The smaller vent (750 m x 1.5 km) is situated directly above the JNP trend.  
404 The second is  $\sim 5$  km to the SW and larger, at 1.5 km x 1.5 km, with a central 500 m  
405 depression interpreted to be a central crater (Fig. 10). RMS amplitude extraction reveals the  
406 central crater of both vents (Fig. 10). As neither vent was penetrated by a well and no surface  
407 flows were mapped away from the vents, it cannot be concluded whether they are volcanic  
408 or hydrothermal. Stratigraphic data from the neighbouring Challum wells were used to  
409 constrain a rough stratigraphic age for the vents, placing them towards the base of the Hutton  
410 Sandstone ( $\sim 178$ -200 Ma). It is unclear on the basis of the 3D seismic reflection data what the  
411 age of these vents is. They appear to sit near the top of the Nappamerri Group, however, this  
412 would place them in the middle Triassic  $\sim 240$  Ma,  $\sim 60$  Myrs older than the rest of the WVP.  
413 An alternative explanation would be the emplacement of these vents at the very base of the  
414 Jurassic in this region (a maximum age of  $\sim 200$  Ma, Fig. 2), as they appear to cross-cut all of  
415 the Triassic Nappamerri Group stratigraphy. This second explanation is preferable as it would  
416 fit with the proposed age for the rest of the WVP.

## 417 **5. Description of Igneous Rocks in Well Data within the Eastern Nappamerri** 418 **Trough**

### 419 **5.1 Extrusive Igneous Rocks**

#### 420 *5.1.1 Lambda I*

421 The Lambda I well was drilled in 1984 by Delhi Petroleum Pty. Ltd. At a depth of 1570.9 m,  
422 283 m of igneous rocks were intersected, directly underlying the base of the Birkhead Fm.  
423 (Fig. 12). The upper 33 m of basalt are heavily weathered, fractured and vesicular, as noted in  
424 the Lambda well report (Short, 1984). This is represented by poor seismic imaging due to the  
425 low density and acoustic velocity of the upper 33 m relative to the rest of the volcanic  
426 succession (Fig. 12A). The remaining 250 m of basalt is fresh and crystalline. It typically has

427 low gamma ray values, with consistently high density and acoustic velocity (Fig. 12A). There  
428 are localised areas where the density drops drastically, however, these are associated with  
429 increases in the caliper and may therefore point to caving of the wellbore when it was drilled  
430 or fractures within the basalt, rather than lithological variations. At the base of the basalt ~1.5  
431 m of core was cut, within which the fine grained, crystalline nature of the basalt is apparent  
432 (Fig. 12A, see picture).

433 Interval velocity histograms were created for the Lambda I volcanics. They were then binned  
434 with a bin spacing of 0.125 m order to create a velocity histogram (Fig. 12C). These were  
435 superimposed on the velocity histogram fields of Nelson *et al.*, (2009) that were obtained  
436 from boreholes on the Faroe Islands in the North Atlantic in order to compare the acoustic  
437 velocities of igneous rocks in the Nappamerri Trough with values from elsewhere. It can be  
438 seen in Fig. 12C that the Lambda I volcanics show a very strong similarity to the tabular basalt  
439 analysed by Nelson *et al.* (2009).

440 Additionally, vitrinite reflectance data (Boothby, 1986) were available for sediments  
441 deposited on top of the Lambda-I volcanics (Fig. 12B). Notably, in the sediment contact with  
442 the volcanics, there is no deviation towards high %RoMax, suggesting that the Lambda I  
443 volcanics had little thermal effect on the overlying organic matter. If this were an intrusion, it  
444 is expected that the VR values would be elevated (Stewart *et al.*, 2005) and the absence of  
445 such elevated values implies that the basalt is extrusive.

446 K-Ar dating was conducted on a bag of drill cuttings taken from a depth of 1658 m. Although  
447 the samples were too altered to be used for total rock analysis, fresh plagioclase within the  
448 cuttings was separated for analysis and used to determine an age of 227 +/- 3 Ma, suggesting  
449 emplacement of the basalt during the early Triassic (Murray, 1994). However, in Lambda-I,  
450 the basalt is situated between the Jurassic Birkhead Fm. and the Triassic Nappamerri Gp.,  
451 supporting a Late Triassic to Jurassic age (Draper, 2002). K-Ar dating of basaltic volcanic  
452 rocks is often unreliable (Schofield *et al.*, 2015), due to unquantified argon loss (Kelley, 2002).  
453 It is noted within the well report that the loss of Argon due to subsequent thermal events or  
454 contamination of drill cuttings is not accounted for in the quoted error (Murray, 1994). In  
455 combination with the extensive seismic evidence for Middle to Late Jurassic age volcanics, we  
456 deem a Jurassic age of eruption most likely.

457 *2D Seismic across the Lambda I well*

458 A single 2D seismic line intersecting the Lambda I well was available (Fig. 13). Within the 2D  
459 line, the tabular basalt intersected by the Lambda I well corresponds to a high amplitude  
460 reflection most pronounced at the location of the well but also continuing ~3 km to the west  
461 of the survey. The centre of the survey (and the location of the well) corresponds with a ~1.5  
462 km wide anticline that exhibits doming on the order of ~150 ms.  
463 Below the anticline and the location of the volcanics, the 2D seismic reflections are visibly  
464 distorted, being most pronounced beneath the location of the well where a velocity pull-up  
465 effect, similar to those observed below the igneous rocks in the Winnie 3D survey, is visible.  
466 We interpret the Lambda I volcanics to be a central vent drilled by the well, with a lava flow  
467 extending 3 km to the west of the survey.

468 Stratigraphically, the Birkhead Fm. extends across the whole survey, however, the Hutton  
469 Sandstone and equivalent sediments (not penetrated by the Lambda I well) are seen to onlap  
470 the Lambda I volcanics. The lava flow extending away from Lambda I sits atop Triassic  
471 Nappamerri Group sediments of the Cooper Basin whereas the volcanics penetrated by  
472 Lambda I appear to cross cut the Triassic stratigraphy. In combination with the well data, we  
473 believe a Hutton to Birkhead Fm. age (178 – 163 Ma) for the volcanics to be most likely,  
474 although we cannot discount that some of the volcanics may be Late Triassic in age.

#### 475 *5.1.2 Orientos 2*

476 Similarly to Lambda I, Orientos 2 drilled through volcanics situated at 1555 m, beneath the  
477 Jurassic age Adori Sandstone (Fig. 14). The well drilled through 34 m of volcanics before  
478 drilling was ceased, before reaching the base of the volcanics. The volcanics are described as  
479 dark green, grey black with quartz inclusions and common amphiboles. Similar to the Lambda  
480 I well, Orientos 2 also encountered ~14 m of chloritic, weathered basalt identifiable by low  
481 density and sonic values at the top of the volcanic succession and by the cuttings described in  
482 the end-of-well report (Bucknill, 1990). Draper (2002) noted that Orientos 2 was drilled <1  
483 km from Orientos 1, which did not intersect basalt, suggesting that the basalt in Orientos 2  
484 might be intrusive in origin. However, we note that the Padme, Anakin and Charal wells were  
485 all drilled less than 2-5 km from what appear to be extrusive volcanics identified in the Winnie  
486 3D survey, but due to the localised nature of the volcanics, they are not noted in any of the  
487 well logs. As such, we do not take the absence of volcanics in Orientos 1 to be indicative of  
488 an intrusive origin for the Orientos 2 volcanics. Due to the similarity in their log signature and



489 the lithological information recorded in the end-of-well report (Bucknill, 1990), we believe  
490 Orientos 2 drilled through a series of Jurassic-aged extrusive basalts.

#### 491 *2D Seismic across the Orientos 2 well*

492 A single 2D seismic reflection survey line running south to north across the Orientos 2 well  
493 path was available. High amplitude reflections running across the survey appear similar to the  
494 extrusive volcanics interpreted in the Winnie 3D survey, with a ~ 1 km reflection penetrated  
495 by Orientos 2 and a ~ 4 km reflection ~100 m to the north of the Orientos 2 reflection. Like  
496 the Lambda 1 volcanics, we interpreted these to be two lava flows, although vents visible  
497 below the flows suggest these flows may be made up of multiple eruptions.

498 Stratigraphically the flows sit on top of the Triassic Nappamerri Group and are onlapped and  
499 age equivalent to the Birkhead and Hutton Sandstone formations (178 – 160 ma). However,  
500 the northernmost vent and the Orientos 2 vent are situated directly below the Adori  
501 Sandstone raising the possibility of some volcanic rocks in the area that are younger than 160  
502 Ma.

## 503 **5.2 Intrusive Igneous Rocks**

### 504 *5.2.1 Warnie East 1*

505 Igneous rocks intersected within the Warnie East 1 well are lithologically unique amongst the  
506 igneous rocks penetrated by wells in the WVP. Located at 2103 m depth within the Permian  
507 Toolachee Fm, the 65 m thick basalt is fine grained and dominated by plagioclase laths  
508 intergrown with augite (Fig. 16). The upper 12 m of the volcanics appear altered and  
509 calcareous, containing phenocrysts of augite with minor pale green talc and minor calcite  
510 veining (Boothby, 1986).

511 The age of the igneous rocks is unclear based on available data. Palynological data indicates  
512 that sedimentary rocks immediately overlying igneous rocks in the Warnie East 1 well are  
513 Permian in age (belonging to the Toolachee Fm.). Furthermore, sedimentary rocks below the  
514 basalt to 2228 m are barren of palynological data. Like Lambda-1, K-Ar dating was conducted  
515 on a sample of drill core from 2163 m (Murray, 1994). Again, the rock was too altered to be  
516 used for whole rock K-Ar and, instead, unaltered pyroxene was used for dating. A middle  
517 Cretaceous age of  $100 \pm 9$  Ma was calculated (Murray, 1994), significantly younger than the  
518 rest of the WVP and the Permian host rock within which the intrusion is located. Draper

519 (2002) found the age dating to be 'equivocal' due to the large difference in age for the Lambda-  
520 I extrusive basalt ( $227 \pm 3\text{Ma}$ ) and the Warnie East intrusive basalt ( $100 \pm 9\text{Ma}$ )(ages from  
521 Murray, 1994). It is therefore important consider the K-Ar ages and the stratigraphical  
522 position of the igneous rocks with respect to other data.

523 Vitrinite reflectance data were acquired within the Warnie East I well. (Fig. 16B). Samples of  
524 vitrain were obtained and mean maximum reflectance of vitrinite calculated (Smith, 1987).  
525 Vitrinite reflectance samples adjacent (directly above and below) to the basalt show a marked  
526 increase to 4.5% relative to surrounding Toolachee sediments that are typically 1.5-1.75% (Fig.  
527 16). Whereas extrusive volcanics appear to have little thermal effect on the surrounding  
528 sediments (e.g. Grove, 2014), igneous intrusions typically show uniform heating on either side  
529 of the volcanics, as is observed here. Coupled with its stratigraphic position within the  
530 Toolachee Fm., where no other volcanics have been documented within the Cooper Basin,  
531 we conclude that Warnie East I contains the sole identified intersection of an intrusion in the  
532 WVP.

#### 533 *2D Seismic across the Warnie East I well*

534 As with the previous two wells, a 2D seismic reflection survey line runs across the Warnie  
535 East well (Fig. 17). Unlike the Lambda I and Orientos 2 volcanics, the igneous rocks within  
536 the Warnie East I well sit within the Toolachee Fm., a highly reflective sequence of  
537 heterogeneous lithologies consisting of sandstones, siltstones and coals. As such, the igneous  
538 rocks are difficult to distinguish on seismic reflection survey data, although a shallow saucer-  
539 shaped reflection intersects the well path of the Warnie East I well at the depth that igneous  
540 rocks are located. The reflection is ~1.5 km wide and transects the Toolachee Fm. over a  
541 depth range of 50 ms. The shallow saucer shape that the reflection event exhibits is common  
542 among igneous intrusions within sedimentary basins, corroborating the well data that suggests  
543 the igneous rocks are intrusive in nature.

544

## 545 **6. Description of Anomalous Igneous Rocks within the southern Nappamerri** 546 **Trough**

547 This study has so far dealt with igneous rocks of a very consistent lithology preserved within  
548 or above the Central Nappamerri Trough. However, the Kappa I well and Snowball 3D

549 seismic reflection survey, located on the very southern edge of the mapped extent of the  
550 WVP, preserve igneous rocks of a very different character (Figs. 18 -20).

### 551 **6.1 Kappa I Well**

552 The Kappa I well was drilled in 1997 on behalf of Santos Limited (Allen, 1998). The aim of  
553 the well was to evaluate the Toolachee, Patchawarra and Epsilon formations (Allen, 1998).  
554 Kappa I is located above a large anticline and is the southernmost of a string of prospects  
555 located above the Kinta structural trend, which deepens northwards into the Nappamerri  
556 Trough (Fig. 1)(Allen, 1998). Between 1895 and 2115 m, the Kappa well intersected a 120 m  
557 thick succession of volcanics below a thinned 21 m succession of Hutton Sandstone (Fig. 18).  
558 Within the well report, the volcanics are ascribed a late Permian to Middle Triassic age (Allen,  
559 1998).

560 The primary lithological information for the volcanics comes from assorted rock chips and  
561 cuttings. Due to the large amount of alteration, the volcanics appear as a chloritized basalt  
562 with abundant plagioclase, chlorite, carbonates and quartz (Allen, 1998). The rock is mottled  
563 and light green to a reddish brown colour (Allen, 1998). However, some variation was noted.  
564 Firstly, a vesicular microporphyritic basalt was identified that consisted of olivine and  
565 pyroxene phenocrysts contained within a fine grained or glassy groundmass (Allen, 1998).  
566 Secondly, less abundant coarse grained holocrystalline basalt that was composed of randomly  
567 oriented plagioclase laths, ferromagnesian crystals and accessory magnetite plus ilmenite  
568 (Allen, 1998). Importantly, and pervasively throughout the succession, a fibrous chlorite has  
569 replaced much of the ferromagnesian minerals and groundmass as well rimming and filling  
570 vesicles within the basalt (Allen, 1998).

571 The Igneous succession in Kappa I also has an unusual petrophysical expression. In our  
572 interpretation, we have divided the volcanics into two facies; in situ basalt and a volcanoclastic  
573 breccia (Fig. 18). The in situ basalt (e.g. the section between 1900 m and 1960 m (Fig. 18)) has  
574 a 'saw-tooth' response with a relatively low gamma response of ~40. Acoustic velocities from  
575 the sonic velocity log (~4 kms<sup>-1</sup>) are consistently lower than those observed in the Lambda I  
576 and Orientos 2 wells (~ 5.5-6 kms<sup>-1</sup>). The chaotic, saw-tooth response is indicative of the  
577 highly altered nature of the volcanic succession in Kappa I and the compound nature of the  
578 lava flows (Millet *et al.*, 2015; Hardman *et al.*, 2018a) (Fig. 18). The resistivity throughout the  
579 section interpreted to be in situ volcanics consistently measures 15 Ωm. As with the Lambda

580 well, we constructed a velocity histogram for the igneous rocks in the Kappa I well. When  
581 compared to Nelson *et al.*'s velocity histograms (2009) the best match was with that of  
582 Compound-braided flows (Fig. 18).

583 The volcanoclastic breccia typically consists of poorly sorted, subangular, volcanoclastic igneous  
584 rock of very fine sand to granule size (Allen, 1998). The log response for the volcanoclastic  
585 breccia is characterised by a jagged petrophysical response when compared to the in situ  
586 basalt. Although the gamma ray values (~40 api) are similar to those of the in situ basalt, the  
587 acoustic velocities (between 2800 and 4 kms<sup>-1</sup>) are consistently lower. Furthermore, the  
588 volcanoclastic breccia is water saturated with a resistivity of 2 – 3 Ωm, although this may also  
589 be a reflection of the magnetite and ilmenite within the basalt. Finally, below 2050 m to the  
590 base of the volcanic succession, the Caliper tool widened significantly suggesting the  
591 volcanoclastics in this part of the succession are considerably unconsolidated and/or fractured.

## 592 **6.2 Snowball 3D Seismic Survey**

593 The Snowball 3D seismic reflection survey is situated ~ 5 km south of the southwest tip of  
594 the Winnie 3D survey, on the border of Queensland and South Australia. Unfortunately, the  
595 Kappa I well is located ~2 km outside of the Snowball 3D survey data that was available to  
596 used within this study. Furthermore, no sonic velocity data were acquired for the Kappa I  
597 well. In order to tie this well to the Snowball 3D survey, a pseudo TWT/depth plot was  
598 created using the velocity data synthesised for the wells drilling within the central Nappamerri  
599 Trough (Fig. 19)(Halifax, Ety, Anakin, Padme, Charal).

600 The Snowball 3D seismic reflection data are displayed such that a downward increase in  
601 acoustic impedance corresponded to a red, negative reflection (European polarity). The  
602 dominant frequency within the Jurassic succession was ~35 Hz, however, the average velocity  
603 of the igneous rocks in the Kappa I survey was 4 kms<sup>-1</sup>, lower than the other igneous rocks  
604 in the WVP. Hence, a higher than average vertical resolution (lower resolvable thickness) of  
605 ~29 m and a detection limit of 4 m were calculated.

606 The top of the Kappa I volcanics is interpreted to correlate with a bright, laterally continuous  
607 red reflection that was present across the whole of the Snowball 3D survey (Figs. 19 & 20).  
608 Above the top Kappa I volcanics a second reflector, deemed here the 'Top Volcanic Mounds,'  
609 was mapped in parts of the Snowball 3D survey adjacent to a series of mound-like structures,  
610 appearing in places to downlap onto the top Kappa I volcanics (Fig. 20). The centres of these-

611 mound shaped structures are marked by a notable brightening of the reflector that is underlain  
612 by vertical vents similar to those seen in the other surveys. We thus interpret these mound  
613 structures to be a series of volcanic edifices.

614 The volcanics interpreted to be present in the Snowball 3D survey are notably different to  
615 those preserved in the Nappamerri Trough (e.g. Figs 7-9). Rather than isolated, monogenetic  
616 vents or flows, they are interpreted to represent a thick package (up to ~150 ms) of mixed  
617 volcanics and volcanoclastic breccias (based on evidence from Kappa-I) that thin towards the  
618 southwest of the survey (Fig. 20A) (i.e. the southern edge of the Nappamerri Trough).  
619 Although the true extent of them is not imaged within the survey (they are interpreted to  
620 extend beyond the survey limits), laterally they extend over 6 km. Spectral decomposition  
621 was used to gain a better understanding of these volcanics in 3D (Fig. 20C). We found darker  
622 colours surrounding the vents with these colours interpreted to represent the extent of the  
623 lava flow fields.

### 624 **6.3 Interpretation of Snowball Volcanics**

625 The volcanic succession is described as pyroclastic in the Kappa-I well report. Whilst this  
626 interpretation can account for some of the altered volcanoclastics, it does not explain the  
627 extensive sequence of altered basalt. An alternative explanation for the extensive sequence  
628 of altered basalt is differing sedimentation and eruption rates within the Eromanga succession  
629 deposited above the Nappamerri Trough. However, Mid-Late Jurassic sedimentation rates at  
630 Kappa-I of  $2.4 \text{ m.my}^{-1}$  (calculated by dividing the thickness of the Hutton to Adori succession  
631 by a duration of 23 Myrs) do not appear materially different to those in the Warnie or Lambda  
632 wells ( $2.8$  and  $2.5 \text{ m.my}^{-1}$  respectively). Hence, alteration does not appear to be a consequence  
633 of extensive surface exposure.

634 A more compelling explanation for the Kappa I volcanics is hydrothermal alteration. In  
635 volcanic regions, many lakes are typically fed by hot springs. In the East African Rift, discharge  
636 of hydrothermal water can produce authigenic chlorite with calcite and quartz forming pore  
637 filling cements (Renaut *et al.*, 2002). These minerals, particularly chlorite, are noted extensively  
638 within the petrological description of the Kappa I well. Additionally, the Kappa I well lies  
639 above the Kinta structural trend which could have provided a pathway for hydrothermal fluids  
640 into the Eromanga succession (Kulikowski *et al.*, 2015). Basin-wide hydrothermal fluid  
641 circulation has been noted within the Cooper Basin (Zwingmann *et al.*, 2001; Middleton *et al.*,

642 2014, 2015). In the Nappamerri Trough, these fluids are believed to have formed due to rifting  
643 of the eastern Australian margin during the mid-Cretaceous (Middleton, 2015). We propose  
644 that the Kappa I well represents a succession of volcanoclastic and primary volcanic rocks that  
645 was highly altered by hydrothermal fluids.

## 646 **7. Airborne Geophysical Surveys of the Nappamerri Trough**

### 647 **7.1 Gravity Data**

648 Alongside seismic and well data, airborne geophysical surveys were examined in order  
649 to further delineate the regional distribution of the WVP (Fig. 21A). The gravity data in this  
650 study were adopted from Tracey & Bacchin (2008). In southern Queensland, the Nappamerri  
651 Trough is typically characterized by a broad gravity low. However, a pronounced ~50 x 50  
652 km gravity high is apparent in the northeast Nappamerri Trough (Fig. 1B). Gravity modelling  
653 of the Cooper Basin suggests that localised gravity lows adjacent to the 50 x 50 km high within  
654 the Nappamerri Trough are the result of low density granites and granodiorites within the  
655 basement (Meixner *et al.*, 2012). Furthermore, the quantity of mapped intrusive and extrusive  
656 volcanics increases towards the centre of the 50 x 50 km gravity anomaly (Fig. 1B). We  
657 interpret the 50 x 50 km gravity anomaly to represent an expression of the WVP, as it  
658 highlights an increase in the volume of igneous rocks towards the centre of the Nappamerri  
659 Trough and perhaps also a weak point between granitic bodies that facilitated the transport  
660 of magma into the Eromanga succession. Our lack of constraint on the exact size of the WVP  
661 means we cannot confirm that the thickness and areal extent of the igneous rocks are  
662 sufficient to produce the size of the gravity anomaly observed in the Nappamerri Trough.

### 663 **7.2 Magnetic Data**

664 In addition to gravity data, a total magnetic intensity survey has been analysed (Fig. 22).  
665 Previous investigations of magnetic anomalies in the Cooper Basin by Meixner *et al.* (2000)  
666 have concluded that the sources of magnetic anomalies all occur at or below the base of the  
667 Cooper Basin succession, due to the absence of any significant magnetic sources within the  
668 sedimentary sequences of the Cooper and Eromanga basins. The Nappamerri Trough is  
669 generally marked by a low in the magnetic intensity whilst the bounding ridges are magnetic  
670 highs. However, a ~75 x 40 km magnetic intensity high runs from the Innamincka Ridge across  
671 the northern extent of the WVP in a NW-SE direction, with many smaller (<8 km<sup>2</sup> anomalies)  
672 scattered throughout the Nappamerri Trough (Fig. 22A-D). Basalt is highly susceptible to

673 being magnetised (Tarling, 1966), which has facilitated the recognition of buried volcanic rocks  
674 elsewhere in the world (Segawa *et al.*, 1975). Notably, many of the smaller magnetic anomalies  
675 do crudely correspond to the location of lava flows in the Winnie 3D survey (Fig. 22D).  
676 However, the large 75 x 40 km anomaly does not correspond with extrusive igneous rocks,  
677 otherwise this would have been imaged in the northern Gallus 2D lines. Without good seismic  
678 imaging below the Cooper Basin sediments, or boreholes that drill down through the entire  
679 Cooper Basin succession, it is difficult to confidently identify what this magnetic anomaly  
680 represents. We postulate that this could be an expression of the plumbing system of the  
681 WVP, although this is highly speculative. If true, it could point to an extensive network of  
682 igneous intrusions that are not imaged by available data.

## 683 **8. Discussion**

### 684 **8.1 The Age of the Warnie Volcanic Province**

685 Within this manuscript we have detailed the rough age of igneous rocks within the Cooper  
686 and Eromanga basins. Here we synthesise the different methods used to define an age range  
687 for the eruption of the igneous rocks.

688 K-Ar dating was conducted on both the Lambda I extrusive basalt and the Warnie East  
689 I intrusive basalt deducing an age of  $227 \pm 3$  and  $100 \pm 9$  Ma, respectively (Murray 1994).  
690 However, the large differences in age for these igneous rocks led Draper (2002) to question  
691 the validity of the results suggesting they were “equivocal.” Furthermore, Murray (1994)  
692 noted that loss of argon due to subsequent thermal events was not accounted for in the  
693 quoted error of the ages. K-Ar dating has been shown to be unreliable due to unquantified  
694 argon loss (Kelley, 2002; Schofield *et al.*, 2015) and in combination with the altered lithology  
695 of many of the igneous rocks within the Warnie Volcanic Province (Murray, 1994) we cannot  
696 consider the K-Ar dating to be reliable in the absence of further evidence for the age of these  
697 rocks.

698 Stratigraphically, all the extrusive igneous rocks analysed within well data are situated between  
699 Jurassic sedimentary rocks (the Hutton and Birkhead fms.) and the Triassic Nappamerri  
700 Group. which supports a late Triassic to Jurassic age (Draper, 2002). The corroboration of  
701 well data with 3D seismic reflection data has allowed us to define further intrusive and  
702 extrusive volcanic events that are strata-concordant with the Birkhead Fm. and Hutton  
703 Sandstone, placing them between ~178 and 160 Ma. The oldest extrusive volcanics identified

704 using 3D seismic reflection data are the vents within the northern Challum 3D survey that  
705 appear to sit near the top of the Nappamerri Group below the Hutton Sandstone. This could  
706 extend the age of the Warnie Volcanic Province into the Triassic which would agree with the  
707 K-Ar dating for the Lambda 1 well. Equally, the vents could be interpreted as cross-cutting  
708 the Triassic strata which would give them an Early Jurassic age. In the absence of further data,  
709 their exact age is unclear.

710 We conclude that the vast majority of igneous rocks identified using 3D seismic reflection  
711 data and well data throughout this study have been constrained to a broad age range between  
712 ~178 and 160 Ma spanning the Middle Jurassic, however, further work is encouraged to better  
713 define the age of the Warnie Volcanic Province.

## 714 **8.2 Structural Controls on the Emplacement of the Warnie Volcanic Province**

715 From the late Triassic to the early Jurassic, the Eromanga Basin was subject to an east-west  
716 compressional event named the Hunter-Bowen event (Mayromatidis, 2005; Kulikowski &  
717 Amrouch, 2017), which uplifted the basin and inverted the major highs. Subsequently, the  
718 basin underwent post-compressional flexural relaxation with the resultant accommodation  
719 space infilled by the Middle to Late Jurassic succession discussed within this manuscript (Lowe-  
720 Young, 1997; Mayromatidis, 2005). During this time, a strike-slip extensional regime is thought  
721 to have been present (Kulikowski, 2018). In this context, it is interesting to consider whether  
722 the stress regime of the Cooper Basin helped to control the location and morphology of  
723 igneous rocks within the WVP and, more broadly, the location of the WVP within central  
724 Australia.

### 725 *8.2.1 The Influence of Basement Structure on the Location of Igneous Rocks*

726 Within other basins, such as those in the North Atlantic, it has been noted how the location  
727 of igneous intrusions and volcanism is controlled by the basin structure, in particular the  
728 location of major faults (Schofield *et al.*, 2015; McClean *et al.*, 2017; Hardman *et al.*, 2018a).  
729 To investigate whether basement structure and faulting had a direct control on volcanism  
730 erupted during the Jurassic, we have utilised the 3D seismic reflection datasets available.

731 We have already considered the Top Basement structure within the Winnie 3D survey and  
732 interpreted faulting of the Top Basement, in particular the 25 km long Central Nappamerri  
733 Fault. We superimposed the location of vents within the Winnie 3D survey on top of a TWT



734 map of the Top Basement to see if there was any relationship between basement structure  
735 and the location of the vents (Fig. 9C). On a broad scale, two vents are located directly above  
736 the Central Nappamerri Fault (CNF) with the others situated adjacent to the mapped Top  
737 Basement Horizon (i.e. where it deepens to > 3600 ms and is no longer mappable). On a  
738 broad scale, the location of vents does appear to be related to the basement structure.

739 We also superimposed the location of the Madigan 3D volcanoes on top of the NGMA (2003)  
740 basement map (Fig. 25). Like the igneous rocks in the Winnie 3D survey, the two volcanoes  
741 imaged in the Madigan 3D survey sit atop the tip of the 25 km Challum Fault and atop a  
742 second, ~5 km fault northwest of the main Challum Fault. This reinforces the idea that the  
743 location of igneous rocks was largely controlled by the basin structure.

#### 744 *8.2.2 The Influence of Discontinuities and Faults within the Eromanga Succession on the* 745 *Morphology of Igneous Rocks*

746 Here, we consider how basin structure controlled the morphology of igneous rocks within  
747 the Nappamerri Trough. Using the Winnie 3D survey, the length, width and elongate direction  
748 of the volcanoes, lava flows and intrusions was picked (Fig. 23). The high quality of the Winnie  
749 3D survey facilitated confident mapping of the outline of individual volcanic events, however,  
750 the Gallus 2D and Snowball 3D surveys were not considered as the outline of individual  
751 volcanics could not be picked confidently. The data shows that igneous rocks in the area are  
752 roughly/typically twice as long as they are wide (Fig. 23). Furthermore, almost all the igneous  
753 rocks are elongated in a NW-SE direction, closely matching the strike of the faults within the  
754 Nappamerri Trough. It is clear that during eruption and emplacement of the igneous rocks,  
755 the basin structure exerted a strong control on the morphology of lava flows and igneous  
756 intrusions.

757 However, we have also considered fracturing and faulting within the Eromanga succession and  
758 its control on the morphology of lava flows and igneous intrusions in the Nappamerri Trough.  
759 In vertical seismic reflection sections, faulting of the Eromanga Basin stratigraphy is not clearly  
760 imaged within the Winnie 3D survey, largely due to the considerable noise within the section.  
761 However, spectral decomposition produced for the Top Volcanics horizon images a number  
762 of discontinuities (shown as black lines) within the colour blend (Fig. 24A). These  
763 discontinuities are not thought to be a product of the acquisition and processing of the seismic  
764 data, due to their non-linear nature and their coincidence with other geological features such

765 as the igneous rocks and the CNF. When mapped, the features form a series of largely NE-  
766 SW trending lineaments (Fig. 24B). Although imaging of the discontinuities is best in the SW  
767 of the survey, where there are fewer igneous rocks, it is evident that many of the igneous  
768 rocks are aligned with these features suggesting they must have exerted some topographical  
769 or structural control when the igneous rocks were emplaced or erupted over the Nappamerri  
770 Trough (Fig. 24). As they do not resemble any sedimentary features such as valleys or fluvial  
771 systems, we interpret these features to be faulting or fracturing of the Eromanga succession  
772 above the Nappamerri Trough.

773 Determining the tectonic activity responsible for the faulting within the Nappamerri Trough  
774 and, hence, the location and morphology of igneous rocks within the WVP is difficult due to  
775 the complex structural and stress history of the Cooper Basin. Throughout the basin, a  
776 conjugate set of large NNE-SSW and field scale SE-NW striking dextral strike-slip faults  
777 developed under a SSE-NNW strike-slip stress regime (Kulikowski *et al.*, 2018). This is  
778 pertinent when applied to the central Nappamerri Trough, as Kulikowski *et al.* (2018)  
779 identified a series of vertical SE-NW structural lineaments with normal displacement or no  
780 displacement. Due to their vertical nature, it is thought that these faults developed as strike  
781 slip faults during successive periods of flexural relaxation or sag. The faulting identified within  
782 this study is also determined to consist of little offset with an orientation that matches that  
783 of the strike-slip faulting determined by Kulikowski *et al.*, (2008) (Fig. 24A-D). We surmise  
784 that sag within the basin produced a series of faults and fractures within the basin that  
785 controlled the morphology of igneous rocks in the WVP.

### 786 **8.3 The Plumbing System of the WVP**

787 Due to the risks associated with drilling igneous rocks within the Warnie Volcanic Province,  
788 being able to identify the presence of them is especially important. Whilst this manuscript has  
789 dealt with surface vents, flows and shallowly emplaced igneous intrusions (~100-200 ms below  
790 the paleo land surface, here believed to be ~Top Birkhead), we have only briefly discussed  
791 the plumbing system of the Warnie Volcanic Province and the lack of constraint on the  
792 presence of dykes and deeper sills

793 Within this study we have already noted that vents are observed to extend through the  
794 Cooper Basin succession, below the extrusive and intrusive igneous rocks identified in the  
795 Eromanga Basin succession above (e.g. Fig. 9). Vents are positioned directly above visible offset

796 in the basement or adjacent basement highs (Fig. 9C). Furthermore, when viewed in a TWT  
797 cross section, the vents are all vertical, with no sills observed >200 ms below the palaeo-land  
798 surface (taken here to be Top Birkhead). This suggests that the magmatic plumbing system of  
799 the WVP is dominantly vertical throughout the Nappamerri Trough.

800 However, whilst the intrusions identified within the Winnie 3D survey are emplaced at  
801 shallow depths (~100-200 ms in Fig. 8) below the palaeo-land surface, the intersection of an  
802 intrusion within the Permian succession of the Warnie East well (410 m below the Birkhead  
803 Fm., Fig. 14) suggests that the plumbing system of the WVP is not well understood and may  
804 be subject to lateral transport of magma, in addition to the predominantly vertical vents  
805 observed in this manuscript. When detailing the magnetic data we discussed the importance  
806 of a ~75 x 40 km magnetic intensity high that runs from the Innamincka Ridge across the  
807 northern extent of the WVP in a NW-SE direction (Fig. 22B). Without good seismic imaging  
808 of the stratigraphy below the Permian Cooper Basin succession, it is difficult to confidently  
809 identify what this represents. Notably, it does not correspond to an increase in the  
810 concentration of extrusive volcanics, otherwise this would have been imaged in the Gallus 2D  
811 survey (Fig. 11A). This 75 x 40 km magnetic anomaly could be an expression of an extensive  
812 network of igneous intrusions that are not imaged within the available data, however, a  
813 confident interpretation would require high quality 3D seismic reflection survey data covering  
814 the area north of the Winnie 3D survey.

#### 815 **8.4 The Broader Record of Jurassic Volcanism in Eastern Australia**

816 We believe it is important to consider the WVP in the context of the broader record of  
817 Jurassic volcanic activity in eastern Australia. Coeval with the eruption of the WVP, the  
818 Eromanga Basin was undergoing post-compressional flexural relaxation with thermally  
819 controlled subsidence in the absence of significant fault control (Gallagher & Lambeck, 1989  
820 Mayromatidis, 2005). Subsidence has been attributed to subduction of the Pacific plate  
821 beneath southern and eastern Australia, during which time rifting also initiated between  
822 Australia and Antarctica (Griffiths, 1971; Johnstone *et al.*, 1973).

823 Evidence for Jurassic volcanic activity is pervasive throughout the sedimentary basins of  
824 eastern Australia, manifested by volcanic arc-derived sediment within the Eromanga Basin  
825 (Boult *et al.*, 1998), silicic tuffs in the Surat Basin (Wainman *et al.*, 2015) and widespread  
826 volcanogenic zircons within the Eromanga Basin (Bryan *et al.*, 1997). This volcanoclastic

827 material is thought to be derived from an acid to intermediate volcanic arc positioned off the  
828 coast of Queensland during the Jurassic however, the remnants of this arc volcanism are yet  
829 to be identified (Patton, 1986, Boulton *et al.*, 1997). Jurassic alkali basalt has been intersected on  
830 the Marion Plateau (~400 km east of Townsville in Queensland), although this may also be  
831 related to rifting in the region during the Jurassic (Isern *et al.*, 2002).

832 ~1500 km south of the Marion Plateau, mafic and ultramafic breccia pipes and igneous  
833 intrusions are noted in the Eastern Highlands and Sydney Basin with K-Ar dating suggesting  
834 ages of between 193 and 163 Ma (McDougall and Wellman, 1976). To the north west of the  
835 Sydney Basin, in New South Wales, lower Jurassic intrusions and volcanics of the Garawilla  
836 alkali basalts and alkaline Mittagong complexes are noted in the Gunnedah Basin (195-177 Ma)  
837 (Sutherland, 1973, Gurba & Weber, 2001). Further south of the Sydney and Gunnedah basins,  
838 Jurassic volcanics are scattered throughout Victoria and Tasmania (Veevers, 1984). These  
839 include voluminous tholeiitic intrusions in Tasmania (165 m.y.) that are thought to have been  
840 buried under a thick pile of since eroded extrusive volcanics (Sutherland, 1973; McDougall &  
841 Wellman, 1976).

842 ~1000 km to the north-west, the Wisanger Basalt is a ~170 Ma, 20 km fragmented lava flow  
843 emplaced on top of Permian fluvial sediments on Kangaroo Island (McDougall & Wellman,  
844 1976). Geochemically, it is similar to the Tasmanian and Antarctic tholeiitic dolerite and  
845 basalts that are usually attributed to the Ferrar Large Igneous Province and extension that latterly  
846 resulted in the separation of Australia and Antarctica (Compston *et al.*, 1968; Milnes *et al.*,  
847 1982). Of note in South Australia, Jurassic kimberlites record the extension of Mesozoic  
848 kimberlites found along the margin of southern Gondwana, above the subducting Pacific plate  
849 (Tappert *et al.*, 2009), differing petrologically from the predominantly basaltic volcanism found  
850 elsewhere in eastern Australia.

851 Plate reconstructions indicate that the Eromanga Basin was located at significant distances  
852 (~750 km) from the oceanic trench of the subducting Pacific plate (Veevers, 1984) (Fig. 27).  
853 Importantly, alongside the WVP, the South Australian Kimberlites are the only other Jurassic  
854 volcanics documented in eastern Australia that occur away (>500 km) from a significant plate  
855 boundary (here we have ascribed the Wisanger Basalts to the zone of separation between  
856 Australia and Antarctica and, hence, a 'significant' plate boundary). We therefore believe the  
857 Warnie Volcanic Province to be an intraplate volcanic province and, as the origin of intraplate

858 volcanism can often be contentious (Conrad *et al.*, 2011), it is important to consider the  
859 source of this volcanism and implications for the formation of intraplate volcanism.

### 860 **8.5 The Origin of the Warnie Volcanic Province**

861 The WVP was located far from active plate boundaries during the Jurassic (Fig. 27A). When  
862 considering the source of intraplate volcanism, several different mechanisms must be  
863 considered:

- 864 • The presence of a mantle plume
- 865 • Asthenospheric upwelling due to extension
- 866 • Local scale mantle convection

867 Mantle plumes are typically associated with the eruption of voluminous flood basalt provinces  
868 that often mark the earliest volcanic activity of major hot spots (Richard *et al.*, 1989).  
869 Furthermore, mantle plumes cause dynamic uplift of the land's surface of up to several  
870 hundred kms followed by surface subsidence due to the withdrawal of mantle plume material  
871 and loading of the crust with the volcanic sequence (Nadin *et al.*, 1997; Dam *et al.*, 1998; Leng  
872 & Zhong, 2010; Hartley *et al.*, 2011; Hardman *et al.*, 2018b). No evidence of major surface  
873 uplift in the Cooper and Eromanga Basins is coeval with the emplacement and eruption of the  
874 WVP (Hall *et al.*, 2015). Furthermore, subsidence and sag throughout the emplacement of the  
875 WVP is minor, with no large changes in sedimentary facies noted throughout the Jurassic  
876 lower non-marine Eromanga succession (Alexander & Hibburt, 1996). No major crustal  
877 and/or lithospheric extension is evidenced by the lack of major Jurassic faults, during a time  
878 in which the basin underwent post-compressional flexural relaxation in a strike slip  
879 extensional regime (Lowe-Young, 1997; Mayromatidis, 2005; Kulikowski, 2018). Furthermore,  
880 the small spatial area covered by the Warnie Volcanic Province (~7500 km<sup>2</sup> within the  
881 Nappamerri Trough area) and, by extension, the volume of magma emplaced is too low to be  
882 related to a mantle plume source (Conrad *et al.*, 2011).

883 Low-effusive volcanism occurring within tectonic plates has been also attributed to  
884 several locally operating processes, such as minor upwelling plumes (Courtilot *et al.*, 2003;  
885 Conrad *et al.*, 2011), downwelling drops (Elkins-Tanton *et al.*, 2006) and sub-lithospheric  
886 (Ballmer *et al.*, 2009) or edge-driven convection (Conrad *et al.*, 2010). In the case of edge-  
887 driven convection, mantle flow can induce upwelling and volcanism through interaction with  
888 lithospheric or asthenospheric heterogeneities (Conrad *et al.*, 2011; Davies & Rawlinson,

889 2014). In the Newer Volcanic Province in South Australia, <5 kyr volcanism forming as a  
890 product of edge driven convection is noted to consist of basaltic monogenetic volcanoes <4  
891 km<sup>2</sup> in size covering an area of ~20,000 km<sup>2</sup> (Demidjuk *et al.*, 2007; Davies & Rawlinson, 2014),  
892 bearing a striking similarity to the WVP (the volcanism is basaltic and individual volcanoes like  
893 Mount Gambier are of a similar scale (~1.5 x 1.5 km) to the volcanoes imaged in the  
894 Nappamerri Trough area). Although not much is known about the crustal structure below  
895 the eastern Nappamerri Trough, seismic reflection profiles have revealed that Devonian  
896 troughs to the east of the study area are associated with crustal thinning of 7 – 10 km (Mathur,  
897 1983). Furthermore, on a continental scale, the Moho is observed to shallow to ~20 km below  
898 the Cooper Basin (and more broadly, Central Australia) (Kennett *et al.*, 2011). Therefore,  
899 there is observable lithospheric thinning below the basins in Central Australia that could have  
900 produced edge driven convection.

901         However, because Central Australia was relatively inactive during the Jurassic, we  
902 must consider driving mechanisms for asthenospheric flow beneath the continent during the  
903 eruption and emplacement of the WVP. As we have already detailed, the Pacific plate was  
904 subducting beneath eastern Australia during the Jurassic. In intraplate volcanic provinces  
905 adjacent to subduction zones (e.g. Western North America, China), there is a causal link  
906 between subduction and intraplate volcanism, in that subduction below the continental crust  
907 acts as a driving force for asthenospheric shear and, hence, the mantle upwelling that produces  
908 intraplate volcanism (Conrad *et al.*, 2011; Tang *et al.*, 2014; Zhou *et al.*, 2018). If the extension  
909 in the area during the Jurassic is not great enough to stimulate volcanism, then an alternative  
910 model may involve rapid asthenospheric shear produced by the subducting Pacific Plate,  
911 localised beneath SW Queensland due to edge driven convection.

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

922 recommend further studies to be conducted on the geochemical signature of the basalts of  
923 the WVP.

924 Due to its low volume and small areal extent, we do not believe that the WVP was  
925 the source of the volcanically derived sediment that was distributed throughout much of  
926 Australia during the Mesozoic (Boult *et al.*, 1998; MacDonald *et al.*, 2013; Barham *et al.*, 2016).  
927 However, our findings raise the possibility that other, yet unidentified, intra-basinal volcanic  
928 sources may contribute to Mesozoic volcanogenic sedimentation in eastern Australia.

929 Finally, it must be considered why the WVP has not been documented until now  
930 despite the presence of volcanic rocks being known for over three decades. By our estimates,  
931 only 0.13% of the wells drilled in the Cooper Basin between 1959 and 2015 drilled the WVP  
932 (based on Hall *et al.*, 2016's estimate of the number of wells), with 35 years of exploration  
933 since the first well that drilled the volcanics. This is despite the WVP occupying ~6% of the  
934 geographic extent of the Cooper Basin. Largely, this is due to the lack of data and attention  
935 given to the Nappamerri Trough region until recently. Acquisition of the high-quality Winnie  
936 3D seismic reflection survey facilitated confident delineation of the WVP. This study also  
937 underlines the importance for collaboration between industry and academia. Whilst volcanics  
938 have been described within industry reports and imaged within data acquired, they have been  
939 overlooked within the literature. The obscurity of the WVP in an area of such intense  
940 exploration points to the probability of other undiscovered volcanic provinces globally. It is  
941 therefore an important analogue in the search for undiscovered intraplate volcanism that may  
942 inform our understanding of the mantle processes occurring beneath continental interiors.

943

## 944 **9. Conclusions**

945 We have integrated seismic, well, gravity and magnetic data and clarified the extent and  
946 character of igneous rocks emplaced above the Nappamerri Trough of the Cooper Basin  
947 within Eromanga Basin stratigraphy. Monogenetic volcanoes, igneous intrusions and compound  
948 lava flows extending over ~7500 km<sup>2</sup> are proposed to have been active between ~180 – 160  
949 Ma forming part of the proposed 'Warnie Volcanic Province.' Regionally, the distribution of  
950 igneous rocks is controlled by basement structure. On a continental scale, we interpret the  
951 Warnie Volcanic Province to be a product of intraplate convective upwelling above the  
952 subducting Pacific slab.

953

**954 10. Acknowledgements**

955 We wish to thank Santos Ltd. for providing us with the Snowball 3D seismic survey. In particular we  
956 wish to thank Jenni Clifford and Lance Holmes who provided helpful feedback and 2D seismic lines  
957 covering the Lambda 1, Orientos 2 and Warnie East 1 wells. We also wish to thank Beach Energy, in  
958 particular Rob Menpes, for the helpful discussions and feedback on the manuscript in addition  
959 to helping us with the analysis of the magnetic data. The work contained in this paper contains  
960 work conducted during a PhD study undertaken as part of the Natural Environment Research Council  
961 (NERC) Centre for Doctoral Training (CDT) in Oil & Gas [grant number NEM00578X/I] and is fully  
962 funded by NERC whose support is gratefully acknowledged

963

964

965

966

967



968 **11. References**

- 969 Alexander, E.M. and Sansome, A., 1996, Lithostratigraphy and Environments of Deposition, in  
970 Alexander, E.M. and Hibburt, J., (Eds), Petroleum Geology of South Australia, Volume 2: Eromanga  
971 Basin, p 49 - 86.
- 972 Allen P., 1998. Kappa I Well Completion Report. Compiled for Santos Limited.
- 973 Archer, S.G., Bergman, S.C., Iliffe, J., Murphy, C.M. and Thornton, M., 2005. Palaeogene igneous  
974 rocks reveal new insights into the geodynamic evolution and petroleum potential of the Rockall  
975 Trough, NE Atlantic Margin. *Basin Research*, 17(1), pp.171-201.
- 976 Bacchin, M., Milligan, P. R., Wynne, P., and Tracey, R., 2008. Gravity Anomaly Map of the Australian  
977 Region (third edition, scale 1:15 000 000, Geoscience Australia, Canberra. Baker, J.C.,
- 978 Bai, G.P., Hamilton, P.J., Golding, S.D. and Keene, J.B., 1995. Continental-scale magmatic carbon  
979 dioxide seepage recorded by dawsonite in the Bowen-Gunnedah-Sydney Basin system, eastern  
980 Australia. *Journal of Sedimentary research*, 65(3).
- 981 Baksi, Ajoy K. "Critical evaluation of the age of the Deccan Traps, India: Implications for flood-basalt  
982 volcanism and faunal extinctions." *Geology* 15.2 (1987): 147-150.
- 983 Barham, M., Kirkland, C.L., Reynolds, S., O'Leary, M.J., Evans, N.J., Allen, H., Haines, P.W., Hocking,  
984 R.M., McDonald, B.J., Belousova, E. and Goodall, J., 2016. The answers are blowin' in the wind: Ultra-  
985 distal ashfall zircons, indicators of Cretaceous super-eruptions in eastern Gondwana. *Geology*, 44(8),  
986 pp.643-646.
- 987 Beeson, Marvin H., Terry L. Tolan, and James Lee Anderson. "The Columbia River Basalt Group in  
988 western Oregon; geologic structures and other factors that controlled flow emplacement  
989 patterns." Geological Society of America Special Papers 239 (1989): 223-246.
- 990 Bell & Butcher, 2002. On the emplacement of sill complexes: evidence from the Faroe-Shetland Basin.  
991 Geological Society, London, Special Publications(2002),197(1):307
- 992 Boothby, P.G., 1986. Warnie East I Well Completion Report. Compiled for Delhi Petroleum Pty  
993 Ltd.
- 994 Breed, W.J., 1964. Morphology and lineation of cinder cones in the San Francisco Volcanic  
995 Field. *Mus. North. Ariz. Bull*, 40, pp.65-71.
- 996 Bryan, S.E., Constantine, A.E., Stephens, C.J., Ewart, A., Schön, R.W. and Parianos, J., 1997. Early  
997 Cretaceous volcano-sedimentary successions along the eastern Australian continental margin:  
998 Implications for the break-up of eastern Gondwana. *Earth and Planetary Science Letters*, 153(1), pp.85-  
999 102

- 1000 Bucknill, M., 1990. Orientos 2 Well Completion Report. Compiled for Delhi Petroleum Pty Limited.
- 1001 Burger, D. and Senior, B.R., 1979. A revision of the sedimentary and palynological history of the  
1002 northeastern Eromanga Basin, Queensland. *Journal of the Geological Society of Australia*, 26(3-4), pp.121-  
1003 133.
- 1004 Cas, R.A.F., van Otterloo, J., Blaikie, T.N. and van den Hove, J., 2017. The dynamics of a very large  
1005 intra-plate continental basaltic volcanic province, the Newer Volcanics Province, SE Australia, and  
1006 implications for other provinces. *Geological Society, London, Special Publications*, 446(1), pp.123-172
- 1007 Christie, P., Gollifer, I. and Cowper, D., 2006. Borehole seismic studies of a volcanic succession from  
1008 the Lopra-1/1A borehole in the Faroe Islands, northern North Atlantic. *Geological Survey of Denmark  
1009 and Greenland Bulletin*, 9, pp.23-40.
- 1010 Compston, W., McDougall, I. and Heier, K.S., 1968. Geochemical comparison of the mesozoic basaltic  
1011 rocks of Antarctica, South Africa, South America and Tasmania. *Geochimica et Cosmochimica  
1012 Acta*, 32(2), pp.129-149.
- 1013 Conrad, C.P., Bianco, T.A., Smith, E.I. and Wessel, P., 2011, Patterns of intraplate volcanism controlled  
1014 by asthenospheric shear, *Nature Geoscience*, v. 4, p. 317-321.
- 1015 Davies, D.R. and Rawlinson, N., 2014, On the origin of recent intraplate volcanism in  
1016 Australia, *Geology*, v. 42, pp. 1031-1034.
- 1017 Demidjuk, Z., Turner, S., Sandiford, M., George, R., Foden, J. and Etheridge, M., 2007, U-series  
1018 isotope and geodynamic constraints on mantle melting processes beneath the Newer Volcanic  
1019 Province in South Australia, *Earth and Planetary Science Letters*, v. 261, p. 517-533.
- 1020 Draper, J.J. ed., 2002. *Geology of the Cooper and Eromanga Basins, Queensland*. Department of Natural  
1021 Resources and Mines
- 1022 Duddy, I.R., 2003. Mesozoic: a time of change in tectonic regime. *Geology of Victoria*, pp.239-286.
- 1023 Ebinghaus, A., Hartley, A.J., Jolley, D.W., Hole, M. and Millett, J., 2014. Lava–Sediment Interaction and  
1024 Drainage-System Development In A Large Igneous Province: Columbia River Flood Basalt Province,  
1025 Washington State, US ALAVA–DRAINAGE INTERACTION, COLUMBIA RIVER FLOOD BASALT  
1026 PROVINCE. *Journal of Sedimentary Research*, 84(11), pp.1041-1063.
- 1027 Gallagher, K. and Lambeck, K.U.R.T., 1989, Subsidence, sedimentation and sea-level changes in the  
1028 Eromanga Basin, Australia, *Basin Research*, v. 2, p. 115-131.
- 1029 Gallagher, K., 1990. Permian to Cretaceous subsidence history along the Eromanga–Brisbane  
1030 geoscience transect. *The Eromanga–Brisbane Geosciences Transect: A Guide to Basin Development across  
1031 Phanerozoic Australia in Southern Queensland: Bureau of Mineral Resources Bulletin*, 232, pp.133-151.

- 1032 Gatehouse, C.G., 1972, Formations of the Gidgealpa Group in the Cooper Basin., Australasian Oil and  
1033 Gas Review, 18(12), 10-15
- 1034 Gebhardt, A.C., De Batist, M., Niessen, F., Anselmetti, F.S., Ariztegui, D., Habertzettl, T., Kopsch, C.,  
1035 Ohlendorf, C. and Zolitschka, B., 2011. Deciphering lake and maar geometries from seismic refraction  
1036 and reflection surveys in Laguna Potrok Aike (southern Patagonia, Argentina). *Journal of Volcanology  
1037 and Geothermal Research*, 201(1-4), pp.357-363.
- 1038 Glass, L.M. and Phillips, D., 2006, The Kalkarindji continental flood basalt province: A new Cambrian  
1039 large igneous province in Australia with possible links to faunal extinctions, *Geology*, v. 34, p. 461-464.
- 1040 Goldstein, B., Menpes, S., Hill, A., Wickham, A., Alexander, E., Jarosz, M., Pepicelli, D., Malavazos, M.,  
1041 Staritski, K., Taliangis, P., Coda, J., Hill, D. & Webb, M. 2012. Roadmap for Unconventional Gas Projects  
1042 in South Australia. South Australia Department for Manufacturing, Innovation, Trade, Resources and  
1043 Energy, Energy Resources Division,  
1044 <http://www.statedevelopment.sa.gov.au/resources/unconventional-gas-projects>
- 1045 Gravestock, D.I., Hibburt, J. and Drexel, J.F. eds., 1998. *Petroleum Geology of South Australia: Cooper  
1046 Basin*. Petroleum Group, Primary Industries and Resources SA.
- 1047 Greenstreet, C. 2015. From play to production: the Cooper unconventional story — 20 years in the  
1048 making. APPEA 2015 extended abstract.
- 1049 Griffiths, J.R., 1975. New Zealand and the Southwest Pacific margin of Gondwanaland. In: K.S.W.  
1050 Campbell (Editor), *Gondwana Geology*. A.N.U. Press, Canberra, pp. 619- 637.
- 1051 Grove, C., 2014. *Direct and indirect effects of flood basalt volcanism on reservoir quality sandstone* (Doctoral  
1052 dissertation, Durham University).
- 1053 Gurba, L.W. and Weber, C.R., 2001, Effects of igneous intrusions on coalbed methane potential,  
1054 Gunnedah Basin, Australia, *International Journal of Coal Geology*, v. 46, p. 113-131.
- 1055 Hall, L.S., Hill, A.J., Troup, A., Korsch, R.J., Radke, B.M., Nicoll, R.S., Palu, T., Wang, L. and Stacey, A.,  
1056 2016, *Cooper Basin Architecture and Lithofacies*, Geoscience Australia.
- 1057 Hall, L.S, Palu, T.J., Murray, A.P., Boreham, C.J., Edwards, D.S., Hill, A.J., Troup, A., 2018.  
1058 Hydrocarbon Prospectivity of the Cooper Basin, Australia. *AAPG Bulletin*.
- 1059 Hamilton, D.S., Holtz, M.H., Ryles, P., Lonergan, T. and Hillyer, M., 1998. Approaches to identifying  
1060 reservoir heterogeneity and reserve growth opportunities in a continental-scale bed-load fluvial  
1061 system: Hutton Sandstone, Jackson field, Australia. *AAPG bulletin*, 82(12), pp.2192-2219.
- 1062 Heine, C. and Müller, R.D., 2005. Late Jurassic rifting along the Australian North West Shelf: margin  
1063 geometry and spreading ridge configuration. *Australian Journal of Earth Sciences*, 52(1), pp.27-39.

- 1064 Hillis, R.R., Morton, J.G.G., Warner, D.S. and Penney, R.K., 2001. Deep basin gas: A new exploration  
1065 paradigm in the Nappamerri Trough, Cooper Basin, South Australia. *The APPEA Journal*, 41(1),  
1066 pp.185-200.
- 1067 Holford, S.P., Schofield, N., Jackson, C.L., Magee, C., Green, P.F. and Duddy, I.R., 2013. Impacts of  
1068 igneous intrusions on source reservoir potential in prospective sedimentary basins along the western  
1069 Australian continental margin.
- 1070 Holt, S.J., Holford, S.P. and Foden, J., 2013. New insights into the magmatic plumbing system of the  
1071 South Australian Quaternary Basalt province from 3D seismic and geochemical data. *Australian Journal*  
1072 *of Earth Sciences*, 60(8), pp.797-817.
- 1073 Homberg, C., Hu, J.C., Angelier, J., Bergerat, F. and Lacombe, O., 1997. Characterization of stress  
1074 perturbations near major fault zones: insights from 2-D distinct-element numerical modelling and field  
1075 studies (Jura mountains). *Journal of Structural Geology*, 19(5), pp.703-718.
- 1076 Hulme, G., 1974. The interpretation of lava flow morphology. *Geophysical Journal International*, 39(2),  
1077 pp.361-383.
- 1078 Isern, A.R., Anselmetti, F.S. and Blum, P., 2002. Constraining Miocene sea level change from carbonate  
1079 platform evolution, Marion Plateau, northeast Australia, Sites 1192–1199. In *Proceedings of the Ocean*  
1080 *Drilling Program. Initial Reports* (Vol. 194, p. 88)
- 1081 Jell, P.A. ed., 2013. *Geology of Queensland*. Geological Survey of Queensland.
- 1082 Jerram, D.A. and Widdowson, M., 2005. The anatomy of Continental Flood Basalt Provinces: geological  
1083 constraints on the processes and products of flood volcanism. *Lithos*, 79(3), pp.385-405. Beeson, 1989
- 1084 Johnstone, M.H., Lowry, D.C. and Quilty, P.G., 1973. The geology of South-western Australia - a  
1085 review. *J. Proc. R. Soc. West. Aus.*, 56: 5-15.
- 1086 Kelley, S. (2002) K-Ar and Ar-Ar Dating, in noble gases in geochemistry and cosmochemistry.  
1087 In: *Reviews in Mineralogy and Geochemistry*, Vol. 47 (Ed. by D. Porcelli, C.J. Ballentine & R. Wieler), pp.  
1088 785–818, Mineral Society America, Washington, DC.
- 1089 Kennett, B., Salmon, M., Saygin, E. and AusMoho Working Group., AusMoho: the variation of Moho  
1090 depth in Australia, *Geophysical Journal International*, 187, 946-958, 2011, [doi:10.1111/j.1365-](https://doi.org/10.1111/j.1365-246X.2011.05194.x)  
1091 [246X.2011.05194.x](https://doi.org/10.1111/j.1365-246X.2011.05194.x)
- 1092 Kereszturi, G. and Németh, K., 2012. Monogenetic basaltic volcanoes: genetic classification, growth,  
1093 geomorphology and degradation. In *Updates in Volcanology-New Advances in Understanding Volcanic*  
1094 *Systems*. InTech
- 1095 Kermani, M.B. and Morshed, A., 2003. Carbon dioxide corrosion in oil and gas production—a  
1096 compendium. *Corrosion*, 59(8), pp.659-683.

- 1097 Khair, H.A., Cooke, D. and Hand, M., 2013. The effect of present day in situ stresses and paleo-  
1098 stresses on locating sweet spots in unconventional reservoirs, a case study from Moomba-Big Lake  
1099 fields, Cooper Basin, South Australia. *Journal of Petroleum Exploration and Production Technology*, 3(4),  
1100 pp.207-221.
- 1101 Khair, H.A., Cooke, D. and Hand, M., 2015. Seismic mapping and geomechanical analyses of faults  
1102 within deep hot granites, a workflow for enhanced geothermal system projects. *Geothermics*, 53,  
1103 pp.46-56.
- 1104 Khair, H.A., Cooke, D. and Hand, M., 2015. Paleo stress contribution to fault and natural fracture  
1105 distribution in the Cooper Basin. *Journal of Structural Geology*, 79, pp.31-41.
- 1106 Kulikowski, D., Amrouch, K., Cooke, D. and Gray, M.E., 2018, Basement structural architecture and  
1107 hydrocarbon conduit potential of polygonal faults in the Cooper-Eromanga Basin,  
1108 Australia, *Geophysical Prospecting*, v. 66, p. 366-396.
- 1109 Lanzilli, E., 1999. *The Birkhead Formation: reservoir characterisation of the Gidgealpa south dome and*  
1110 *sequence stratigraphy of the Eromanga Basin, Australia* (Doctoral dissertation, University of South  
1111 Australia).
- 1112 Leaman, D.E., 1975. Form, mechanism, and control of dolerite intrusions near Hobart, Tasmania. *J.*  
1113 *Geol. Soc. Aust.*, 22: 175-186.
- 1114 Macdonald, G.A., 1972. *Volcanoes*, 510 pp.
- 1115 MacDonald, J.D., Holford, S.P., Green, P.F., Duddy, I.R., King, R.C. and Backé, G., 2013. Detrital zircon  
1116 data reveal the origin of Australia's largest delta system. *Journal of the Geological Society*, 170(1), pp.3-  
1117 6.
- 1118 Magee, C., Jackson, C.L. and Schofield, N., 2014. Diachronous sub-volcanic intrusion along deep-water  
1119 margins: Insights from the Irish Rockall Basin. *Basin Research*, 26(1), pp.85-105.
- 1120 Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A., Bastow, I.D., Schofield, N.,  
1121 Stevenson, C.T., McLean, C., McCarthy, W. and Shtukert, O., 2016. Lateral magma flow in mafic sill  
1122 complexes. *Geosphere*, 12(3), pp.809-841.
- 1123 Mark, N.J., Schofield, N., Pugliese, S., Watson, D., Holford, S., Muirhead, D., Brown, R. and Healy, D.,  
1124 2017. Igneous intrusions in the Faroe Shetland basin and their implications for hydrocarbon  
1125 exploration; new insights from well and seismic data. *Marine and Petroleum Geology*.
- 1126 Mathur, S.P., 1983, Deep crustal reflection results from the central Eromanga Basin,  
1127 Australia, *Tectonophysics*, v. 100, pp. 163-173.

- 1128 MCDUGALL, I. & WELLMAN, P. 1976. Potassium argon ages for some Australian Mesozoic  
1129 igneous rocks. *Journal of the Geological Society of Australia*, 23, 1-9.
- 1130 McLean, C.E., Schofield, N., Brown, D.J., Jolley, D.W. and Reid, A., 2017. 3D seismic imaging of the  
1131 shallow plumbing system beneath the Ben Nevis Monogenetic Volcanic Field: Faroe–Shetland  
1132 Basin. *Journal of the Geological Society*, 174(3), pp.468-485
- 1133 Meeuws, F.J., Holford, S.P., Foden, J.D. and Schofield, N., 2016. Distribution, chronology and causes of  
1134 Cretaceous–Cenozoic magmatism along the magma-poor rifted southern Australian margin: Links  
1135 between mantle melting and basin formation. *Marine and Petroleum Geology*, 73, pp.271-298.
- 1136 Meixner, T.J., Gunn, P.J., Boucher, R.K., Yeates, T.N., Richardson, L.M. and Frears, R.A., 2000. The  
1137 nature of the basement to the Cooper Basin region, South Australia. *Exploration Geophysics*, 31(2),  
1138 pp.24-32.
- 1139 Menpes, S., Hill, A.J. & Pepicelli, D. 2013. Characteristics of the Gidgealpa Group Composite Resource  
1140 Play in the Cooper Basin, South Australia. Unconventional Resources Technology Conference,  
1141 Denver, 2013.
- 1142 Millett, J.M., Hole, M.J., Jolley, D.W., Schofield, N. and Campbell, E., 2016. Frontier exploration and  
1143 the North Atlantic Igneous Province: new insights from a 2.6 km offshore volcanic sequence in the  
1144 NE Faroe–Shetland Basin. *Journal of the Geological Society*, 173(2), pp.320-336.
- 1145 Millett, J.M., Wilkins, A.D., Campbell, E., Hole, M.J., Taylor, R.A., Healy, D., Jerram, D.A., Jolley,  
1146 D.W., Planke, S., Archer, S.G. and Blischke, A., 2016. The geology of offshore drilling through basalt  
1147 sequences: Understanding operational complications to improve efficiency. *Marine and Petroleum*  
1148 *Geology*, 77, pp.1177-1192.
- 1149 Milnes, A.R., Cooper, B.J. and Cooper, J.A., 1982. The Jurassic Wisanger Basalt of Kangaroo Island,  
1150 South Australia. *Transactions of the Royal Society of South Australia*, 106, pp.1-13.
- 1151 Murray, C.G., 1994. *Basement cores from the Tasman fold belt system beneath the Great Artesian Basin in*  
1152 *Queensland*. Department of Minerals and Energy, Queensland.
- 1153 Nadin, P.A., Kuszniir, N.J. and Cheadle, M.J., 1997, Early Tertiary plume uplift of the North Sea and  
1154 Faeroe-Shetland basins, *Earth and Planetary Science Letters*, v. 148, p. 109-127.
- 1155 Nelson, C.E., Jerram, D.A. and Hobbs, R.W., 2009, Flood basalt facies from borehole data:  
1156 implications for prospectivity and volcanology in volcanic rifted margins, *Petroleum Geoscience*, v. 15,  
1157 p. 313-324.
- 1158 Németh, K., 2010. Monogenetic volcanic fields: Origin, sedimentary record, and relationship with  
1159 polygenetic volcanism. *What is a Volcano?*, 470, p.43.

- 1160 Németh, K. and Kereszturi, G., 2015. Monogenetic volcanism: personal views and  
1161 discussion. *International Journal of Earth Sciences*, 104(8), pp.2131-2146.
- 1162 Pitkin, M.C., Wadham, T.H., McGowen, J.M. and Thom, W.W., 2012, January. Taking the first steps:  
1163 Stimulating the Nappamerri Trough resource play. In *SPE Asia Pacific Oil and Gas Conference and*  
1164 *Exhibition*. Society of Petroleum Engineers.
- 1165 Planke, S., Symonds, P.A., Alvestad, E. and Skogseid, J., 2000. Seismic volcanostratigraphy of large-  
1166 volume basaltic extrusive complexes on rifted margins. *Journal of Geophysical Research: Solid*  
1167 *Earth*, 105(B8), pp.19335-19351.
- 1168 Pokalai, K., Fei, Y., Ahmad, M., Haghghi, M. and Gonzalez, M., 2015. Design and optimisation of  
1169 multi-stage hydraulic fracturing in a horizontal well in a shale gas reservoir in the Cooper Basin,  
1170 South Australia. *The APPEA Journal*, 55(1), pp.1-14.
- 1171 Rateau, R., Schofield, N. and Smith, M., 2013. The potential role of igneous intrusions on  
1172 hydrocarbon migration, West of Shetland. *Petroleum Geoscience*, 19(3), pp.259-272.
- 1173 Reid, A.J., Korsch, R.J., Hou, B. and Black, L.P., 2009. Sources of sediment in the Eocene Garford  
1174 paleovalley, South Australia, from detrital-zircon geochronology. *Australian Journal of Earth*  
1175 *Sciences*, 56(S1), pp.S125-S137.
- 1176 Renaut, R.W., Jones, B., Tiercelin, J.J. and Tarits, C., 2002. Sublacustrine precipitation of  
1177 hydrothermal silica in rift lakes: evidence from Lake Baringo, central Kenya Rift Valley. *Sedimentary*  
1178 *Geology*, 148(1-2), pp.235-257.
- 1179 Reynolds, S.D., Mildren, S.D., Hillis, R.R., Meyer, J.J. and Flottmann, T., 2005, Maximum horizontal  
1180 stress orientations in the Cooper Basin, Australia: implications for plate-scale tectonics and local  
1181 stress sources, *Geophysical Journal International*, v. 160, p. 331-343.
- 1182 Reynolds, P., Holford, S., Schofield, N. and Ross, A., 2017. 3-D Seismic Imaging of Ancient Submarine  
1183 Lava Flows: An Example From the Southern Australian Margin. *Geochemistry, Geophysics, Geosystems*.
- 1184 Reynolds, P., Holford, S., Schofield, N. and Ross, A., 2017. The shallow depth emplacement of mafic  
1185 intrusions on a magma-poor rifted margin: An example from the Bight Basin, Southern  
1186 Australia. *Marine and Petroleum Geology*, 88, pp.605-616
- 1187 Richards, M.A., Duncan, R.A. and Courtillot, V.E., 1989. Flood basalts and hot-spot tracks: plume heads  
1188 and tails. *Science*, 246(4926), pp.103-107.
- 1189

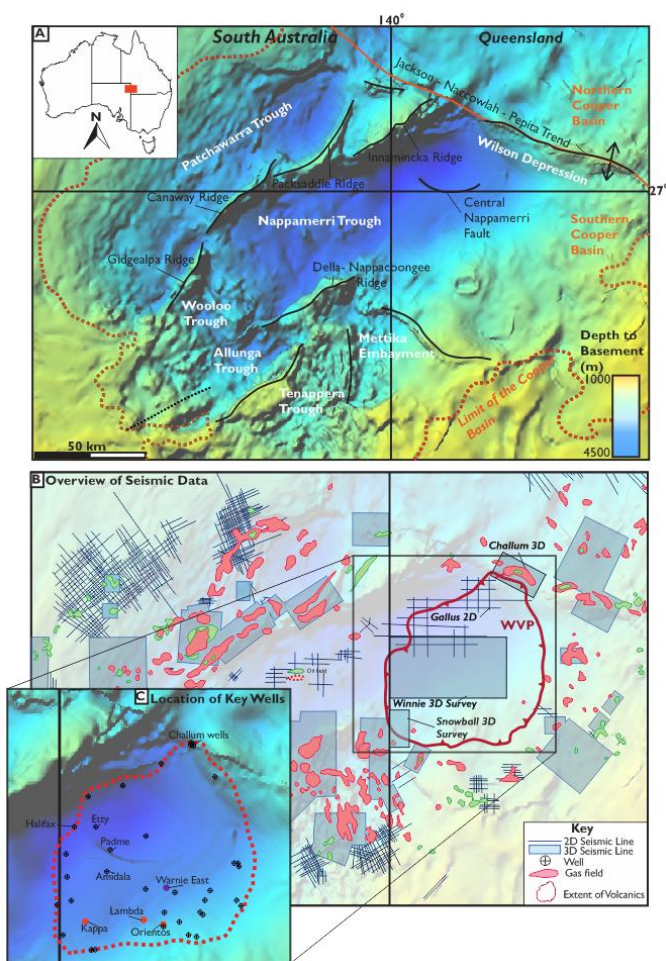
- 1190 Rider, M. and Kennedy, M., 2011. *The Geological Interpretation of Well Logs*.
- 1191 "SA Department for Manufacturing, Innovation, Trade, Resources and Energy" (2003) National  
1192 Geoscience Mapping Accord (NGMA) Cooper Eromanga Basins Project - Cooper Formation  
1193 Depths. Bioregional Assessment Source Dataset. Viewed 27 November  
1194 2017, <http://data.bioregionalassessments.gov.au/dataset/7d00f7c5-0ee3-407d-ac07-5c884c0c4b70>.
- 1195 Schofield, N. and Jolley, D.W., 2013. Development of intra-basaltic lava-field drainage systems within  
1196 the Faroe–Shetland Basin. *Petroleum Geoscience*, 19(3), pp.273-288.
- 1197 Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., Passey, S.R., Muirhead, D., Grove, C.,  
1198 Magee, C., Murray, J. and Hole, M., 2017. Regional magma plumbing and emplacement mechanisms of  
1199 the Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within  
1200 sedimentary basins. *Basin Research*, 29(1), pp.41-63.
- 1201 Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., Passey, S.R., Muirhead, D., Grove, C., Magee,  
1202 C., Murray, J. and Hole, M., 2017. Regional magma plumbing and emplacement mechanisms of the  
1203 Faroe-Shetland Sill Complex: implications for magma transport and petroleum systems within  
1204 sedimentary basins. *Basin Research*, 29(1), pp.41-63.
- 1205 Schofield, N., Jolley, D., Holford, S., Archer, S., Watson, D., Hartley, A., Howell, J., Muirhead, D.,  
1206 Underhill, J. and Green, P., 2018, January. Challenges of future exploration within the UK Rockall  
1207 Basin. In *Geological Society, London, Petroleum Geology Conference series* (Vol. 8, No. 1, pp. 211-229).  
1208 Geological Society of London.
- 1209 Scott, M.P., Stephens, T., Durant, R., McGowen, J., Thom, W. and Woodroof, R., 2013, November.  
1210 Investigating hydraulic fracturing in tight gas sand and shale gas reservoirs in the Cooper Basin. In *SPE*  
1211 *Unconventional Resources Conference and Exhibition-Asia Pacific*. Society of Petroleum Engineers.
- 1212 Segawa, J. and Oshima, S., 1975. Buried Mesozoic volcanic–plutonic fronts of the north-western Pacific  
1213 island arcs and their tectonic implications. *Nature*, 256(5512), p.15.
- 1214 Short, D.A., 1984. Lambda No.1 Well Completion Report. Compiled for Delhi Petroleum Pty. Ltd.
- 1215 Song, B., Economides, M.J. and Ehlig-Economides, C.A., 2011, January. Design of multiple transverse  
1216 fracture horizontal wells in shale gas reservoirs. In *SPE Hydraulic Fracturing Technology Conference*.  
1217 Society of Petroleum Engineers.
- 1218 Stewart, A.K., Massey, M., Padgett, P.L., Rimmer, S.M. and Hower, J.C., 2005. Influence of a basic  
1219 intrusion on the vitrinite reflectance and chemistry of the Springfield (No. 5) coal, Harrisburg,  
1220 Illinois. *International Journal of Coal Geology*, 63(1-2), pp.58-67.



- 1221 Stewart, A.J., Raymond, O.L., Totterdell, J.M., Zhang, W. & Gallagher, R. 2013. Australian Geological  
1222 Provinces, 2013.01 edition. scale 1:2 500 000. Geoscience Australia, Canberra,  
1223 <http://www.ga.gov.au/metadata-gateway/metadata/record/83860>
- 1224 Sutherland, F.L., 1978. Mesozoic-Cainozoic volcanism of Australia. *Tectonophysics*, 48(3-4), pp.413-  
1225 427.
- 1226 Tang, Y., Obayashi, M., Niu, F., Grand, S.P., Chen, Y.J., Kawakatsu, H., Tanaka, S., Ning, J. and Ni, J.F.,  
1227 2014. Changbaishan volcanism in northeast China linked to subduction-induced mantle  
1228 upwelling. *Nature Geoscience*, 7(6), pp.470-475
- 1229 Tappert, R., Foden, J., Stachel, T., Muehlenbachs, K., Tappert, M. and Wills, K., 2009. Deep mantle  
1230 diamonds from South Australia: A record of Pacific subduction at the Gondwanan  
1231 margin. *Geology*, 37(1), pp.43-46.
- 1232 Tarling, D.H., 1966. The magnetic intensity and susceptibility distribution in some Cenozoic and  
1233 Jurassic basalts. *Geophysical Journal International*, 11(4), pp.423-432.
- 1234 Tracey R, Bacchin M, & Wynne P., 2008, In preparation. AAGD07: A new absolute gravity datum  
1235 for Australian gravity and new standards for the Australian National Gravity Database.  
1236 Exploration Geophysics.
- 1237 Trude, J., Cartwright, J., Davies, R.J. and Smallwood, J., 2003, New technique for dating igneous  
1238 sills, *Geology*, v. 31, p. 813-816.
- 1239 Tucker, R.T., Roberts, E.M., Henderson, R.A. and Kemp, A.I., 2016, Large igneous province or long-  
1240 lived magmatic arc along the eastern margin of Australia during the Cretaceous? Insights from the  
1241 sedimentary record, *Geological Society of America Bulletin*, v. 128, p. 1461-1480.
- 1242 Veevers, J.J. and Conaghan, P.J., 1984, *Phanerozoic earth history of Australia*, Oxford University Press,  
1243 USA.
- 1244 Wainman, C.C., McCabe, P.J., Crowley, J.L. and Nicoll, R.S., 2015, U–Pb zircon age of the Walloon  
1245 Coal Measures in the Surat Basin, southeast Queensland: implications for paleogeography and basin  
1246 subsidence, *Australian Journal of Earth Sciences*, v. 62, p. 807-816.
- 1247 Wall, Mostyn, Joe Cartwright, Richard Davies, and Andrew McGrandle. "3D seismic imaging of a  
1248 Tertiary Dyke Swarm in the Southern North Sea, UK." *Basin Research* 22, no. 2 (2010): 181-194
- 1249 Watson, D., Schofield, N., Jolley, D., Archer, S., Finlay, A.J., Mark, N., Hardman, J. and Watton, T.,  
1250 2017. Stratigraphic overview of Palaeogene tuffs in the Faroe–Shetland Basin, NE Atlantic  
1251 Margin. *Journal of the Geological Society*, 174(4), pp.627-645.

- 1252 Watts, K.J., 1987, The Hutton Sandstone-Birkhead Formation Transition, ATP 269P(1), The APEA  
1253 Journal, Volume 27 Number 1, p 215 - 228.
- 1254 Wiltshire, M.J., 1989. Mesozoic stratigraphy and palaeogeography, eastern Australia Journal?
- 1255 Wood, C.A., 1980. Morphometric evolution of cinder cones. *Journal of Volcanology and Geothermal*  
1256 *Research*, 7(3-4), pp.387-413.
- 1257 Yew, C.C. and Mills, A.A., 1989. The occurrence and search for Permian oil in the Cooper Basin,  
1258 Australia. Journal?
- 1259 Zhou, Q., Liu, L. and Hu, J., 2018, Western US volcanism due to intruding oceanic mantle driven by  
1260 ancient Farallon slabs, *Nature Geoscience*, v. 11, p. 70.
- 1261

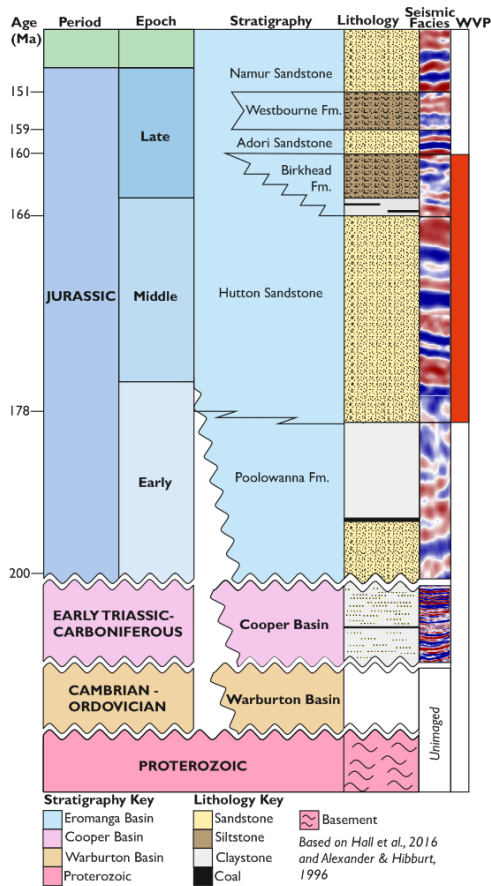
1262 **12. Figures**



1263

1264 **Figure 1.** Location map of the location of the Warne Volcanic Province and the data available. **A** Top  
 1265 basement map adapted from the NGMA (2003). Key structures of the southern Cooper Basin  
 1266 highlighted. **B** Location map highlighting the location of the Warne Volcanic Province within the  
 1267 Cooper Basin. Top basement map superimposed with the location of 3D and 2D seismic surveys  
 1268 utilised in this study and the location of key exploration wells.

1269

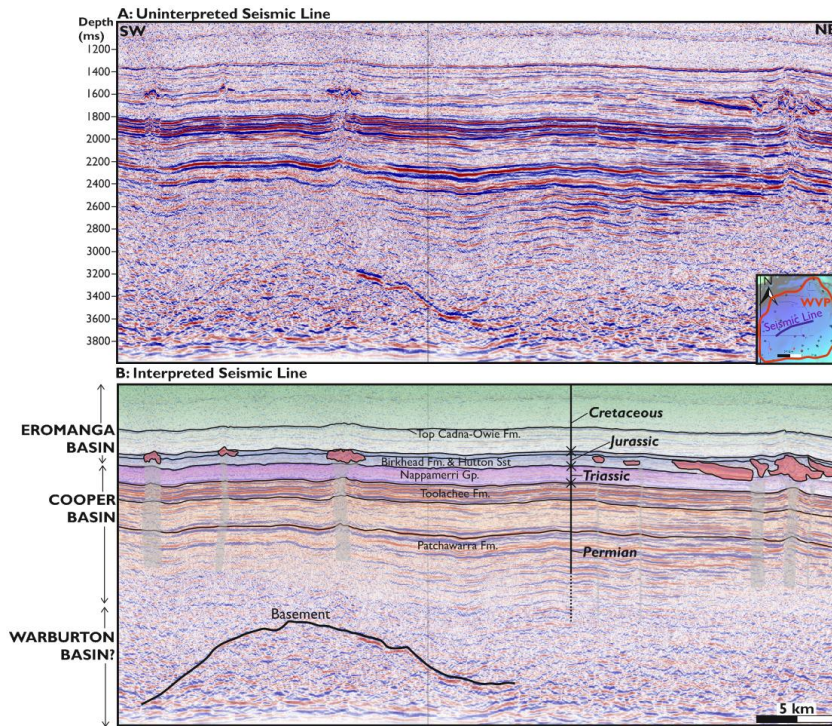


1270

1271

1272 **Figure 2.** Stratigraphic column for the stratigraphy discussed within the paper, based on the work  
 1273 of Alexander & Hibburt (1996), Hall et al. (2016) & Reid et al. (2009). Seismic facies for each section  
 1274 is taken from the Winnie 3D survey of the eastern Nappamerri Trough. Rough stratigraphic location  
 1275 of the WVP highlighted.

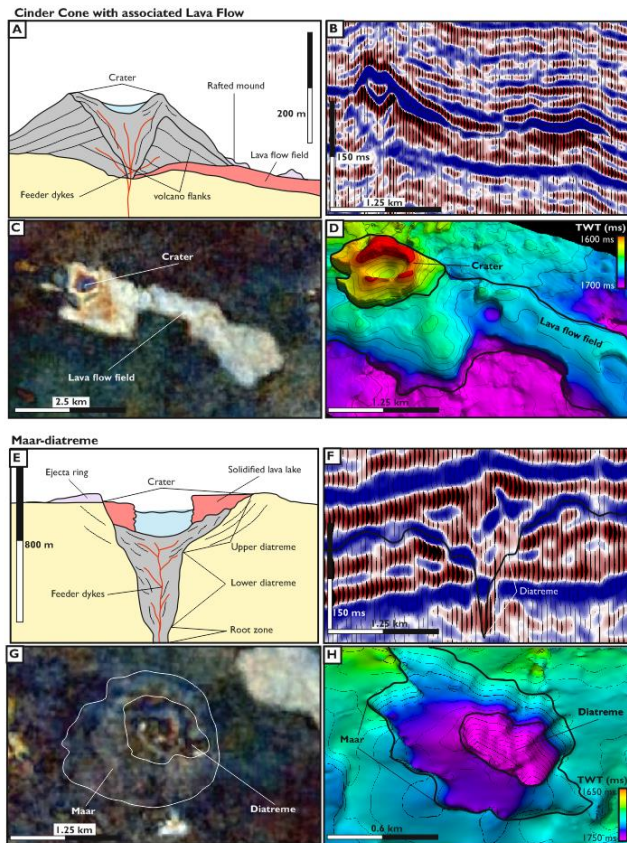
1276



1277

1278 **Figure 3.** Seismic line from the Winnie 3D survey of the Nappamerri Trough highlighting the broad  
1279 stratigraphy of the study area. **A** Uninterpreted line. **B** Interpreted line. Note the stacked nature of  
1280 the Eromanga, Cooper and Warburton Basins and the stratigraphic location of the Warne Volcanic  
1281 Province.

1282



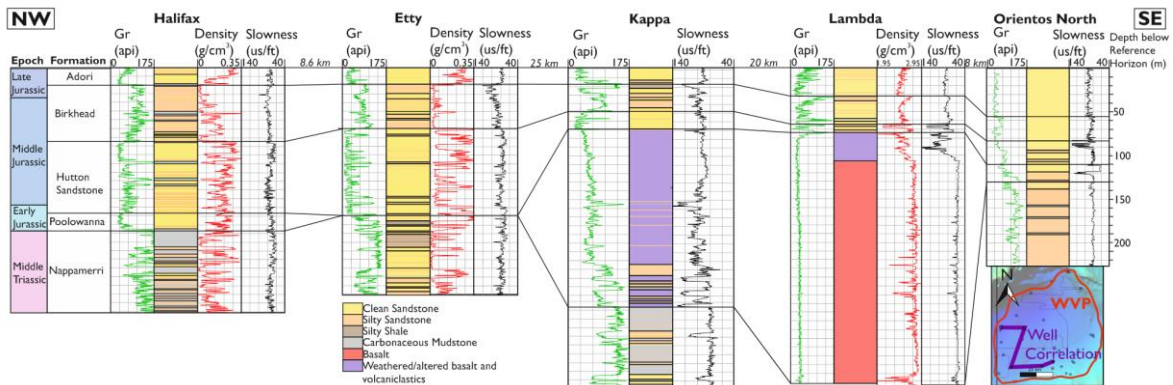
1283

1284 **Figure 4.** Examples of different monogenetic vents. **A** Cross section through a cinder cone, adapted  
 1285 from Nemeth & Kereszturi (2015). **B** Seismic line across a cinder cone and lava flow, taken from the  
 1286 Winnie 3D survey, highlighting the general morphology, seismic response. Note the characteristic eye  
 1287 shape within the centre of the vent. **C** Plan view spectral decomposition of the cinder cone in **B**  
 1288 highlighting how different it is from the surrounding sediments. **D** Oblique view of the same cinder  
 1289 cone shown in TWT. **E** Cross section through a Maar-diatreme, adapted from Nemeth & Kereszturi  
 1290 (2015). **F** Seismic line across a proposed Maar-diatreme from the Winnie 3D survey. Note how it cuts  
 1291 down into the subsurface with an internally chaotic seismic response. **G** Plan view spectral  
 1292 decomposition of a Maar-diatreme. **H** Oblique, TWT view of the proposed Maar-diatreme.

1293

1294

1295

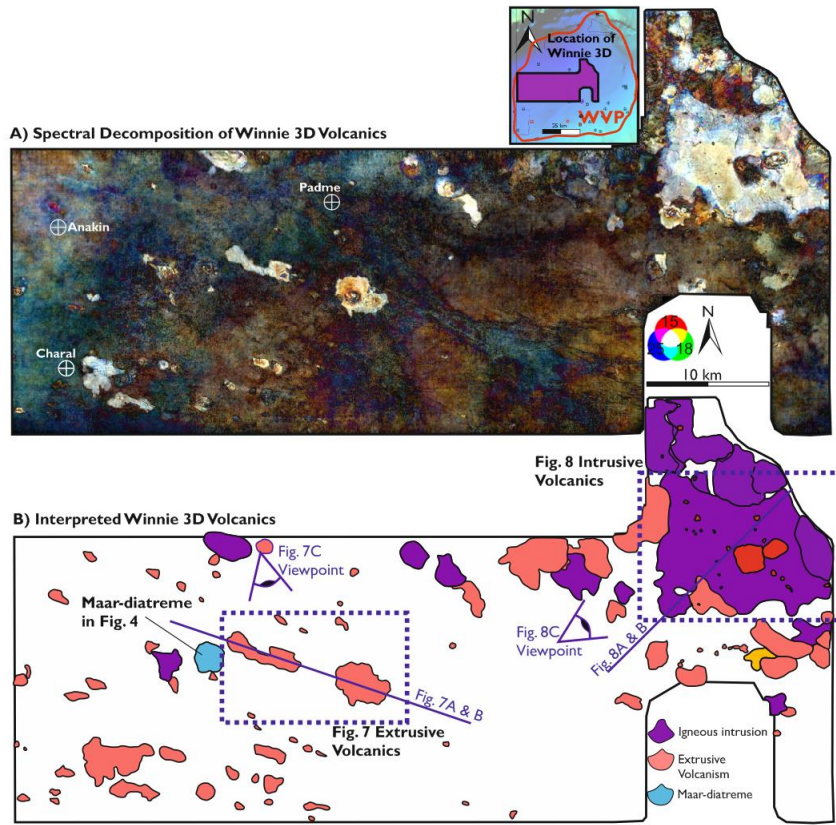


1296

1297 **Figure 5.** Well correlation across the eastern Nappamerri Trough showing the changes in facies  
 1298 across the area and the thickness of the volcanics intersected. Note in areas of thickened volcanics  
 1299 (i.e. the Kappa and Lambda wells) the Hutton sandstone and Birkhead fm. are thinned considerably  
 1300 suggesting sedimentary systems were diverted away from areas of eruption. As noted in the text, the  
 1301 change from the clean sandstones of the Hutton Sandstone to silty sandstones in the Birkhead fm. is  
 1302 associated with an influx of volcanic arc derived sediment from eastern Australia.

1303

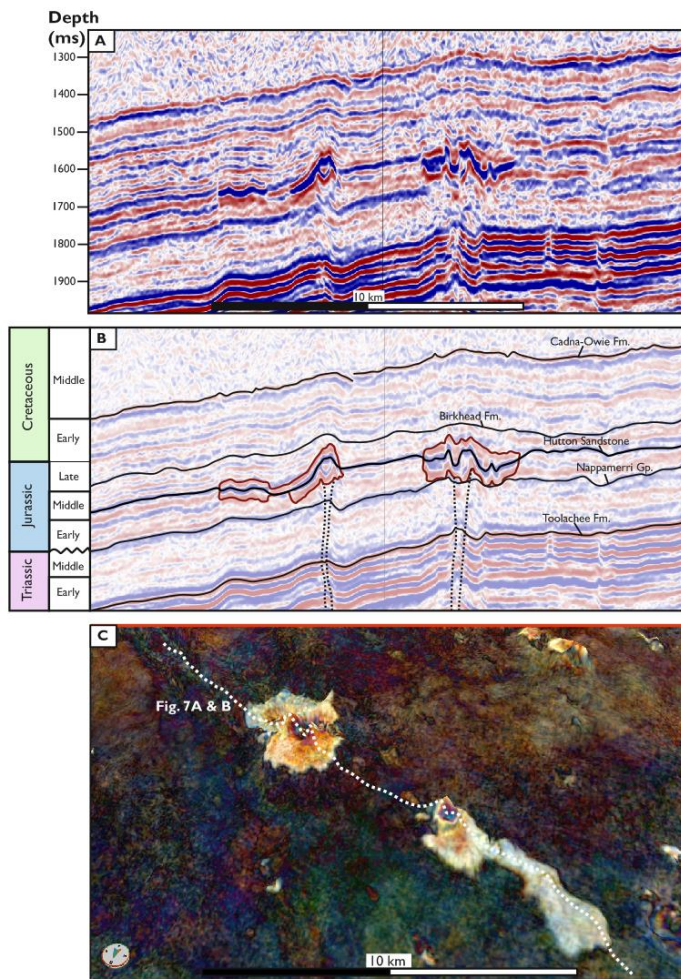
1304



1305

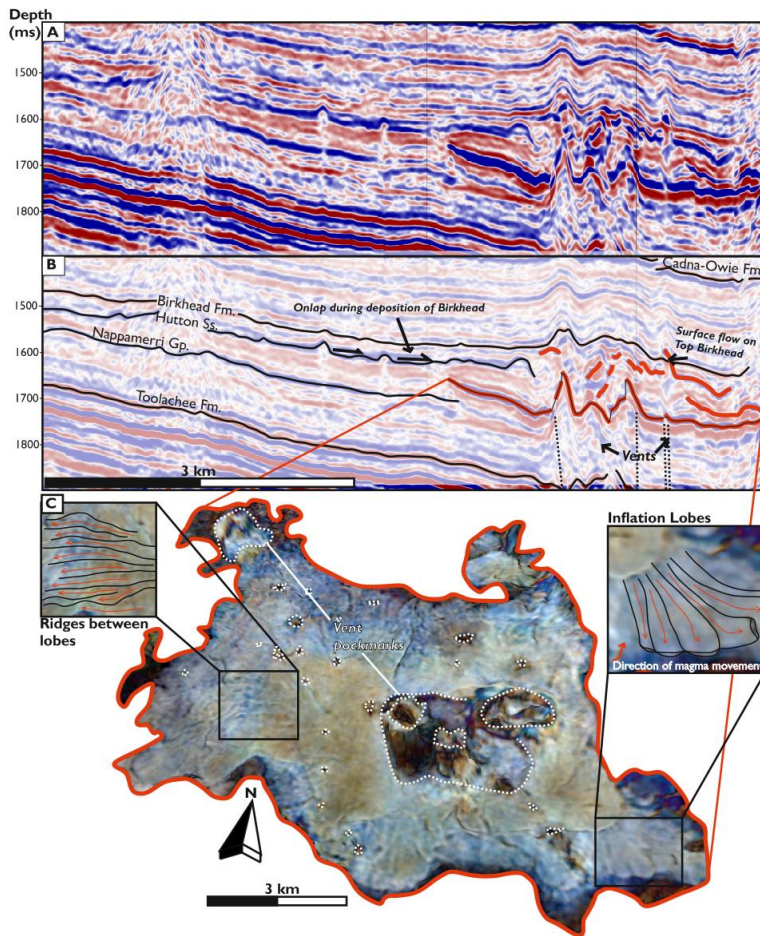
1306 **Figure 6.** Spectral decomposition of a horizon mapped across the volcanics of the Winnie 3D survey.  
1307 **A** Uninterpreted spectral decomposition. **B** Interpreted spectral decomposition highlight extrusive  
1308 volcanics and the location of igneous intrusions. Note the increased number of intrusions towards the  
1309 north east of the Winnie 3D survey.





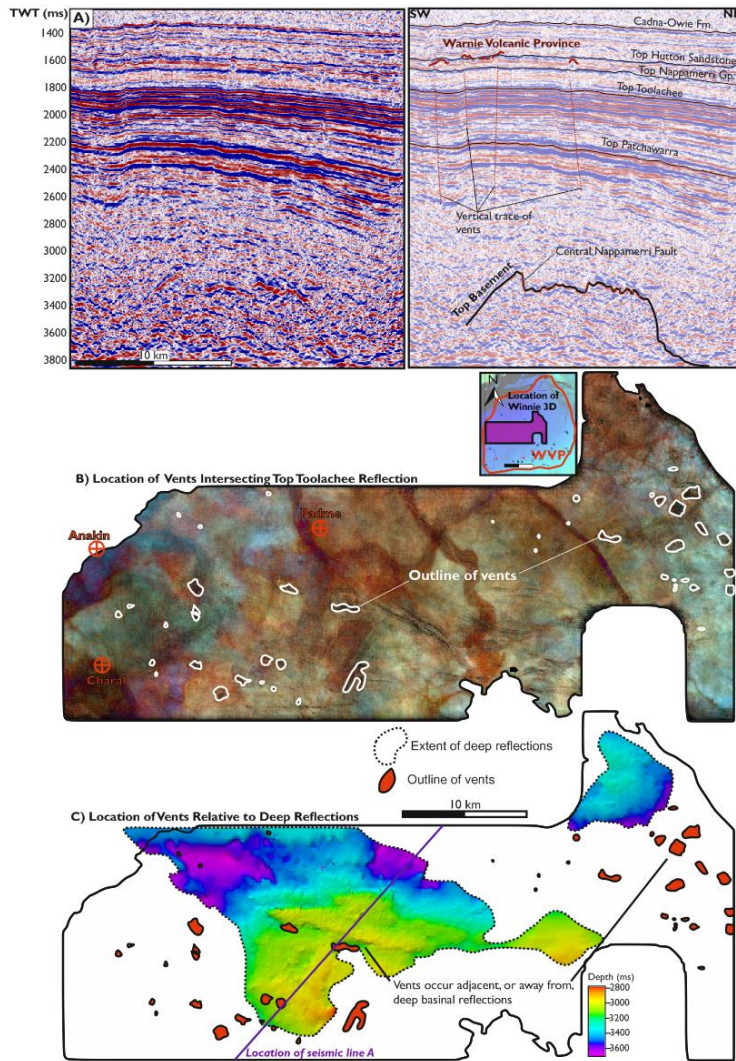
1310

1311 **Figure 7.** 3D Seismic across two monogenetic vents that extend into surface flows, from the Winnie  
 1312 3D survey. **A** Uninterpreted line across the vents. **B** Interpreted line across the vents. Note the vertical  
 1313 zone of disrupted seismic directly below the vents, indicative of underlying plumbing system that fed  
 1314 the flows. **C** Spectral decomposition of a horizon mapped across the vents, highlighting their 3D  
 1315 morphology.



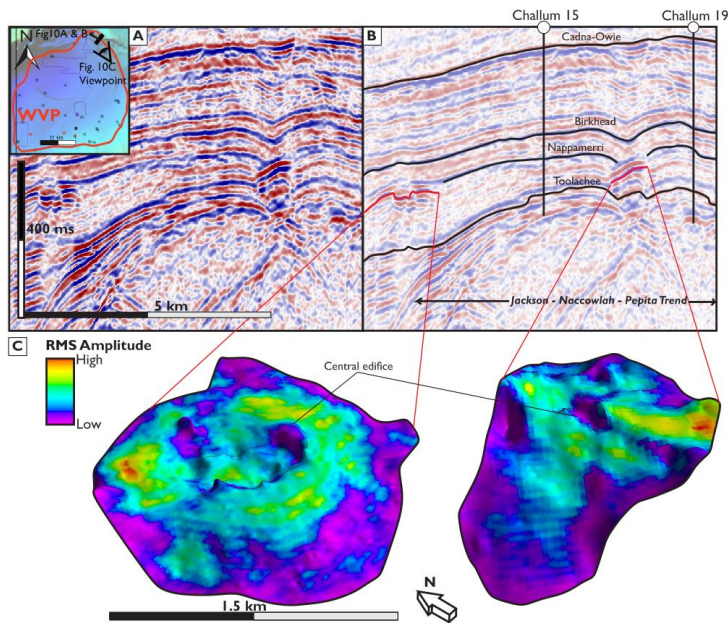
1316

1317 **Figure 8.** Seismic across the large intrusion in the Winnie 3D survey. **A** Uninterpreted seismic line.  
1318 **B** Interpreted seismic line, illustrating the uplift of the overburden and the numerous vents and  
1319 overlying volcanics associated with the intrusion. **C** Spectral decomposition of the intrusion, highlight  
1320 the pockmarks of vents that pass through the intrusion and morphological characteristics associated  
1321 with the intrusion.



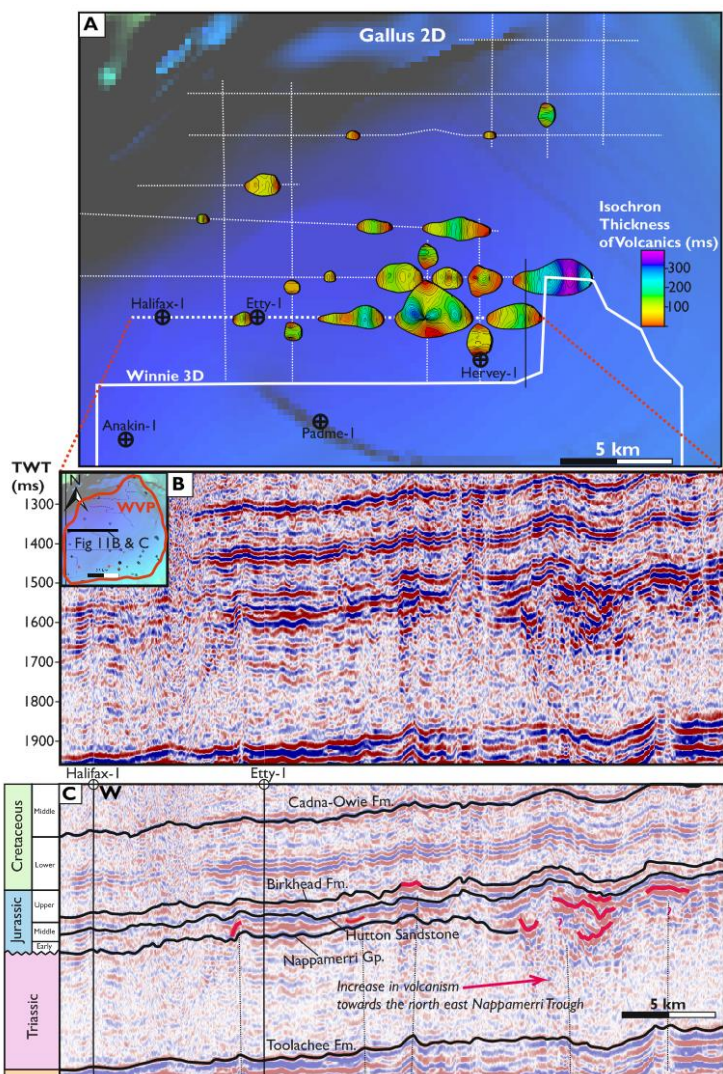
1322

1323 **Figure 9.** The basement structure and it's relation to vents within the Winnie 3D survey. **A**  
1324 Uninterpreted and interpreted seismic line across the Winnie 3D survey, highlighting the deep  
1325 basement reflections and their relation to vents feeding the WVP. **B** Spectral decomposition of the  
1326 Top Toolachee horizon, highlighting the location of vents underlying the WVP. **C** Location of vents  
1327 mapped using the Top Toolachee horizon superimposed on a TWT map of the top basement horizon.



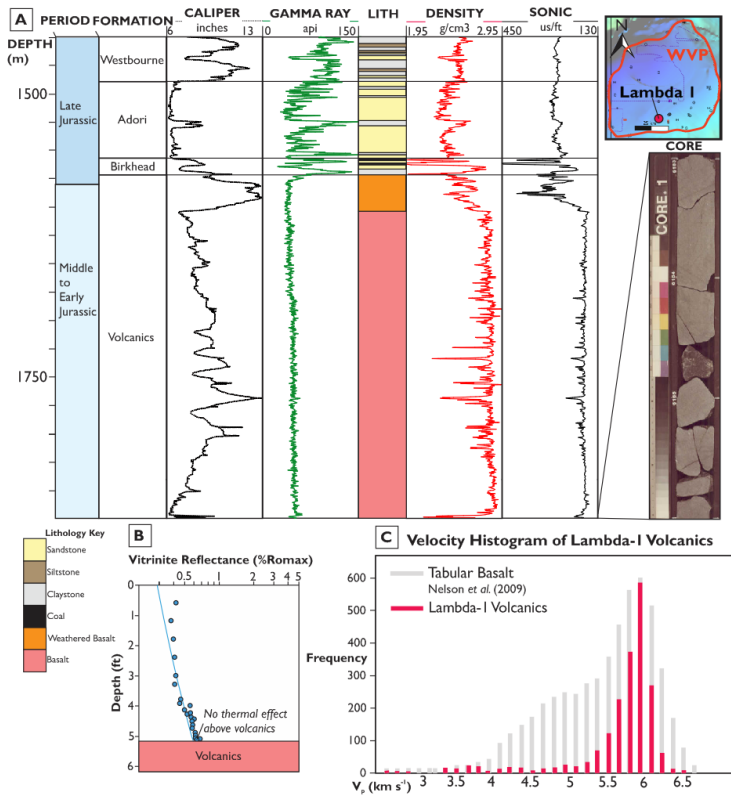
1328

1329 **Figure 10.** Seismic cross volcanics within the Madigan 3D survey. **A** Uninterpreted seismic line taken  
 1330 across the two volcanic features. **B** Interpreted seismic horizon, showing the location of two Challum  
 1331 wells and the Challum vents. **C** 3D view of the Challum vents, with an RMS amplitude extraction  
 1332 draped over the horizons.



1333

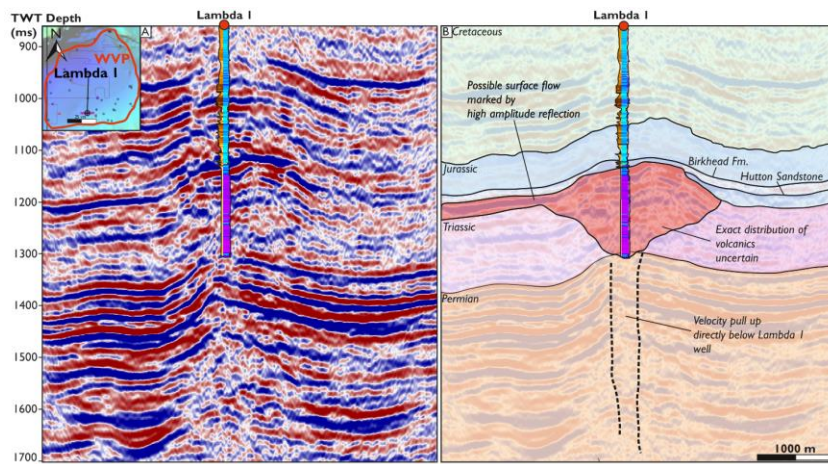
1334 **Figure 11.** Seismic images of the Gallus 2D survey. **A** Isochron thickness map of the volcanics  
 1335 identified throughout the Gallus 2D survey. **B** Uninterpreted seismic line from the Gallus 2D survey.  
 1336 **C** Interpreted seismic line from the Gallus 2D survey. An increase in the volume of volcanics towards  
 1337 the east of the survey is apparent.



1338

1339 **Figure 12.** Well data for the volcanics from the Lambda-I well. **A** Composite log of the volcanic  
 1340 succession in the Lambda-I well. Includes an image of the core taken from the base of the volcanic  
 1341 succession. **B** Vitrinite reflectance curve for the succession above the volcanics taken from Boothby  
 1342 (1986). Little thermal effect is observed. **C** Velocity histogram of the Lambda-I volcanics  
 1343 superimposed on Nelson *et al.*'s (2009) velocity histogram of Tabular basalt.

1344



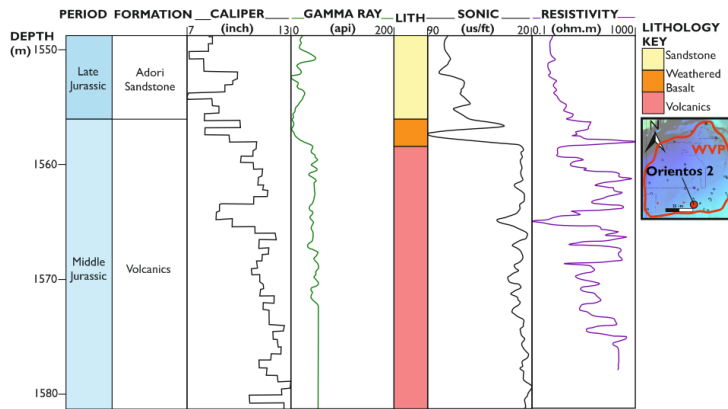
1345

1346 **Figure 13.** West to east seismic line running across the Lambda I well. The extent of the Lambda I  
 1347 vent has been inferred base on the thickness of volcanics within the well.

1348

1349

1350

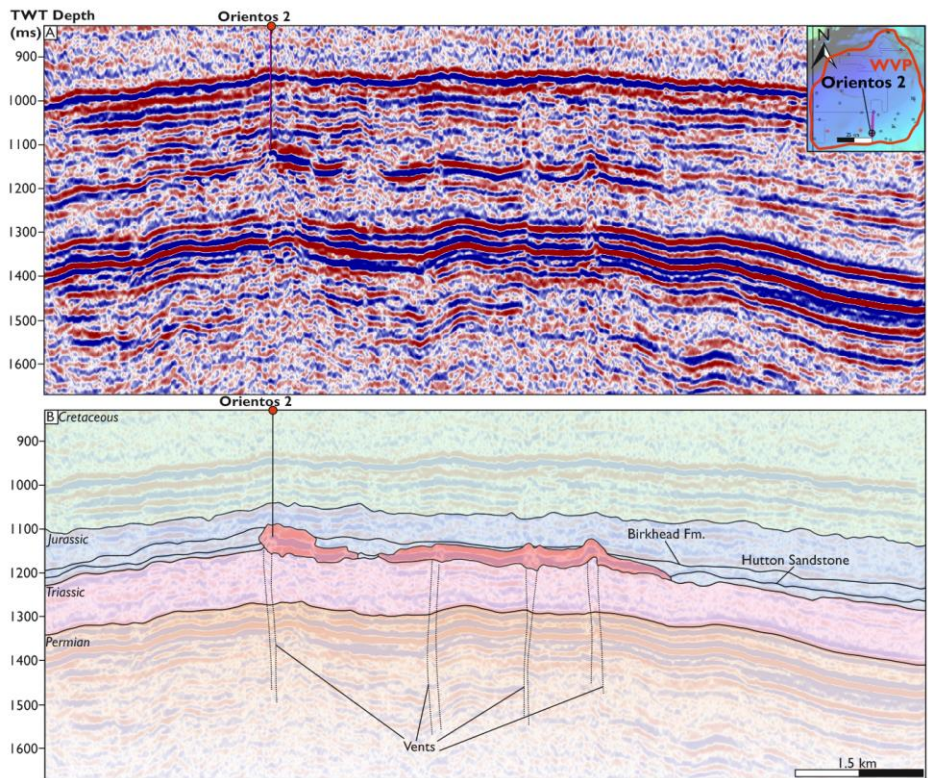


1351

1352 **Figure 14.** Digitised composite log for the volcanics within the Orientos 2 well.

1353





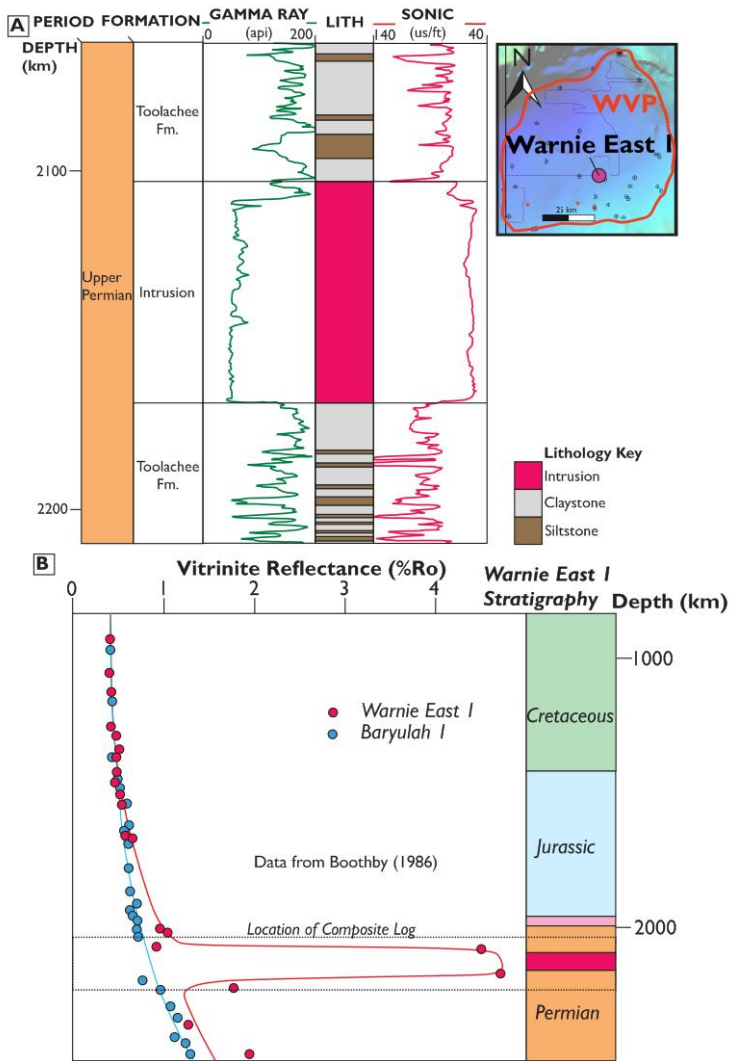
1354

1355 **Figure 15.** South to North 2D seismic line running across the location of the Orientos 2 well. A  
 1356 series of tabular basalt lava flows emplaced on top of the Triassic Nappamerri group are visible, with  
 1357 Orientos 2 intersecting the top of the southernmost flow.

1358

1359

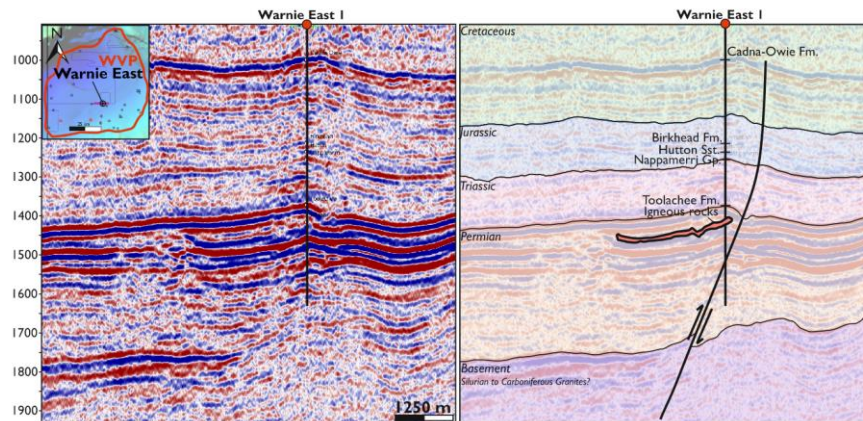
1360



1361

1362 **Figure 16.** Well data for intrusive volcanic rocks within the Warnie East I well. **A** Composite log  
1363 across the intrusion in the Warnie East well. **B** Vitrinite reflectance profile across the intrusion in the  
1364 Warnie East well taken from Boothby (1986). Thermal effect both above and below the well is noted.

1365



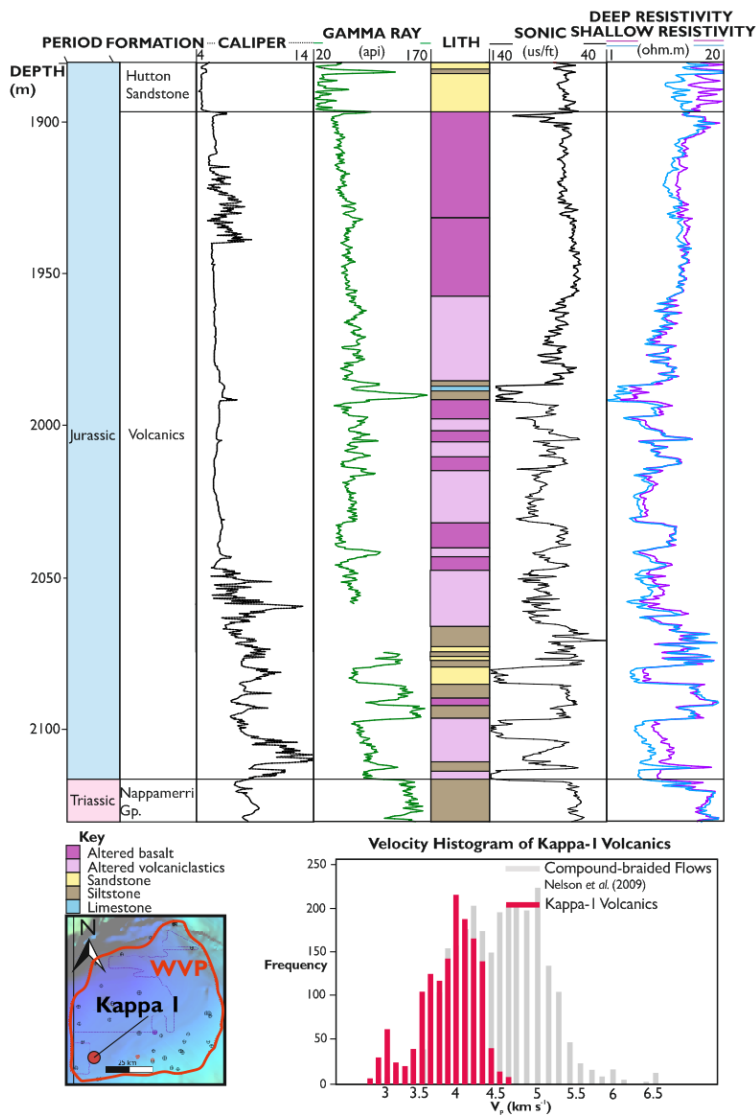
1366

1367 **Figure 17.** 2D seismic line running from west to east across the Warnie East I well. The exact  
 1368 location of the igneous rocks is unclear on the line, however, a shallow saucer-shaped reflection with  
 1369 the Toolachee Fm. intersects Warnie East I at the depth igneous rocks are found. Also notable is the  
 1370 presence of a rollover anticline adjacent to a growth fault.

1371

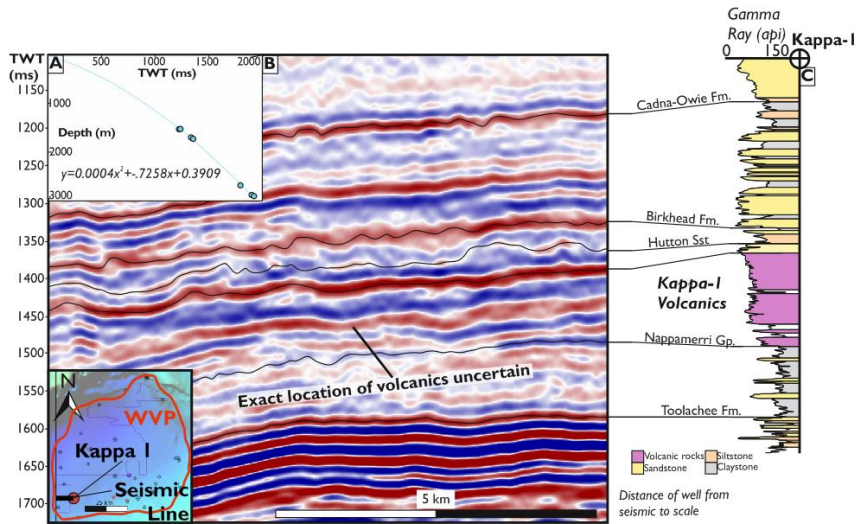
1372

1373



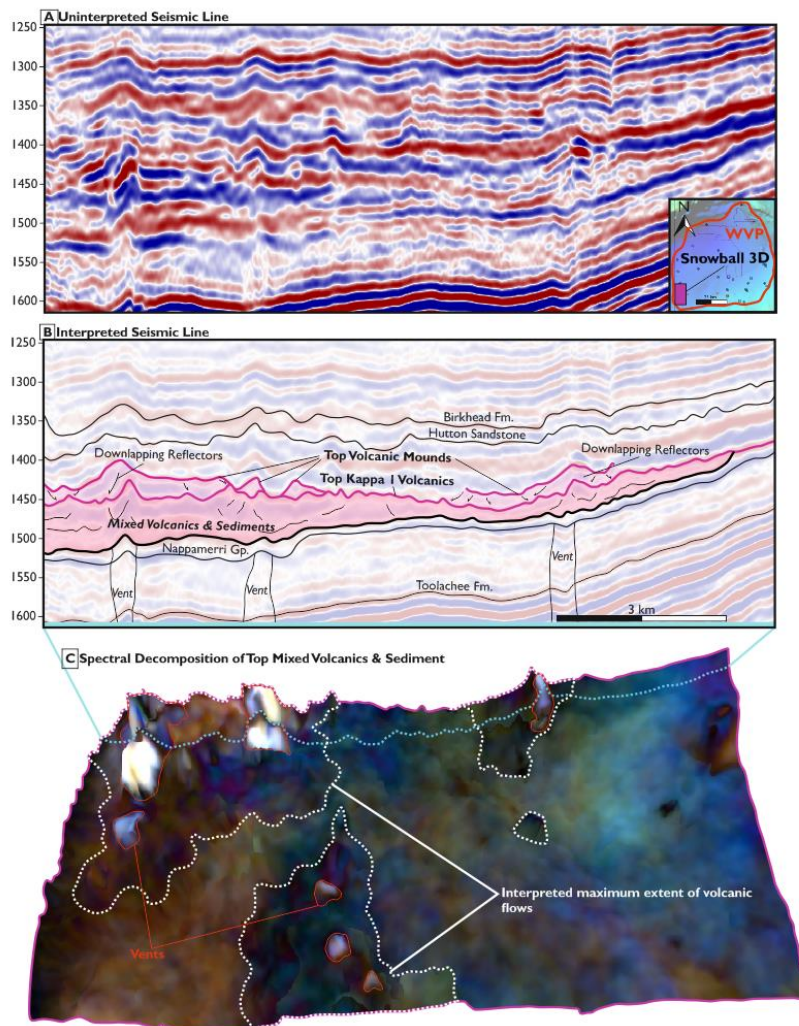
1374

1375 **Figure 18.** Well data for the Kappa-I well. **A** Composite log for the Kappa-I well volcanics. **B**  
1376 Velocity histogram for the Kappa-I well volcanics, superimposed on top of Nelson *et al.*'s (2009)  
1377 velocity histogram for compound-braided volcanics.



1378

1379 **Figure 19.** Position of the Kappa-I well in relation to the Snowball 3D survey. **A** TWT to depth  
 1380 relationship used to convert the Kappa-I well data from depth to time in order to display it adjacent  
 1381 to the Snowball 3D survey. **B** Line across the Snowball 3D survey with the position of formation tops  
 1382 based on the Kappa-I well displayed. **C** Gamma ray curve from the Kappa-I well with formation tops  
 1383 marked.

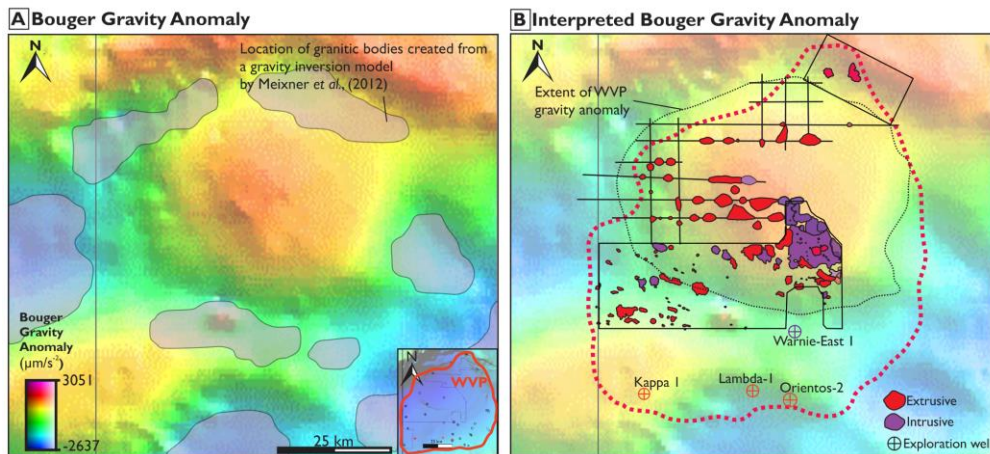


1384

1385 **Figure 20.** Seismic across volcanics within the Snowball 3D survey. **A** Uninterpreted seismic line. **B**  
1386 Interpreted seismic line. Thick package of mixed volcanics & sediments based off of the Kappa-I well  
1387 volcanics. **C** Spectral decomposition of the top mixed volcanics & sediment horizon. Location of vents  
1388 noted by bright white colour with interpreted flow fields based on dark colours adjacent to vents.

1389

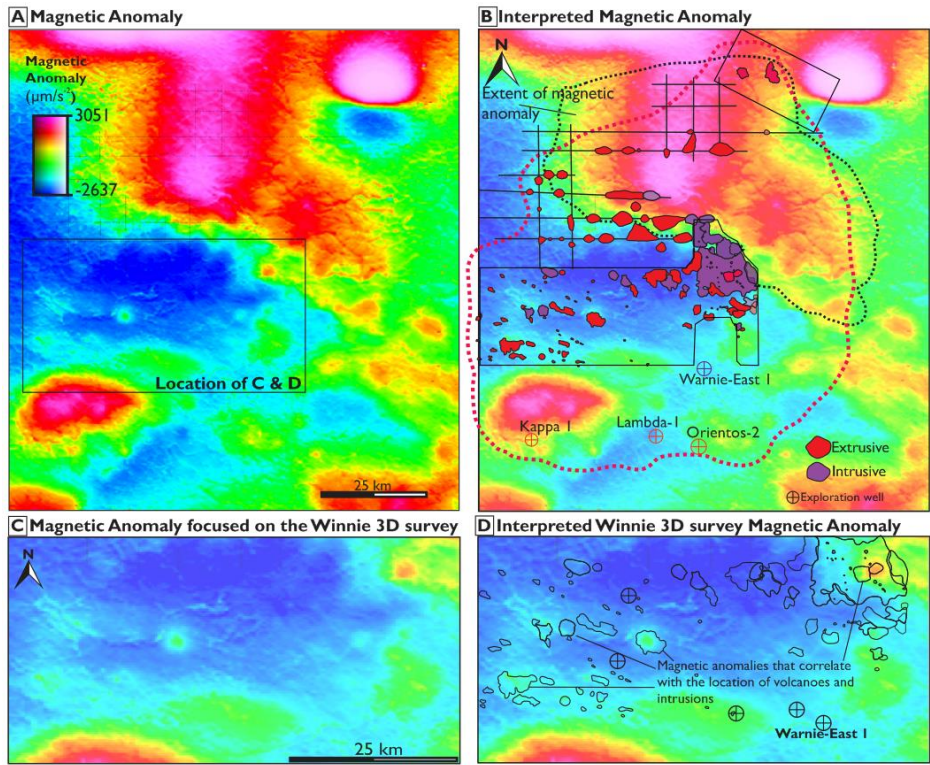
1390



1391

1392 **Figure 21.** Bouguer gravity anomaly adopted from Tracey & Bacchin (2008). The gravity data shows  
1393 spherical cap-corrected Bouguer anomalies with a high pass filter with a cut-off wavelength of 500 m.  
1394 Spacing coverage is typically 11 km, with more closely spaced grids (2 km) in areas of economic interest  
1395 (Tracey & Bacchin, 2008). **A.** Uninterpreted bouguer gravity anomaly overlain with the location of  
1396 granitic bodies created from Meixner *et al.*'s (2002). Granitic bodies are expressed as lower values in  
1397 the gravity anomaly, located adjacent to the 50 x 50 km gravity high below the Warnie Volcanic  
1398 Province. **B.** Bouguer gravity anomaly superimposed with the location of the igneous rocks within the  
1399 Warnie Volcanic Province.

1400



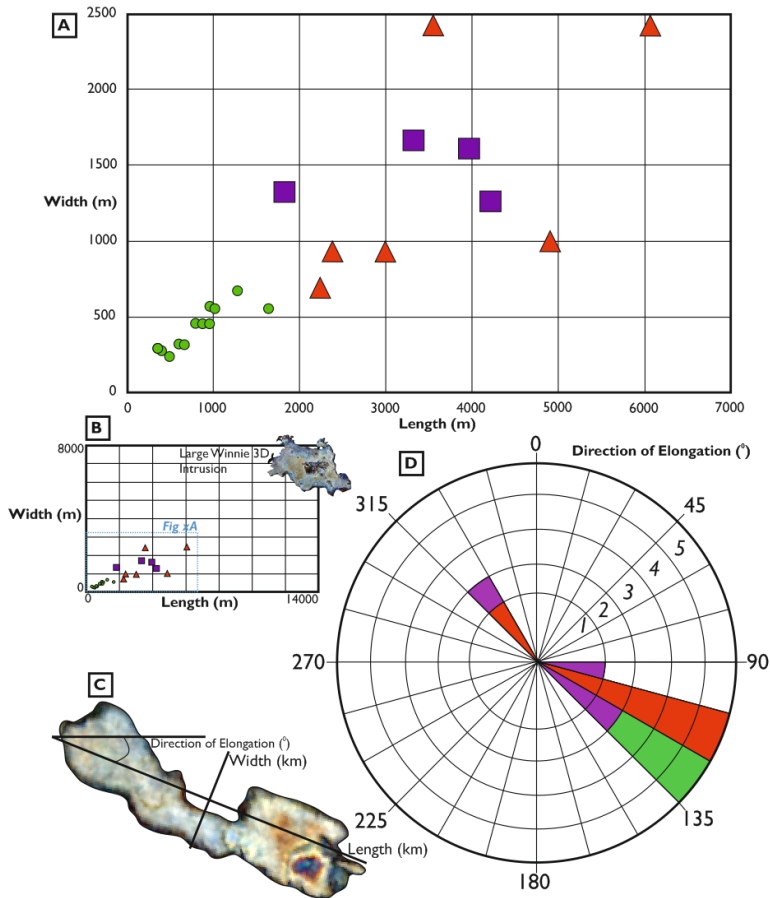
1401

1402 **Figure 22.** Total magnetic intensity across the Warnie Volcanic Province. This data was obtained for  
1403 study from the Queensland Department of Natural Resources and Mines database. The survey was  
1404 flown in an east-west direction at a height of 60 m with a distance of 400 m between the traverse  
1405 lines. **A.** Unannotated total magnetic intensity over the eastern Nappamerri Trough. Location of C  
1406 and D highlighted. **B.** Total magnetic intensity superimposed with the location of igneous rocks  
1407 interpreted within the Warnie Volcanic Province. **C** Unannotated total magnetic intensity for the area  
1408 covered by the Winnie 3D survey. **D** Total magnetic intensity superimposed with the location of  
1409 igneous rocks interpreted within the Winnie 3D survey. Note the close correspondence between  
1410 some magnetic anomalies and the location of igneous rocks.

1411



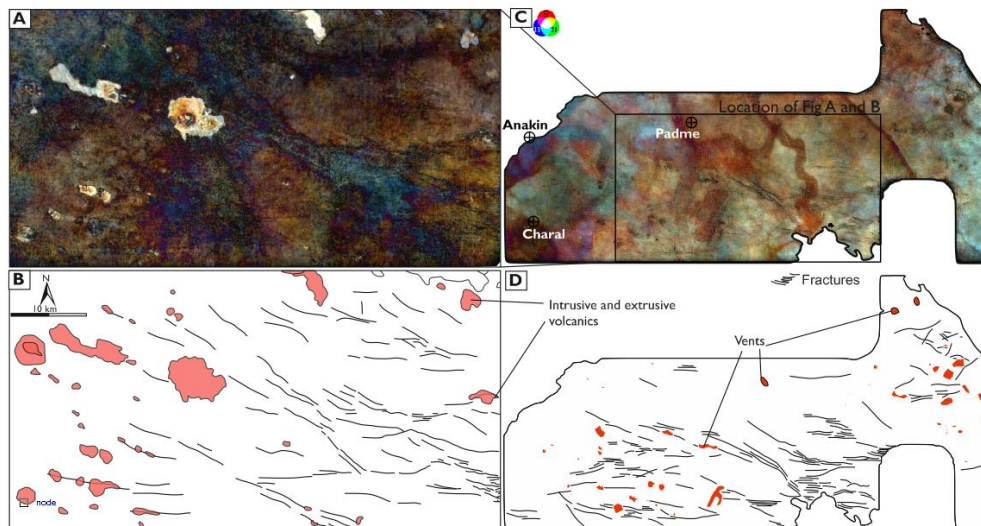
1412



1413

1414 **Figure 23:** Size and orientation of volcanics within the Winnie 3D and Madigan 3D surveys. **A** Size  
1415 of vents, intrusions and volcanic flows. **B** Figure A, with the singular large intrusion superimposed on  
1416 it, highlighting the shear the scale of this volcanic features. **C** Measurements taken for each individual  
1417 volcanic feature. **D** Direction of elongation for the volcanics, highlighting that they are elongate in a  
1418 SE-NW direction.

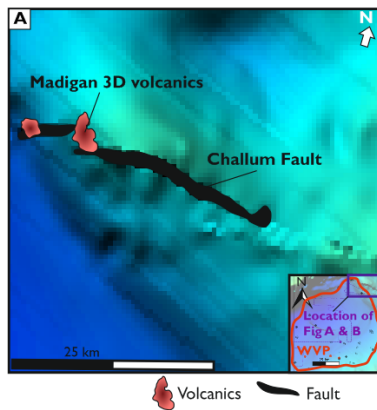
1419



1420

1421 **Figure 24:** Mapping of minor faults within the Nappamerri trough. **A** Spectral decomposition of the  
 1422 Top Volcanics horizon from the Winnie 3D survey. **B** Interpretation of A with discontinuities and  
 1423 the location of volcanics highlighted. **C** Spectral decomposition of the Top Toolachee horizon. **D**  
 1424 Interpretation of discontinuities within the Toolachee Horizon and the location of volcanics  
 1425 highlighted.

1426



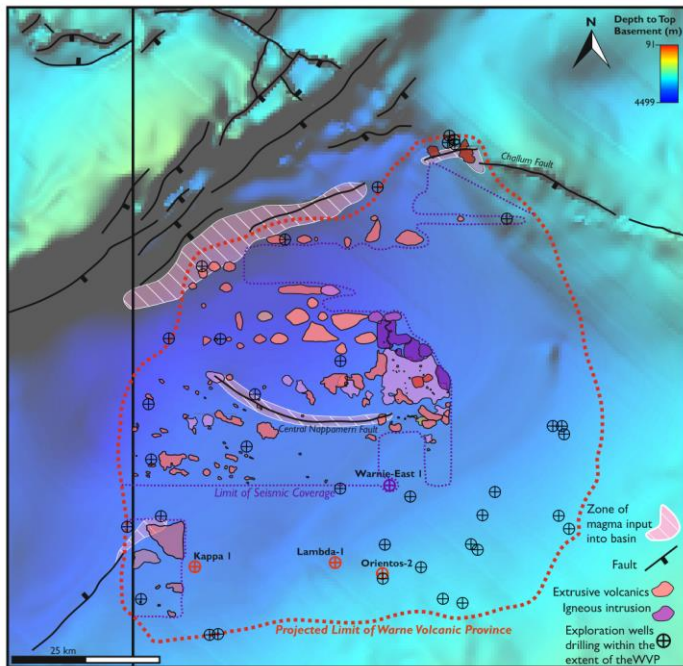
1427

1428 **Figure 25: A** Location of the Challum Fault and Madigan 3D volcanics superimposed on a Depth to  
1429 top basement map adapted from NGMA (2003). Madigan 3D volcanics located above the North  
1430 West tip of the Challum Fault.

1431

1432

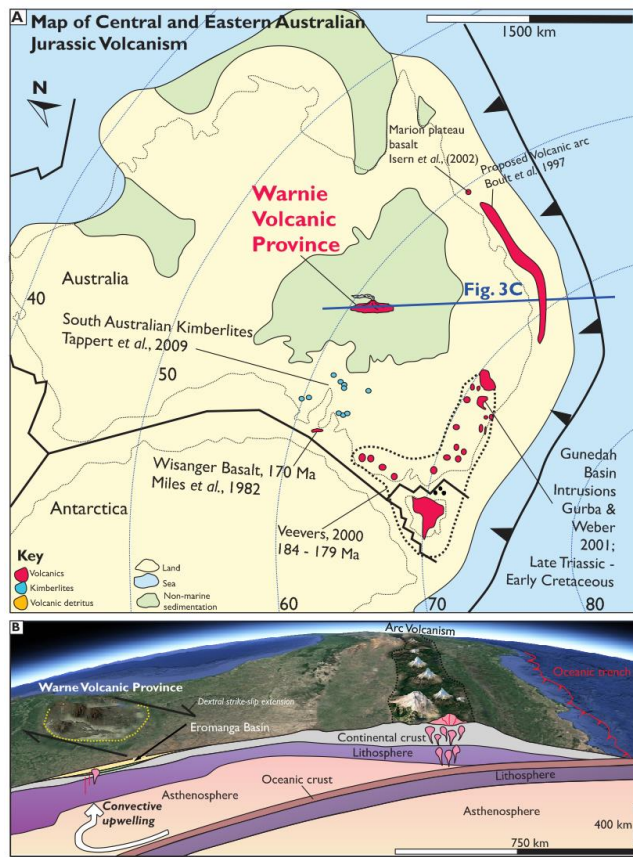
1433



1434

1435 **Figure 26:** Regional map of the Warnie Volcanic Province. Depth to top basement map adapted  
1436 from NGMA (2003). Location of extrusive volcanics and igneous intrusions based on seismic data.  
1437 The volcanics, however, are thought to extend beyond the limit of seismic coverage towards the  
1438 projected limit of the Warnie Volcanic Province. Zones of magma input into the basin are based off  
1439 of the main basement bounding faults identified within the study, although many more minor input  
1440 points are expected to occur within the Nappamerri trough from faults not imaged within this study.

1441



1442

1443 **Figure 27: A** Map of Australia, superimposed with the location of middle to late Jurassic volcanics  
 1444 in eastern Australia, described in the text. Base map is a magnetics map used to highlight the Great  
 1445 Artesian Basin. **B** Palaeogeographic map of Australia in the middle Jurassic (Oxfordian, 160 Ma),  
 1446 highlighting the tectonic nature of the different volcanics. **C** Oblique view of Australia, highlighting  
 1447 the subducting pacific slab and associated convective upwelling. Steps in lithospheric thickness have  
 1448 adapted from Fishwick *et al.*, (2008).

1449