Magnetic stripes preserved in the continent-ocean transition zone offshore NW Australia

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Key Points

1) We identify seaward-dipping reflectors across the Cuvier Abyssal Plain and use chemical data to argue it is not oceanic crust as thought.
2) Magnetic stripes are thought unique to oceanic crust, but we show they can form in non-oceanic crust in continent-ocean transition zones.
3) We move the continent-ocean boundary of NW Australia oceanwards by >500 km.

Abstract

Magnetic stripes have long been used to define oceanic crust and the onset of submarine sea-floor spreading. Identifying magnetic stripes is crucial for plate kinematic reconstructions, and for estimating spreading rates and timing of continental break-up: the most landward magnetic stripes are assumed to mark the oldest oceanic crust. However, continental crust heavily intruded by magma during active sub-aerial rifting in Ethiopia, records magnetic reversals akin to those observed in oceanic crust, implying magnetic stripes may not be diagnostic of seafloor spreading. Recent work on South Atlantic volcanic passive margins has identified linear magnetic anomalies within the continent-ocean transition zone (COTZ), which is presently overlain by seaward dipping reflector (SDR) sequences of stacked lavas. Perhaps surprisingly, magnetic stripes have rarely been observed in COTZ crust along passive margins elsewhere. We use magnetic, 2D seismic reflection, and geochemical data to examine the lithospheric structure of the Cuvier margin, offshore Northwest Australia, which hosts well-defined, ≤220 km long magnetic stripe anomalies M10N–M5. Although interpreted previously as oceanic crust, we suggest these magnetic stripes occur on a >500 km wide, Early Cretaceous COTZ. We suggest the magnetic anomalies record magnetic reversal signatures originating from sheeted dykes and gabbroic intrusions within the sub-SDR crust. Our interpretation implies the outer limit of Australia's COTZ may thus be up to >500 km further oceanward than previously recognised. Furthermore, this work strengthens a growing consensus that magnetic reversals at rifted margins may not be truly diagnostic of the onset of oceanic crust formation.

Plain Text Summary

Earth's ocean floors are characterised by a barcode-like pattern of magnetic stripes parallel to mid-ocean ridges. These stripes record reversals in Earth's magnetic North and South field

when new rock was forming and moving away from submarine mid-ocean ridges; this is fundamental evidence for continental drift and plate tectonic theory. Magnetic stripes have long been considered unique to oceanic crust, but recent studies suggest they may form on continental crust. We study the Cuvier Abyssal Plain offshore NW Australia, which displays clear magnetic stripes and is thought comprise oceanic crust. We use seismic reflection data, which provides ultrasound-like images of Earth's subsurface, to study the crusts structure and show it contains thick sequences of lavas that were erupted in a sub-aerial environment. We also reinterpret the chemistry of lavas from the proposed mid-ocean ridge that formed the crust, and demonstrate the magma creating these rocks interacted with continental material. Our evidence suggests the Cuvier Abyssal Plain is not formed of oceanic crust, but rather is a hybrid of continental and oceanic crust. Our results mean that: (1) the continent-ocean boundary of NW Australia could be >500 km further offshore; and (2) magnetic stripes may not be diagnostic of oceanic crust.

Index Terms

1020; 1021; 1517; 8105; 8178

Keywords

Magnetic stripe; oceanic crust; continental crust; continent-ocean transition zone; seaward-dipping reflectors; Australia

1. Introduction

Development of magnetic reversal anomalies (stripes) during oceanic crust formation is fundamental to modern plate tectonic theory (e.g., Vine & Matthews, 1963). Magnetic stripes immediately adjacent to passive continental margins are commonly interpreted to mark a basin's oldest oceanic crust, and have historically been used to define the continent-ocean boundary (COB) (e.g., Eagles et al., 2015; Rabinowitz & LaBrecque, 1979; Talwani & Eldholm, 1973; Veevers, 1986). Recognition and accurate mapping of COBs are critical to palinspastic and plate kinematic reconstructions (e.g., Eagles et al., 2015). However, improved long-offset seismic reflection and refraction data reveal continental break-up can produce complex crustal domains up to several hundred kilometres wide, i.e. the continent-ocean transition zone (COTZ), characterised by localized lithospheric thinning and occasional mantle exhumation (see Eagles et al., 2015 and references therein). Uncertainties in data resolution and interpretation make ascertaining the nature of COTZ crust challenging, meaning it is difficult to uniquely define COBs (e.g., Eagles et al., 2015). Furthermore, linear magnetic stripes have recently been identified: (i) in heavily intruded, transitional continental crust of the onshore Afar Rift, Ethiopia (Bridges et al., 2012), which is expected to form part of a COTZ assuming full lithospheric rupture occurs; (ii) along the COTZ offshore Iberia-Newfoundland non-volcanic passive margin, recorded by intrusion of magma into exhumed and serpentinised mantle prior to break-up (Bronner et al., 2011); (iii) within part of the volcanic passive margin COTZ offshore NW Australia (i.e. the Gascoyne margin; Direen et al., 2008); and (iv) in magmatic crust, which is wholly comprised of new igneous material but formed during sub-aerial spreading (i.e. not oceanic crust), offshore South America (Collier et al., 2017; McDermott et al., 2018). Given magnetic stripes can seemingly develop within non-oceanic crust, these observations question whether magnetic stripes can be used to diagnose seafloor spreading and COBs (Rooney et al., 2014).

The Cuvier margin, offshore NW Australia is an ideal location to explore the development of magnetic stripes during the transition to seafloor spreading: it has well-developed magnetic anomalies, calibrated to the global geomagnetic timescale (Robb et al., 2005), and reflection and refraction seismic data capable of imaging the margin's deep crustal structure. Previous seismic refraction and magnetic studies suggest the Cuvier Abyssal Plain (CAP) is underlain by unambiguous oceanic crust, formed by submarine spreading; this interpretation is based on the presence of magnetic stripes distributed about an inferred submarine spreading centre along the Sonne Ridge (Fig. 1) (e.g., Falvey & Veevers, 1974; Larson et al., 1979; MacLeod et al., 2017; Robb et al., 2005). Basalts dredged from the Sonne Ridge are interpreted to have an enriched MORB-like chemistry, supporting the inference that the CAP comprises oceanic crust (Crawford & von Rad, 1994; Dadd et al., 2015). Our concurrent analysis of magnetic and 2D seismic reflection data, coupled with an examination of published chemical data, suggest the well-defined magnetic stripes of the CAP actually occur within the COTZ. In particular, we recognise multiple packages of up to ~3 km thick seaward-dipping reflector (SDR) sequences, which can extend across several defined linear magnetic anomalies, imaged in seismic reflection data spanning ~200 km of the CAP. Furthermore, reinterpretation of chemical data indicates basalts from the Sonne Ridge, interpreted to be an abandoned submarine spreading centre (e.g., MacLeod et al., 2017; Robb et al., 2005), contain a continental signature. Based on these observations and data, we propose the CAP may not be oceanic crust and is instead representative of a COTZ with an outer-limit >500 km oceanwards from where it is currently defined. Our interpretation has important implications for plate reconstructions and heat flow and basin modelling of the NW Australian margin. Furthermore, we argue that magnetic stripes may not be a unique feature of oceanic crust.

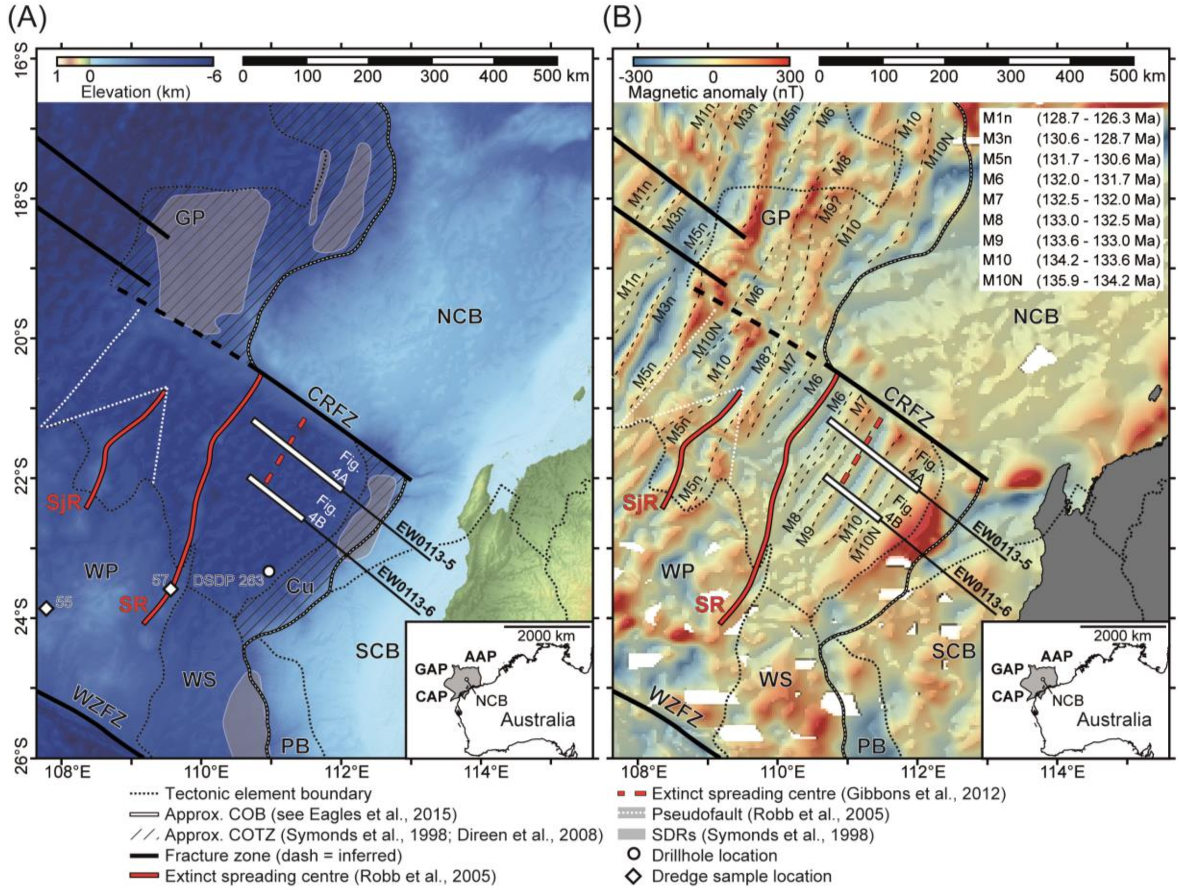

Figure 1: (A) Location map of the study area highlighting key tectonic elements, including areas of recognised seaward-dipping reflectors (SDRs) (Holford et al., 2013; Symonds et al., 1998) and previously interpreted approximate (approx.) limits of the continent-ocean boundary (COB; Eagles et al., 2015) and continent-ocean transition zones (COTZs; Direen et al., 2008; Symonds et al., 1998). Inset: study area location offshore NW Australia. AAP – Argo Abyssal Plain, CAP – Cuvier Abyssal Plain, CRFZ – Cape Range Fracture Zone, GAP – Gascoyne Abyssal Plain, GP – Gallah Province, NCB – North Carnarvon Basin, SCB – South Carnarvon Basin, Cu – Cuvier margin COTZ, SR – Sonne Ridge, SjR – Sonja Ridge, WP – Wallaby Plateau, WS – Wallaby Saddle, WZFZ – Wallaby-Zenith Fracture Zone. Dredge sites 55 (samples 055BS004A and 055BS004B) and 57 (sample 057DR051A) are also shown (Dadd et al., 2015). (B) Total magnetic intensity grid (EMAG2v2), interpreted

magnetic chrons (based on Robb et al., 2005). See Supplementary Figure S1 for an uninterpreted version.

2. Definitions

We define a COTZ as the crustal domain separating unambiguous continental crust and unambiguous normal oceanic crust (Eagles et al., 2015). Along volcanic or magma-rich passive margins, COTZ's commonly comprise seismically isotropic, fast (>7 km s^{-1}) crust, overlain by SDR sequences of sub-aerially erupted, mafic volcanic products (e.g. lava flows) interbedded with terrestrial sedimentary rocks (e.g., Eldholm et al., 1989; Larsen & Saunders, 1998; Menzies et al., 2002; Symonds et al., 1998). These SDR-bearing domains have been further sub-divided into: (i) 'transitional crust', i.e. stretched and heavily intruded continental crust (e.g., Eldholm et al., 1989); (ii) or 'magmatic crust' (also termed 'igneous' crust), which effectively is structurally the same as oceanic crust but instead formed by sub-aerial, rather than submarine, spreading (e.g., Collier et al., 2017; McDermott et al., 2018; Paton et al., 2017). Where we can study active continental break-up and development of a possible future COTZ in Ethiopia, the latter phases of rifting (i.e. prior to rupture) involve localisation of extension into narrow zones (~20 km wide) dominated by dyke intrusion (e.g., Ebinger & Casey, 2001; Keranen et al., 2004; Mackenzie et al., 2005; Maguire et al., 2006).

Observations from rifted margins and active rifts therefore suggest the COTZ at volcanic passive margins is marked by a compositional and structural spectrum some way between continental and oceanic end-members (Fig. 2). From their landward limit, at the age which corresponds to onset of COTZ development, we expect the proportion of intruded material to continental crust (i.e. transitional crust) to increase oceanwards, until no or very little continental crust remains and the COTZ comprises igneous intrusions and extrusions formed in sub-aerial spreading centres (i.e. magmatic crust) (Fig. 2). Given the localisation of dyking within narrow zones we may expect an oceanwards reduction in the continental signature of magma chemistry as they become more MORB-like (Fig. 2). Because uncertainties in data resolution and interpretation mean we cannot identify a distinct boundary between transitional or magmatic crust (cf. Eagles et al., 2015), we henceforth combine these domains and refer to them both simply as 'COTZ crust' (Fig. 2).

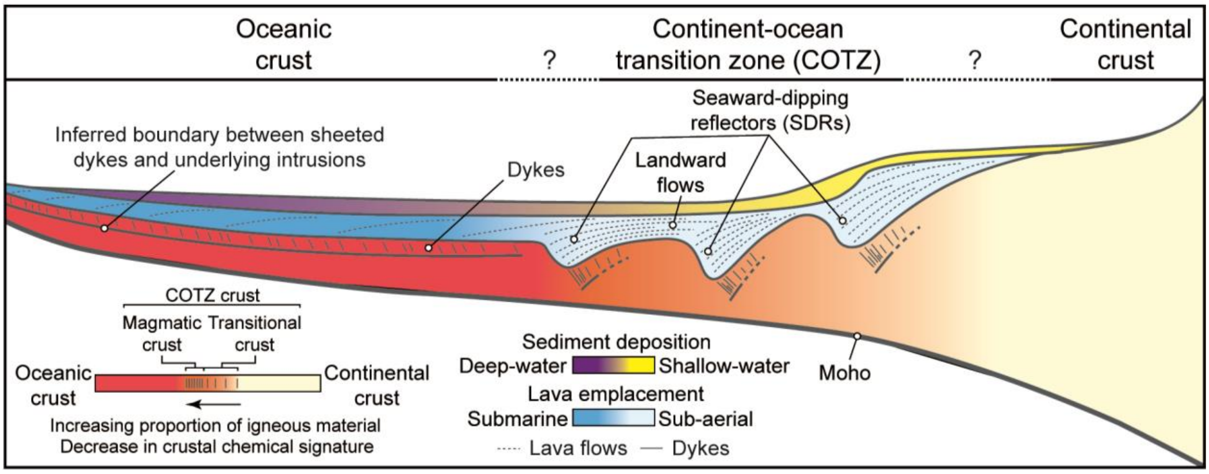

Figure 2: Schematic model (not to scale) of a continent-ocean transition zone along a volcanic passive margin; for simplicity the lithospheric mantle is not shown. As magma intrudes continental crust, likely as dykes at mid- to upper-crustal levels and larger gabbroic bodies in the lower crust, it becomes 'transitional crust' (e.g., Eldholm et al., 1989). Continued intrusion and dyking leads to localisation of magmatism within narrow zones where sub-aerial spreading dominates extension and there is little, if any, continental crust remaining (i.e. magmatic crust) (i.e. 'magmatic crust'; e.g., Collier et al., 2017; Paton et al., 2017). We categorize transitional and magmatic crust as 'COTZ crust'. Sub-aerial spreading centres may feed extensive lava flows that later, through subsidence, become seaward-dipping reflectors (SDRs); SDR subsidence leads to rotation of underlying dykes

(Abdelmalak et al., 2015). A similar rotation of lavas and dykes is observed in oceanic crust (Karson, 2019).

3. Geological Setting

The North Carnarvon Basin forms the southernmost part of the NW Australian volcanic passive margin, bound by the Argo Abyssal Plain to the north, and the Gascoyne Abyssal Plain and CAP to the west (Fig. 1) (Longley et al., 2002; Stagg et al., 2004). Basin formation occurred during multiple phases of Permian-to-Late Jurassic rifting, culminating in Early Cretaceous break-up of the Gascoyne and Cuvier margin rift segments (Longley et al., 2002). We sub-divide the basin into the ~400 km wide Gascoyne and 180 km-wide Cuvier margin sectors, separated by the NW-trending Cape Range Fracture Zone (Fig. 1). A 200–250 km wide COTZ adjacent to the Gascoyne margin (i.e. the Gallah Province), comprises 2–5.5 km thick SDRs and high-velocity lower crust formed during magnetic anomalies M10N–M5n (i.e. ~136–131 Ma), with interpreted normal oceanic crust emplaced from chron M3r (~130 Ma) onwards (Fig. 1) (Direen et al., 2008). Seismic reflection data reveal SDR sequences along the Cuvier margin, beneath the continental slope, within a previously interpreted 50–70 km wide COTZ (Fig. 1) (Hopper et al., 1992; Symonds et al., 1998). The CAP is partly bound to the SW by the Wallaby Plateau (Fig. 1), a large bathymetric high likely comprising thinned continental crust overlain by volcanic and sedimentary rocks (e.g., Colwell et al., 1994; Daniell et al., 2009; Olierook et al., 2015; Stilwell et al., 2012).

The CAP lies ~5 km below sea level and comprises a 1–3.3 km thick sedimentary sequence overlying 6–10.5 km thick crystalline crust, inferred to be oceanic in origin due to the recognition of chrons M10N–M5 (Fig. 1B) (Falvey & Veevers, 1974; Larson et al., 1979). The ~175 km long Sonne Ridge and ~100 km long Sonja Ridge, which bisect the CAP and extend into the Wallaby Plateau (Fig. 1), are interpreted as probable extinct oceanic spreading ridges (e.g., MacLeod et al., 2017; Mihut & Müller, 1998; Robb et al., 2005). The Sonne Ridge has also been interpreted as a pseudofault (i.e. an apparent offset in magnetic stripes formed by ridge jumps; Hey, 1977), based on changes in gravity intensity across it and termination of the Cape Range Fracture Zone directly north of the ridge (Gibbons et al., 2012). In their model, Gibbons et al. (2012) define a new spreading centre ~100 km to the SE and parallel to the Sonne Ridge (Fig. 1). However, Gibbons et al. (2012) use the COB of Heine and Müller (2005) to define the termination of the Cape Range Fracture Zone, but this model does not account for the Gallah Province being part of the Gascoyne COTZ and, hence, the required north-westward extension of the fracture zone (Direen et al., 2008; Robb et al., 2005). We therefore favour and use the interpreted magnetic chron configuration of Robb et al. (2005), centred on the Sonne Ridge, which predicts half-spreading rates adjacent to both Gascoyne and Cuvier segments were similar during chrons M10-M5 (~4.5 cm/yr), decreasing to ~3 cm/yr by chron M3.

4. Dataset and methodology

4.1. Seismic reflection data

We constrain the lithospheric structure of Cuvier margin COTZ using pre-stack time-migrated seismic reflection and OBS-derived velocity data from the EW0113 survey. The seismic reflection survey was acquired in 2001 by the R/V *Maurice Ewing* using an 8445 in^3 airgun array and a 6 km streamer length (Tischer, 2006). Due to extreme amplitude contrasts between the shallow and deep sections of the original migrated data, a time-dependent gain filter and root filter were applied to improve amplitude balance and enhance deep reflectivity (see supplementary information for details). Depth conversion of the seismic data was performed using a velocity model based on velocities interpreted from OBS data by Tischer (2006). The OBS array was co-located with seismic line EW0113-6, which is located ~70 km along-strike from line EW0113-5 (Fig. 1). Each line is >300 km long and extends up to ~200 km out into the CAP from the currently defined COTZ, nearly reaching the Sonne Ridge (Fig. 1).

4.2. Magnetic data

To examine the regional magnetic anomalies, we utilise the EMAG2v2 and EMAG2v3 Earth Magnetic Anomaly Grids (Maus et al., 2009; Meyer et al., 2017). EMAG2v2 is a 2 arc min resolution grid derived from marine, airborne, and satellite magnetic data, but uses a priori information to interpolate magnetic anomalies in areas where data gaps are present (Fig. 3) (Maus et al., 2009; Meyer et al., 2017). In contrast, EMAG2v3 uses more data points to derive magnetic anomaly maps but assumes no a priori information (Fig. 3) (Meyer et al., 2017). In ocean basins with a relatively poor coverage of magnetic data available, such as the CAP, clear linear magnetic anomalies in EMAG2v2 thus typically appear poorly developed or are absent in EMAG2v3 (Fig. 3) (Meyer et al., 2017). This difference in the presence and appearance of linear magnetic anomalies between the EMAG2v2 and EMAG2v3 grids is because knowledge of seafloor spreading processes was incorporated into, and therefore influenced, interpolation during construction of the EMAG2v2 grid (Maus et al., 2009; Meyer et al., 2017). Importantly, the apparent reduction in magnetic stripes observed in EMAG2v3, compared to EMAG2v2 (Fig. 3), does not necessarily mean these features are absent, but rather that the available data is insufficient to unambiguously confirm their presence (Meyer et al., 2017). Comparing the EMAG2v2 and EMAG2v3 grids, coupled with shiptrack magnetic data (Robb et al., 2005), allows us to interrogate the magnetic architecture of the CAP (cf. Meyer et al., 2017). In particular, we use EMAG2v2 to interpret possible magnetic chrons, picked on positive peaks (Fig. 1), and attempt to correlate them to the EMAG2v3 grid and shiptrack magnetic data. From these comparisons, we tied interpreted magnetic stripes to seismic line EW0113-5 using the synthetic profiles of Robb et al. (2005). We use the magnetic polarity reversal sequence and absolute ages of Gradstein and Ogg (2012).

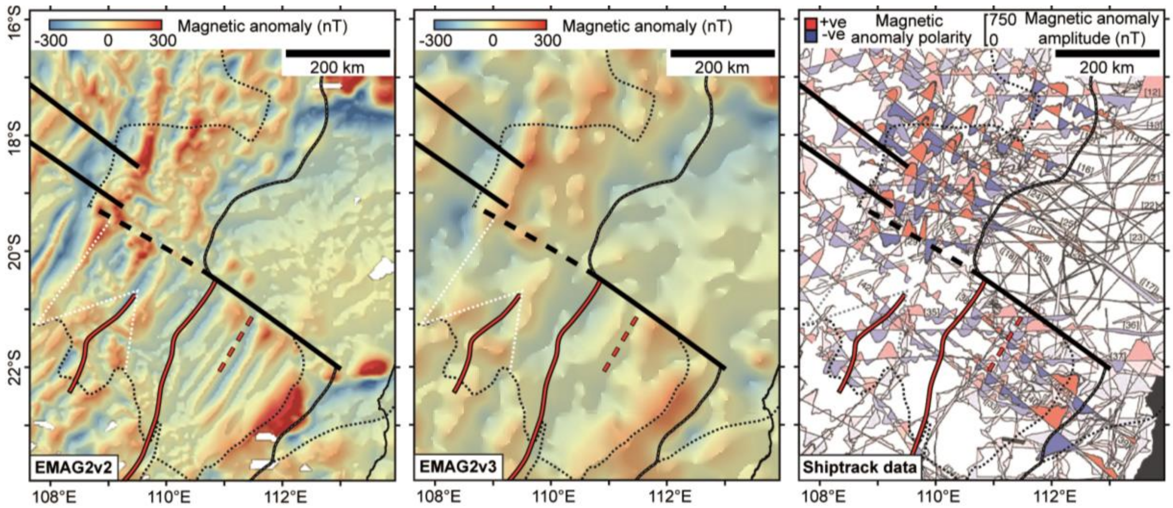

Figure 3: Total magnetic intensity grids EMAG2v2 and EMAG2v3 (Maus et al., 2009; Meyer et al., 2017), compared with shiptrack magnetic data (Robb et al., 2005). Key tectonic elements also shown (see Fig. 1 for legend).

4.3. Geochemical data

To evaluate whether the Sonne Ridge is an extinct seafloor spreading centre (e.g., Mihut & Müller, 1998; Robb et al., 2005), which implies it consists of oceanic crust with a MORB or MORB-like affinity along its length, we examine chemical data for a Sonne Ridge basalt lava sample (i.e. sample 057DR051A; Dadd et al., 2015). The analysed sample was dredged from the south-western section of the Sonne Ridge, where it bounds the south-eastern extent of the Wallaby Plateau (Dadd et al., 2015; Daniell et al., 2009; Olierook et al., 2015). We compare the Sonne Ridge sample to two collected from within the Wallaby Plateau (i.e. samples 055BS004A and 055BS004B), towards its south-western margin (Dadd et al., 2015). The two

Wallaby Plateau basalts yield plagioclase $^{40}Ar/^{39}Ar$ plateau ages of 125.12±0.9 Ma and 123.80±1.0 Ma, whilst two analyses of the Sonne Ridge sample yielded less precise ages of 120±14 Ma and 123±11 Ma (Olierook et al., 2015).

5. Observations and interpretation of the Cuvier Margin structure

5.1. Reflection seismology

5.1.1. Observations

The geological structure imaged in line EW0113-6 is very similar to that of EW0113-5 (Fig. 4), supporting the use of velocities from EW0113-6 in depth conversion. A prominent, continuous, high-amplitude seismic reflection is recognised across the CAP and interpreted as the interface between crystalline crust and overlying sedimentary rocks (Fig. 4). The Moho was picked at the base of a flat-lying zone of moderate to high amplitude, discontinuous seismic reflections, and is ~17 km deep in the SE, shallowing oceanward on EW0113-5 to ≤14 km (Fig. 4A). On EW0113-6, the Moho remains relatively flat at depths of ~16–17 km (Fig. 4B). Overall, the crystalline crust is ~8–10 km thick (Fig. 4).

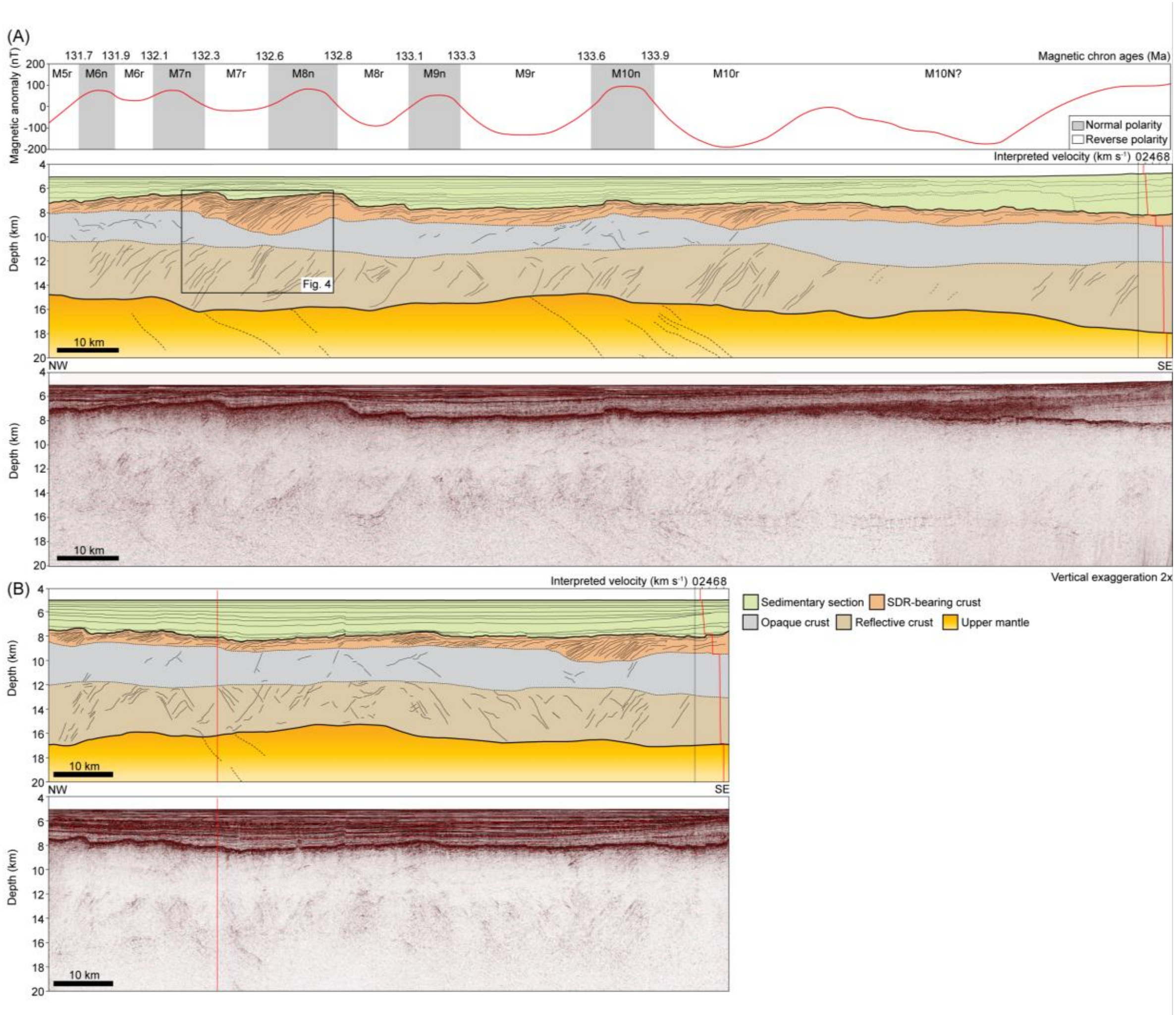

Figure 4: Interpreted and uninterpreted, depth-converted seismic lines (A) EW0113-5 and (B) EW0113-6 showing crustal structure of the Cuvier margin. A co-located magnetic anomaly profile showing interpreted magnetic chrons is presented for (A) (after Robb et al., 2005). Seismic data are displayed with reverse polarity, where a downward increase in acoustic impedance is represented by a negative (red) reflection event and a downward decrease in acoustic impedance is a positive (black) reflection event. For details of the velocity model used, see supplemental information.

The 1–3 km-thick, uppermost crystalline crustal layer comprises a layered, moderate- to high-amplitude seismic facies, which locally contains ≤20 km wide, ≤3 km thick wedges of coherent, high-amplitude, seaward-diverging reflections (Figs 4 and 5). Where well-developed wedges are absent, this crustal layer contains discontinuous, horizontal to gently seaward-dipping reflections (Fig. 4). Seismic velocities for this layer are 4–5 km/s (Fig. 4; Tischer, 2006).

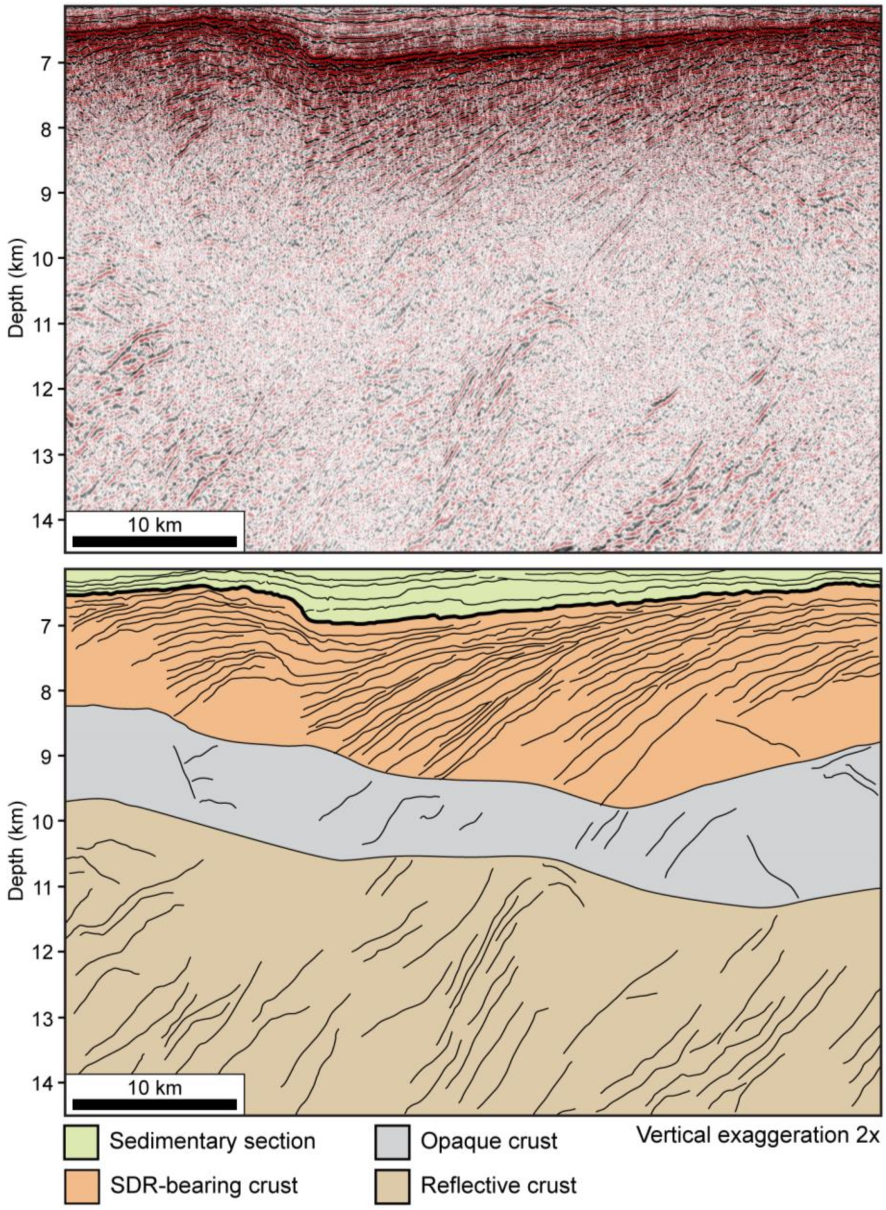

Figure 5: Zoomed in view of EW0113-5 highlighting the seismic character of interpreted SDR packages (see Fig. 4A for location).

The uppermost crystalline layer is underlain by a low-amplitude, weakly-reflective, 1–2.8 km thick, seismic facies layer (i.e. ‘opaque crust’, Figs 4 and 5) and a deeper, low-amplitude, 3.5–6 km-thick, seismic facies layer that locally contains prominent, high-amplitude, dipping reflections (i.e. ‘reflective crust’, Figs 4 and 5). The few reflections that are observed within the opaque crust typically have moderate- to high amplitudes, although low-amplitude also occur, and have variable dips (Figs 4 and 5). Dipping reflections within the reflective crust terminate at the Moho and primarily dip oceanward at 20–30°, although several reflections, particularly on EW0113-6, dip landwards (Figs 4 and 5). Seismic velocities of the opaque and reflective layers are 6.8–7.2 km/s (Fig. 4; Tischer, 2006).

5.1.2. Interpretation of crustal structure

Based on their geometry and seismic velocity, we interpret the divergent reflection wedges in the uppermost crystalline crust layer as SDRs, likely comprising interbedded subaerial igneous rocks deposited in lava flows and terrestrial sedimentary strata (Figs 4 and 5) (e.g., McDermott et al., 2018; Menzies et al., 2002; Planke & Eldholm, 1994). We infer flatter-lying reflections are gently-dipping lavas. The observed structure and velocities of the opaque and reflective crust, defined by transparent seismic facies and discordant high-amplitude reflections respectively (Figs 3 and 4), is consistent with the seismic character of sheeted dyke and lower crustal gabbro intrusions in oceanic crust (e.g., Eittreim et al., 1994; Paton et al., 2017). However, the likelihood that SDR emplacement occurred sub-aerially suggests the CAP could instead comprise COTZ crust. In both the oceanic and COTZ crust scenarios, observed moderate- to high-amplitude reflections within these crustal packages may be interpreted as igneous intrusion contacts, primary layering within gabbros, or lower crustal strain markers (e.g., shear zones) (e.g., Abdelmalak et al., 2015; Paton et al., 2017; Phipps-Morgan & Chen, 1993).

5.2. Magnetic anomalies

Assessment of the EMAG2v2 and ship-track magnetic data reveal 10 km wide, continuous magnetic stripes with lengths of ≤220 km across much of the CAP (Figs 1, 3, and 4). Although magnetic anomalies in the EMAG2v3 grid are suppressed relative to EMAG2v2, linear anomalies can still be distinguished across the CAP and in the Gallah Province (Fig. 3). Due to the lower resolution of magnetic anomalies in the EMAG2v3 grid, magnetic chrons cannot be confidently attributed and we thus rely on EMAG2v2 and shiptrack data to define probable chrons (Fig. 3). Proximal to the Australian continent, long-wavelength magnetic anomalies can only be broadly assigned to chron M10N (Figs 1, 3, and 4) (Robb et al., 2005); within the distal 100 km of seismic line EW0113-5, chrons M10n–M5r (~135.3–131.4 Ma) are clearly defined and have amplitudes of ≤±100 nT (Figs 1, 3, and 4). Chrons M8r–M7n coincide with a prominent ≤3 km thick, ~25 km long, package of seaward-dipping reflectors in the uppermost crystalline crust layer (Fig. 4A).

Robb et al. (2005) interpret the magnetic anomalies M10N–M6 southeast of the Sonne Ridge as conjugate to a more poorly developed set of anomalies northwest of the ridge (Fig. 1). These poorly defined chrons (i.e. M10N–M6) northwest of the Sonne Ridge terminate abruptly against the Cape Range Fracture Zone, abutting younger magnetic chrons on the Gascoyne Abyssal Plain (Fig. 1). Chron M5n is the first to occur continuously along-strike across both the Cuvier and Gascoyne margin segments (Fig. 1).

5.3. Geochemistry of basalts dredged from the Sonne Ridge

The only basalt collected from the Sonne Ridge displays a relatively flat, Rare Earth Element (REE) pattern (Fig. 6A). Based on this observation, Dadd et al. (2015) interpret the basalt to have a slightly enriched MORB-like source, supporting the inference that the CAP comprises oceanic crust (e.g., Hopper et al., 1992; Larson et al., 1979; Mihut & Müller, 1998). Although a flat REE pattern can be indicative of the shallow melting regime of MORB generation, it does not preclude other settings. By replotting the trace element and radiogenic isotopic compositions of the Sonne Ridge sample, we show the sample has characteristics that could be suggestive of a more continental source (Fig. 5). It must be kept in mind that the Sonne Ridge sample is heavily altered (Dadd et al., 2015), which likely explains the elemental enrichment in Pb, Ba, and Rb, as well as elevated $^{87}Sr/^{86}Sr$. However, the negative Nb anomaly, in part defined by neighbouring element Th that is unlikely to be affected by contamination, and unradiogenic ε_{Nd}, cannot be ascribed to alteration (Fig. 6). Instead, the negative Nb anomaly and unradiogenic ε_{Nd} can be interpreted as a chemically evolved, continental or sedimentary contribution to the magmas. Finally, the chemical similarity of the Sonne Ridge basalt to two ~124 Ma samples from the Wallaby Plateau (Fig. 6) is notable because this area is interpreted to comprise intruded continental crust, supported by the recovery of pre-breakup sedimentary rocks from the plateau during dredging (Daniell et al., 2009; Olierook et al., 2015; Stilwell et al., 2012). Therefore, the chemical characteristics of the Sonne Ridge lava suggest the basalt could originate from either melting of sub-continental lithospheric mantle (SCLM) or contamination of a MORB-like magma by assimilation as it ascended through continental crust (cf. Dadd et al., 2015). Importantly, the Sonne Ridge likely represents the rift/spreading axis of the CAP (Robb et al., 2005), such that the basalt sample represents one of the youngest magmas within the system. We thus consider it plausible that older magmas emanating from the ridge system, including the SDRs imaged in the seismic reflection data, could have a more pronounced continental signature.

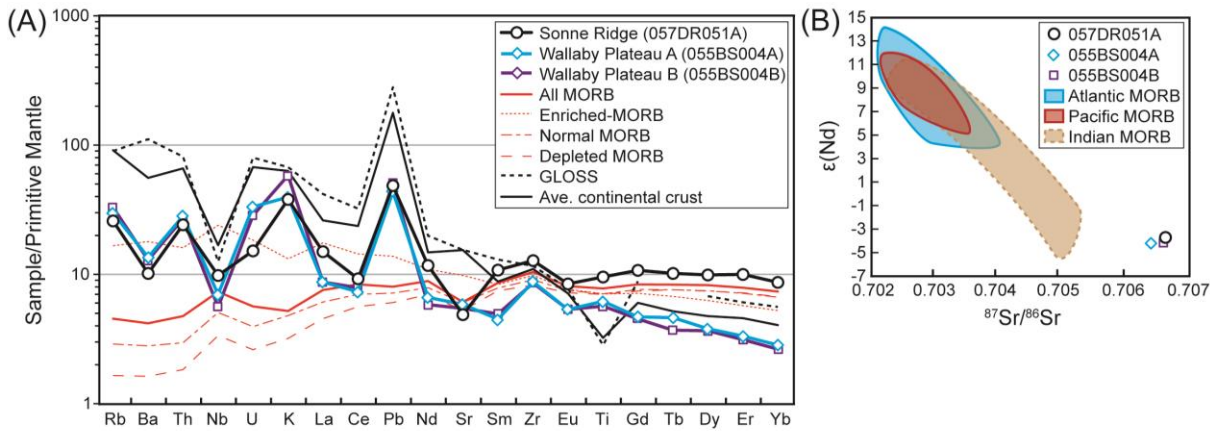

Figure 6: (A) Primitive mantle normalized incompatible element diagram comparing the dredged Sonne Ridge and Wallaby Plateau basalt lava samples with average (ave.) compositions of MORB variants (Hofmann, 2014), Globally Subducting Sediment (GLOSS) (Plank & Langmuir, 1998), and continental crust (Rudnick & Fountain, 1995). (B) Plot of ε(Nd) versus $^{87}Sr/^{86}Sr$, illustrating that the Sonne Ridge and Wallaby Plateau samples are distinct from MORB (based on data collated in Hofmann, 2014).

6. Discussion

6.1. Nature of the Cuvier margin crust

Subsidence profiles for normal oceanic crust predict mid-ocean ridge axes at water depths of ~3 km and subsidence rates of ~90 m/Myr for the first 10 Ma after break-up (e.g., Menard, 1969; Parsons & Sclater, 1977; Stein & Stein, 1992). We identify a previously unrecognised upper-crustal crystalline basement layer within the CAP that contains well-developed, ≤3 km-thick, SDRs and extends >200 km seaward from the previously-interpreted COTZ (Figs 1, 4, and 5). Packages of SDRs observed and drilled on other continental margins indicate the comprising lavas extruded sub-aerially and are typically overlain by sub-aerial to shallow-marine strata deposited during subsequent margin subsidence (e.g., Larsen et al., 1994). Although the observed SDRs across the CAP are not drilled, linking their origin to sub-aerial volcanism conforms with observations from DSDP site 263 (Fig. 1), which intersected Early Cretaceous (≤130.8 Ma), shallow-marine sedimentary rocks immediately deposited immediately on top of the crystalline basement (Veevers & Johnstone, 1974; Willcox & Exon, 1976). The presence of SDRs and overlying shallow-marine sedimentary rocks suggests sub-aerial to shallow-marine conditions were prevalent across the Cuvier margin during formation of the CAP, which is inconsistent with subsidence profiles for normal oceanic crust (e.g., Menard, 1969; Parsons & Sclater, 1977; Stein & Stein, 1992). One possible explanation for the observed sub-aerial to shallow-marine conditions is that the CAP actually comprises COTZ crust rather than oceanic crust, having formed through sub-aerial rifting and spreading (Fig. 7D) (cf. Collier et al., 2017; McDermott et al., 2018; Paton et al., 2017). The chemistry of a basalt sample from the Sonne Ridge, particularly its Nd isotopic composition and refractory trace element abundances (Fig. 6), allows for a contribution of sub-continental lithospheric mantle (SCLM) or interaction with continental crust, supporting the hypothesis that full continental rupture may not have occurred even during the final phases of CAP spreading.

We interpret the previously recognised SDRs beneath the continental slope on the Cuvier margin (Hopper et al., 1992; Symonds et al., 1998) as marking the transition from mechanical- to magma-dominated rifting and the landward limit of the COTZ, which likely comprises heavily intruded continental crust (i.e. ‘transitional’ crust) (Fig. 7A). A progressive localisation in dyking as rifting continued led to the eventual generation of the sub-aerial Sonne Ridge, which was perhaps akin to 20 km wide Quaternary magmatic segments in the Ethiopian Rift (e.g., Ebinger & Casey, 2001; Hayward & Ebinger, 1996; Kendall et al., 2005), where the crust likely comprises >50% new mafic material (Daniels et al., 2014). Our proposed crustal structure for the CAP therefore involves a gradual north-westwards change from continental crust into COTZ crust, which we suggest is likely characterised by 'transitional' crust in the SE and becomes increasingly 'magmatic' towards the Sonne Ridge (Figs 2 and 7). This gradual change in style of the COTZ is consistent with progression from Type I to Type II SDR sequences, which are located above transitional and magmatic crust respectively, observed offshore S America (McDermott et al., 2018). It is plausible remnants of thinned continental blocks may have been incorporated into the COTZ crust during rift jumps (Gibbons et al., 2012; Robb et al., 2005). Importantly, our model implies the Sonne Ridge is not an extinct submarine, oceanic spreading centre (e.g., Falvey & Veevers, 1974; Larson et al., 1979; MacLeod et al., 2017; Mihut & Müller, 1998; Robb et al., 2005)

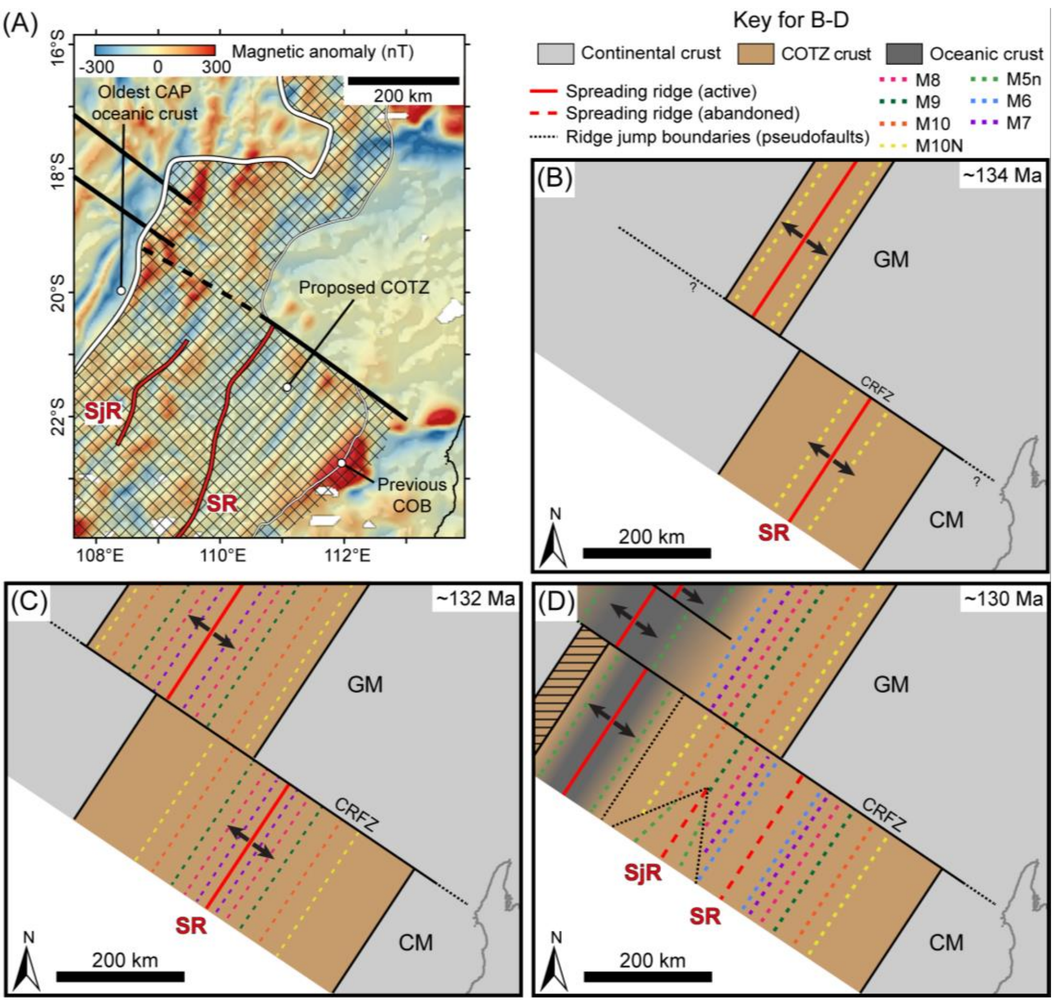

Figure 7: (A) Map showing the potential limits of the COTZ based on interpreting the Cap and Gallah Province as transitional and/or magmatic crust. (B-D) Schematic maps showing the development of COTZ crust and the onset of oceanic crust accretion adjacent to the Gascoyne and Cuvier margins, during formation of chrons (B) M10, (C) M6 and (D) M3r. See Figure 1 for chron ages. Location of present day coastline shown for reference.

Linear magnetic stripes recorded across the CAP reveal an apparent conjugate set of chrons M10N–M6 centred on the Sonne Ridge (Robb et al., 2005), suggesting our inferred COTZ crust may extend out to chron M5n, broadly coincident with the north-western limit of the Gallah Province on the Gascoyne margin (Figs 1 and 7B). Magnetic reversals in the Gallah Province are similar, albeit less developed, to those in the CAP (Direen et al., 2008; Robb et al., 2005). Direen et al. (2008) argue these magnetic anomalies resulted from the stacking of wedges of positively magnetised basalts (including SDRs) and variably magnetised volcaniclastic conglomerates atop transitional magmatic and modified continental crust. We thus suggest that magnetic anomalies along the Gascoyne margin sector are also likely related to geomagnetic polarity reversals recorded by COTZ crust underlying the SDRs. Chemical signatures indicating continental lithosphere contamination, similar to those identified in the CAP, are recorded in basalts from the Gascoyne margin (Direen et al., 2008).

6.1.1. Tectonic-magmatic evolution of the Cuvier and Gascoyne margins

During chrons M10N-M5r (i.e. ~136–131 Ma), we suggest stretching and intrusion of continental crust adjacent to both the Gascoyne and Cuvier margins produced COTZ crust, likely comprising transitional crust, which evolved into magmatic crust as intrusion became localised and the proportion of remnant continental crust decreased (Figs 7B-D). Robb et al. (2005) proposed that, during chron M5r-M5n (~131 Ma), a ridge jump in the Cuvier sector led to abandonment of the Sonne Ridge, with a short-lived period of spreading about the Sonja Ridge preceding development of a new ridge ~250 km northwest of the Sonne Ridge (Fig. 7D). We consider that this jump linked the Cuvier and Gascoyne ridges, promoting the onset of true seafloor spreading from chron M3r (~130 Ma) onwards in both sectors (Fig. 7D). This initiation of oceanic crust formation transferred the conjugate region of COTZ crust recording M10N-M6 anomalies to the Australian plate (Fig. 7D). With the recognition of a >500 km wide zone of COTZ crust, our interpretation implies that the outer limit of NW Australia's COTZ in the Cuvier margin sector may be positioned substantially further oceanward (>500 km) than previously interpreted (Fig. 7A). Extension of the COTZ across the CAP has implications for the timing and kinematics of plate reconstructions of the NW Australian margin, with the onset of true seafloor spreading potentially ~3 Myr later than suggested by previous studies (e.g., Robb et al., 2005).

6.2. Development of magnetic stripes during breakup

Stacked SDR wedges on the CAP overlie COTZ crust and span several chrons (e.g. M8n-M7r, Fig. 3), indicating the magnetic stripes likely record magnetic reversal signatures originating from sub-SDR rocks. Recent forward magnetic modelling of conjugate, ship-track magnetic profiles by Collier et al. (2017) suggest magnetic signals over SDRs arise from a combination of stacked and rotated lavas, producing a long-wavelength positive anomaly that can sometimes mask reversals, and linear magnetic anomalies caused by dyke intrusion in the underlying crust. This is consistent with studies of onshore incipient spreading centres (e.g. Ethiopia), where magnetic anomalies likely originate from axial intrusion by dykes in heavily intruded upper continental crust (Bridges et al., 2012). We suggest that the well-developed linear anomalies over the CAP may therefore originate from intrusions in the COTZ crust underlying the SDRs.

The lack of broad positive magnetic anomalies over the transitional to magmatic crust of the CAP may be due to the relatively low SDR thickness (≤3 km) compared to the South Atlantic margins (<8 km thick; Collier et al., 2017). The less-clearly developed and higher amplitude magnetic reversals on the Gascoyne Abyssal Plain may relate to interference from the greater SDR thicknesses (≤5.5 km) relative to the Cuvier margin (Direen et al., 2008). We suggest that SDR thickness and, thereby, preservation of magnetic anomalies within transitional or magmatic crust can partly be attributed to extension rate. For example, the extension rate during SDR eruption offshore NW Australia (~4.5 cm/yr half rate; Robb et al., 2005) is substantially faster than the inferred extension rates for the South Atlantic during magmatic crust formation (~1.1 cm/yr half-rate; Paton et al., 2017). Slower extension rates (e.g. South Atlantic) likely promote stacking of lava flows (Eagles et al., 2015), leading to interference and development of the long-wavelength positive magnetic anomalies (e.g., Moulin et al., 2010). Extension rate may also influence magnetic anomaly development by affecting the width of magnetic stripes: reversal anomalies will be narrowest at slow spreading ridges (Vine, 1966). The narrower anomalies, combined with the greater potential for vertical stacking of lavas, will tend to suppress magnetic anomaly preservation.

6. Conclusions

We present evidence for a previously unrecognised, >500 km-wide region of continent-ocean transition zone (COTZ) crust adjacent to the Northwest Australian continental margin. We suggest the COTZ crust likely comprises a spectrum of ‘transitional’, i.e. heavily intruded continental crust, and ‘magmatic’ crust formed by addition of igneous material at a sub-aerial ridge. This COTZ crust records well-developed linear magnetic reversal anomalies. Seaward-dipping reflectors (SDRs) overlie the 5–8.5 km thick COTZ crust, which hosts intrusions that are the primary source of the observed magnetic signal. The recognition of this region of

COTZ crust implies that the outer limit of Australia's continent-ocean transition zone may be >500 km further oceanward than previously interpreted. That COTZ crust on volcanic margins can record the development of clear seafloor spreading-type magnetic stripes, implies magnetic stripes alone are not a reliable proxy for the onset of seafloor spreading and the extent of oceanic crust.

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Figure Captions

Figure 1: (A) Location map of the study area highlighting key tectonic elements, including areas of recognised seaward-dipping reflectors (SDRs) (Holford et al., 2013; Symonds et al., 1998) and previously interpreted approximate (approx.) limits of the continent-ocean boundary (COB; Eagles et al., 2015) and continent-ocean transition zones (COTZs; Direen et al., 2008; Symonds et al., 1998). Inset: study area location offshore NW Australia. AAP – Argo Abyssal Plain, CAP – Cuvier Abyssal Plain, CRFZ – Cape Range Fracture Zone, GAP – Gascoyne Abyssal Plain, GP – Gallah Province, NCB – North Carnarvon Basin, SCB – South Carnarvon Basin, Cu – Cuvier margin COTZ, SR – Sonne Ridge, SjR – Sonja Ridge, WP – Wallaby Plateau, WS – Wallaby Saddle, WZFZ – Wallaby-Zenith Fracture Zone.

Dredge sites 55 (samples 055BS004A and 055BS004B) and 57 (sample 057DR051A) are also shown (Dadd et al., 2015). (B) Total magnetic intensity grid (EMAG2v2), interpreted magnetic chrons (based on Robb et al., 2005). See Supplementary Figure S1 for an uninterpreted version.

Figure 2: Schematic model (not to scale) of a continent-ocean transition zone along a volcanic passive margin; for simplicity the lithospheric mantle is not shown. As magma intrudes continental crust, likely as dykes at mid- to upper-crustal levels and larger gabbroic bodies in the lower crust, it becomes 'transitional crust' (e.g., Eldholm et al., 1989). Continued intrusion and dyking leads to localisation of magmatism within narrow zones where sub-aerial spreading dominates extension and there is little, if any, continental crust remaining (i.e. magmatic crust) (i.e. 'magmatic crust'; e.g., Collier et al., 2017; Paton et al., 2017). We categorize transitional and magmatic crust as 'COTZ crust'. Sub-aerial spreading centres may feed extensive lava flows that later, through subsidence, become seaward-dipping reflectors (SDRs); SDR subsidence leads to rotation of underlying dykes (Abdelmalak et al., 2015). A similar rotation of lavas and dykes is observed in oceanic crust (Karson, 2019).

Figure 3: Total magnetic intensity grids EMAG2v2 and EMAG2v3 (Maus et al., 2009; Meyer et al., 2017), compared with shiptrack magnetic data (Robb et al., 2005). Key tectonic elements also shown (see Fig. 1 for legend).

Figure 4: Interpreted and uninterpreted, depth-converted seismic lines (A) EW0113-5 and (B) EW0113-6 showing crustal structure of the Cuvier margin. A co-located magnetic anomaly profile showing interpreted magnetic chrons is presented for (A) (after Robb et al., 2005).

Seismic data are displayed with reverse polarity, where a downward increase in acoustic impedance is represented by a negative (red) reflection event and a downward decrease in acoustic impedance is a positive (black) reflection event. For details of the velocity model used, see supplemental information.

Figure 5: Zoomed in view of EW0113-5 highlighting the seismic character of interpreted SDR packages (see Fig. 4A for location).

Figure 6: (A) Primitive mantle normalized incompatible element diagram comparing the dredged Sonne Ridge and Wallaby Plateau basalt lava samples with average (ave.) compositions of MORB variants (Hofmann, 2014), Globally Subducting Sediment (GLOSS) (Plank & Langmuir, 1998), and continental crust (Rudnick & Fountain, 1995). (B) Plot of ε(Nd) versus $^{87}Sr/^{86}Sr$, illustrating that the Sonne Ridge and Wallaby Plateau samples are distinct from MORB (based on data collated in Hofmann, 2014).

Figure 7: (A) Map showing the potential limits of the COTZ based on interpreting the Cap and Gallah Province as transitional and/or magmatic crust. (B-D) Schematic maps showing the development of COTZ crust and the onset of oceanic crust accretion adjacent to the Gascoyne and Cuvier margins, during formation of chrons (B) M10, (C) M6 and (D) M3r. See Figure 1 for chron ages. Location of present day coastline shown for reference.

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