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1 Magmatism at oceanic core complexes on the ultraslow

2 Southwest Indian Ridge: insights from near-seafloor magnetics

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11 ABSTRACT

12 Oceanic core complexes (OCCs) and detachment faults (DFs) play a key role in crustal accretion at slow and ultraslow spreading centers. We investigate the effect of different magma 13 supply at three OCCs of the Southwest Indian Ridge (SWIR) using high-resolution deep-sea 14 15 bathymetric and magnetic data. The average equivalent thickness of extrusive basalt deduced 16 from the magnetic anomalies, a proxy for the magma supply, decreases from Yuhuang (49.25°E) 17 to Longqi (49.65°E) to Junhui (51.75°E) OCCs. Conversely, serpentinite outcrops become more 18 abundant, the domal OCC morphology flattens as the footwall rotation (measured by the 19 magnetization vector inclination) increases, and hydrothermal evidences become sparse. 20 Combined with results from the amagmatic Easternmost SWIR, our study shows that the magma 21 supply controls the character and evolution of the OCCs and DFs on the SWIR.

22 INTRODUCTION

23 As an essential constituent of slow and ultraslow spreading centers, Oceanic Core

24 Complexes (OCCs) result in asymmetric flanks, corrugated seafloor, and mantle rocks

exhumation. They have not only been found at magma-starved ridge segment ends (Cann et al.,

- 26 1997; Tucholke et al., 1998; Blackman et al., 1998) but are widespread and account for 50% of
- 27 the recent seafloor formed at the Mid-Atlantic Ridge (MAR) (Smith et al., 2006; Escartín et al.,
- 28 2008). Numerical models suggest that magmatism plays a major role in the development of the
- 29 OCCs (Buck et al., 2005; Tucholke et al., 2008; Olive et al., 2010). In contrast, OCCs are still
- poorly known at ultraslow spreading ridges. An end-member is the Southwest Indian Ridge
 (SWIR) east of Melville Fracture Zone (FZ), a nearly amagmatic spreading center which exposes
- smooth seafloor interpreted as the remnants of DF footwalls (Cannat et al., 2006). Seafloor
- sinout seanout merpreted as the remains of DF footwars (Cannat et al., 2000). Seanour
 spreading is purely tectonic there. Conversely, the SWIR exhibits a more robust magma supply
- further west (Sauter et al., 2001). In this area, between the Indomed and Gallieni FZs (Fig. 1A),
- 35 the shallower water depth and lower Mantle Bouguer Anomaly indicate a thicker crust and hotter

36 mantle, and the higher amplitude of the Central Magnetic Anomaly a thicker extrusive basalt

37 layer. We use high-resolution bathymetry and magnetic data to investigate three OCCs, the

38 Yuhuang, Longqi, and Junhui OCCs, in this area, and show that the morphology, magnetic

39 signature, and evolution of these OCCs are tightly related to the magma supply.

40 DATA AND METHODS

41 Near-bottom bathymetry and magnetic data were acquired by "*Qianlong II*" Autonomous Underwater Vehicle (AUV) during DY-43, 49 and 52 cruises from 2014 to 2020. The AUV 42 43 collected data at an altitude of ~ 100 m above seafloor, with a sampling interval of 1 m along 44 lines 400 m apart. Noise introduced by attitude variation is reduced by the method of (Tao et al., 45 2018), and the International Geomagnetic Reference Field (IGRF) model (Thébault et al., 2015) 46 is removed. The magnetic anomaly is gridded at 100 m×100 m interval and inverted to 47 equivalent magnetization by using regularized minimum residual method (See details in Data 48 Repository) assuming a magnetized layer 100 m-thick below the seafloor. Because the anomaly 49 is measured on an uneven observation surface and for the sake of resolution, we calculate the 50 Reduced-To-the-Pole (RTP) magnetic anomaly by forward modelling from the equivalent 51 magnetization (Szitkar et al., 2014).

52 **RESULTS**

53 Geological description of the OCCs

54 We interpret the components of the three OCCs (breakaway, detachment surface, 55 termination) on the shipboard and AUV bathymetry following the criteria of Smith et al. (2006). 56 Yuhuang OCC (Fig. 1B; Suppl. Fig. DR1) strikes in ENE direction, slightly oblique to 57 the E-W axial volcanic zone (AVZ). It extends ~6 km along the spreading direction and drops 58 \sim 1.5 km in elevation from breakaway to termination. The termination separates volcanic terrains 59 to the North and the detachment surface where serpentinite samples were dredged. Further south 60 a chaotic volcanic area, where dredges recovered basalt, hosts a hydrothermal field with large 61 sulfide deposits (Tao et al., 2014; Liao et al., 2018). Longqi OCC (Fig. 1C; Suppl. Fig. DR1) extends ~15 and ~4 km along and across axis, 62 63 respectively. South of the termination, the detachment surface displays corrugations in the 64 spreading direction. Mass wasting is clearly seen on the western end of the OCC. Basalt was 65 dredged all over the area, but serpentinite was only dredged on the detachment surface. High

temperature hydrothermal site Longqi-1 was found on the hanging wall (Tao et al., 2012; 2020),
whereas inactive site Longqi-3 was found in the chaotic area separating the detachment surface

- and the breakaway. Further south, an older volcanic zone and a large DF are identified on the
- 69 regional bathymetry (Fig. DR1).
- Junhui OCC (Fig. 1D; Suppl. Fig. DR1), the easternmost one, extends ~9 and ~6 km
 along and across axis, respectively. The detachment footwall is quite flat. Mass wasting is

- observed in the middle of the area, and smooth seafloor is tentatively identified to the West (Fig.
- 1D and F). Basalt has been dredged east of the area, and serpentinite on the detachment surface
- 74 only. No hydrothermal field has been reported yet.

75 Magnetization Inclination and Footwall Rotation

76 The magnetization acquired by young oceanic basalt at mid-ocean ridges within the last 77 million year is approximately parallel to the present-day geomagnetic field. However, the 78 magnetization vector direction can be affected by subsequent tectonics, such as DFs, as observed 79 on the MAR at 26°N (Szitkar and Dyment, 2015; Szitkar et al., 2019). It is not easy to estimate 80 the footwall rotation at the observed OCCs in the absence of any specific structural or 81 paleomagnetic measurements (e.g., Morris et al., 2009). To address this problem, we explore the 82 full range of possible remanent magnetization directions, calculate their corresponding RTP 83 anomalies and select the range of inclinations that make the anomalies centered on its causative 84 source, in general basaltic features such as the linear breakaways. OCC footwall rotation axes are 85 generally orthogonal to the spreading direction, i.e. broadly east-west for the broadly north-south spreading SWIR. Following the dipole field hypothesis, the magnetization vector trends North 86 and its rotation around a perpendicular axis allows the rotation angle to be estimated directly 87 88 from the inclination data. The inclinations that properly deskew the observed anomalies are -89 75°~-105° (average -90°), -75°~-120° (av. -97.5°), and -85°~-135° (av. -110°) for Yuhuang, 90 Longqi, and Junhui OCCs, respectively. Because the inclination of the dipole field is -57° in the area, we estimate the amount of rotation as 33°±15°, 40.5°±22.5°, and 53°±25° for the Yuhuang, 91

92 Longqi, and Junhui, respectively.

93 **RTP Magnetic Anomaly**

94 RTP anomaly over the Yuhuang OCC trends NE-SW, parallel to the structural orientation 95 (Fig. 1B and E). The strong linear positive anomaly separates the area in three parts, from North to South (1) low and slightly negative anomaly reflecting the weak induced magnetization of 96 97 recovered serpentinites; (2) strong positive linear anomaly associated with basalt, suggesting that 98 the contrast of magnetic signature with the northern part corresponds to a lithological boundary; 99 and (3) strong negative anomalies associated with basalt, suggesting that the transition 100 corresponds to a polarity boundary, most likely the Brunhes-Matuyama boundary (0.78 Ma; e.g., 101 Cande and Kent, 1995). The OCC therefore initiated in the late stage of the Matuyama period. 102 RTP anomaly over the Longqi OCC is generally oriented E-W (Fig. 1C and F). In the north-west 103 corner, around Longqi-1 hydrothermal vent, a strong positive anomaly indicates recent and abundant volcanism. A weak negative magnetic anomaly characterizes serpentinite and the 104 105 detachment surface. Further south, the breakaway, a bathymetric high with basalt outcrops, is 106 marked by three E-W lineated anomalies, from north to south a weak positive anomaly, a strong 107 negative anomaly, and a strong positive anomaly. We interpret this succession of anomalies as a geomagnetic polarity sequence recorded by the remanent magnetization of basalt. The transitions 108

109 north and south of the strong negative anomaly correspond to the polarity reversals between the

110 Brunhes and Matuyama periods (0.78 Ma), and between the younger part of the Matuyama

111 period and the Jaramillo normal episode (0.99 Ma), respectively. The southern side of the strong

- positive anomaly thus records the older end of the Jaramillo episode (1.07 Ma) and is therefore
- 113 underlain by basalt although no sample is available to confirm this hypothesis. The Jaramillo
- anomaly further continues to the west (Fig.1F), as interpreted by Wu et al. (2021). The elevated
- area extending further south toward the termination of the older DF is also probably made of
- 116 volcanics formed during the Matuyama period (Tao et al., 2020). Conversely, the weaker
- 117 transition observed north of the weak positive anomaly corresponds to the lithological transition
- between serpentinites and basalt. These observations indicate that the OCC initiated during the Jaramillo episode between 0.99~1.07 Ma.
- 120 RTP anomaly over the Junhui OCC (Fig. 1D and G) shows weak negative anomalies. In

121 the West, the inferred smooth seafloor does not display any significant signal. In the southeastern

122 corner of the area, a negative E-W anomaly near the breakaway is interpreted as a polarity

- boundary, suggesting that this OCC also initiated during the Late Matuyama period. Northward,
- 124 the lithological boundary between basalt and serpentinite is inferred from a weak E-W anomaly.

125 Modeling

126 Extrusive basalt is the dominant source of marine magnetic anomalies, with additional 127 contribution of the deeper crust and/or uppermost mantle at slower spreading rates (e.g., Dyment 128 and Arkani-Hamed, 1995; Dyment et al., 1997). Magnetics therefore offer an indirect means to 129 evaluate the amount of basalt and other magmatic products, and *in fine* to approach the magma 130 supply for comparison among our study areas. To this end, we use forward modeling to compute 131 the thickness of extrusive basalt that best explains the observed anomalies. However, in order to 132 alleviate the fundamental non-uniqueness of potential field methods, we have to adopt several 133 simplifying hypotheses to determine what we call the equivalent thickness of extrusive basalt 134 (ETB), i.e. the thickness of extrusive basalt if our simplifying hypotheses were correct. We 135 assume that (1) the magnetized crust is 1 km-thick beneath the seafloor – indeed deeper sources 136 have negligible magnetic effect at 100 m altitude; (2) the magnetized crust is made of two layers: 137 an extrusive basalt layer overlying a serpentinite layer; (3) the basalt layer bears only thermo-138 remanent magnetization of 15A/m (See Data Repository Section D); (4) the serpentinite layer 139 bears only induced magnetization of 2A/m (e.g., Oufi et al., 2002). We neglect geological 140 features that do not have a significant magnetic effect. For instance, rubbles on the detachment 141 surface are randomly oriented and the contribution of their magnetization to the anomaly cancels 142 out. The deformed fault zone may bear a consistent magnetization acquired during frictional 143 heating but its thickness is negligible.

Within the above hypotheses, we adjust the depth of the basalt-serpentinite interface, reflected by the thickness of the basalt layer, to account for the RTP anomaly. On detachment surfaces, the ETB is generally negligible, less than 100 m-thick. The polarity of the basalt 147 remanent magnetization is set to normal (respectively reversed) where the RTP anomaly is

148 positive (resp. negative) (See Data Repository Fig. DR3).

149 The modeling results indicate that the synthetic and observed anomalies are in good

agreement (Fig. 2). We estimate the average amount of basalt from the ETB (See Data

151 Repository Section E) to 77.4 \pm 10.7 m (Yuhuang), 68.5 \pm 14.2 m (Longqi), and 30.1 \pm 22.1 m

152 (Junhui). The amount of basalt decreases gradually from Yuhuang to Longqi to Junhui OCCs. As

153 the spreading rate is the same for the three OCCs, these values are representative of the magma

supply. The Yuhuang OCC is more magmatic than the Longqi OCC, and much more magmatic

155 than the Junhui OCC.

156 The ETB varies in average (on sections) from 16% (Yuhuang and Longqi) to 10%

157 (Junhui) of the 500 m-thick basalt layer of standard oceanic crust, suggesting that this proportion

158 of the crustal accretion is magmatic in the study area. This estimate only reflects the crustal

accretion on the SWIR southern flank, as no clear OCC appears on the shipboard multibeam

160 bathymetry of the northern flank for the considered period. In absence of high resolution

161 bathymetric and magnetic data, no inference can be drawn for this flank, and therefore the whole

162 area, for the last ~ 1.5 Ma.

163 **DISCUSSION**

164 Our observations and result suggest that the geology and magnetic signature of the OCCs 165 are causally linked to the magma supply. In decreasing order of the magma supply, from 166 Yuhuang to Longqi to Junhui OCCs, we observe (1) gradually flattening footwall surfaces as 167 reflected by the increasing footwall rotation angles, (2) more abundant serpentinite outcrops, and 168 (3) less evidences of hydrothermalism, whereas (4) the RTP anomalies related to magnetic 169 polarity become weaker, less linear, and cover less area. For even lower magma supply, previous 170 studies of the easternmost SWIR in a nearly amagmatic environment (Cannat et al., 2006, 2019; 171 Sauter et al., 2013) showed smooth footwall surfaces made of serpentinite on both flanks, with 172 consistently weak magnetic anomalies. Figure 3 presents four schematic sections in decreasing 173 order of magmatism. The more magmatic Yuhuang OCC (Fig. 3A) is probably underlain by 174 strong gabbroic cores, resulting from the capture of gabbroic bodies by the footwall near the 175 Lithosphere-Asthenosphere boundary, as reflected by its broad dome morphology and smaller 176 footwall rotation (MacLeod et al., 2009). At the less magmatic Longqi OCC (Fig. 3B), the 177 footwall may include less gabbro bodies resulting in a less-marked dome structure (Ciazela et al., 178 2015), although hot gabbro bodies have not been detected so far by seismic methods in this area 179 (Tao et al., 2020). Furthermore, the observation of two OCCs and an intermediate volcanic zone 180 supports the alternance of detachment and magmatic spreading. The even less magmatic Junhui 181 OCC (Fig. 3C) shows a flatter and longer serpentinite outcrop, suggesting that the footwall only 182 captures rare gabbroic bodies. For amagmatic spreading as the easternmost SWIR (Fig. 3D), the 183 footwall of the DF is not even defined as an OCC sensu stricto because it does not display the 184 typical dome morphology due to its exclusive serpentinite composition. There, DFs are purely

- 185 tectonic, with the previously active DF being terminated by the initiation, across its footwall, of a 186 new DF with opposite slope (Sauter et al., 2013).
- 187 Our results suggest that magmatism and tectonics are controlling in various degrees the
- 188 Yuhuang, Longqi, and Junhui OCCs, which all initiated in response to a decreasing magma
- 189 supply at the ridge axis and will probably end as magmatism gradually resumes. The magma
- 190 supply affects characters of the OCCs such as morphology, serpentinite outcrops and
- 191 underlaying gabbro bodies, hosted hydrothermal vents, and the magnetic signature. Magmatism
- 192 in this area results in the initiation and termination of detachments separated by magmatic
- 193 spreading periods, in alternance. Conversely, amagmatic spreading results in the purely tectonic
- 194 exhumation of serpentinite on alternating DFs, as observed in the Easternmost SWIR. The
- variability of OCCs and DFs along the ultraslow spreading centers may reflect the heterogeneity
- 196 of the along-axis magma supply and therefore offers a proxy to this parameter.

197

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- 205

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298 FIGURE CAPTIONS

299Figure 1. (A) Regional bathymetry from shipboard multibeam echo-sounders. Black boxes show

300 AUV areas in (from west to east) Yuhuang, Longqi, and Junhui OCCs. Inset gives the location of

- 301 study area. (B-D) High-resolution bathymetry of Yuhuang, Longqi, and Junhui areas. At
- 302 Yuhuang OCC, no AUV bathymetry was acquired, and we display shipboard bathymetry
- 303 instead. (E-G) RTP magnetic anomaly of Yuhuang, Longqi, and Junhui areas calculated through
- 304 equivalent magnetization.
- 305

- 306 Figure 2. Forward modelling of the RTP magnetic anomalies on the three investigated areas.
- 307 Each panel A-C and G-I shows, on top, a section across the structure resulting from forward
- 308 modelling where green is serpentinite, red (blue) basalt with normal (reversed) polarity; and, on
- 309 bottom, modelled (red) and observed (blue) RTP anomalies. The location of these section is
- 310 indicated as black lines labelled 1 (panels A-C) and 2 (panels G-I) on maps in the middle
- 311 column. These maps display the modelled RTP anomaly (color) superimposed on the bathymetry
- 312 (shadows). See text for details on the forward modelling.
- 313
- 314 Figure 3. Synthetic cross-sections presenting OCCs and DFs from more to less magmatism as
- 315 suggested by the averaged equivalent thickness of extrusive basalt. A), B), C) display
- 316 interpretations of the Yuhuang, Longqi and Junhui OCCs. D) displays the interpretation of the
- amagmatic Easternmost SWIR after Cannat et al. (2019).





Junhui 1 2







