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# Sub-axial deformation in oceanic lower crust: insights from seismic reflection profiles in the Enderby Basin and comparison with the Oman ophiolite.

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## Abstract

We analyzed high-quality seismic reflection profiles across the ocean-continent transition in the Enderby Basin between the Kerguelen Plateau and the Antarctic margin. There, we observe numerous high-amplitude dipping reflections in the lower oceanic crust which was accreted at a magmatic spreading center as testified by the almost uniform 6.4-7 km thick crust and its unfaulted, flat top basement. The deep reflections are rooting onto the Moho and are dipping both ridgeward and continentward. They occur in dense networks in mature oceanic crust as well as close to the continentward termination of oceanic crust and in the ocean-continent transition zone. The comparison with field observations in the Oman ophiolite suggests that these lower crustal dipping reflectors could correspond to syn-magmatic faults. In Oman, very high temperature (up to syn-magmatic), high temperature (sub-solidus plastic deformation) and low temperature (brittle) deformation coexist along the same fault over distances of a few hundred meters at Moho level. This very high temperature gradient may be explained by the sudden and intense interaction between crystallizing magmas and hydrothermal fluids induced by the episodic nucleation of faults in a context of continuous magmatic spreading. The igneous layering becomes extremely irregular compared to its monotonous sub-horizontal orientation away from the faults which, together with enhanced hydrothermal alteration restricted to the fault zones, might change the physical properties (velocity, density) and increase the reflectivity of syn-magmatic faults. We further speculate that these processes could explain the brightness of the lower crustal dipping reflectors observed in our seismic reflection data. Both the seismic reflection profiles of the Enderby Basin and the Oman ophiolite show evidence for syn-accretion tectonism at depth together with the systematic rotation of originally horizontal lava flows or originally vertical dikes, pre-dating cessation of magmatic activity. This indicates ubiquitous deformation processes within the axial zone of magmatic spreading centers.

48 **Keywords**

49 Lower oceanic crust; oceanic accretionary processes; dipping reflectors; ocean-  
50 continent transition; Enderby Basin; Oman ophiolite.

51 **1. Introduction**

52 Most of the oceanic crust created over the last 200 million years formed at  
53 intermediate- to fast-spreading mid-ocean ridges (50-200 km/Ma full rate) (Karson,  
54 2002). Despite the widespread occurrence of such magmatic crust, direct observations  
55 of its lower part made essentially of gabbroic cumulates are particularly scarce. There  
56 are only two locations (Hess Deep and Pito Deep in the Pacific Ocean) where *in situ*  
57 fast-spread plutonic crust is exposed in response to ridge propagation. Rocks from  
58 such deep horizons have been collected by submersible, remotely operated  
59 underwater vehicle and drilling, the section recovered by drilling being typically several  
60 tens of meter in length only (e.g. Brown et al., 2019; Gillis et al., 2014). No *in situ*  
61 observations within the lowermost oceanic crust accreted at fast-spreading ridges have  
62 been made elsewhere, apart from some sites in large offset transform faults, where  
63 crustal structures might not be representative of standard accretion processes (cf.  
64 Constantin et al., 1996).

65 Therefore, our knowledge of the deep crustal magmatic system along fast-spreading  
66 mid-oceanic ridges is mostly derived from seismic studies of the East Pacific Rise  
67 (EPR) and ancient analogues (e.g. ophiolites) although the tectonic setting of their  
68 genesis is still debated (MacLeod et al., 2013). Seismic reflection data have shown  
69 that there is a near static region of high melt proportions, the axial magma lens (AML),  
70 1-3 km wide and a few hundred meters high, at a depth of 1-2 km beneath the ridge  
71 axis, for much of its length (e.g. Detrick et al., 1987). Beneath the AML, tomographic  
72 studies have indicated that there is a low velocity zone a few kilometers wide (e.g.  
73 Toomey et al., 1990), which is inferred to consist of a crystal mush, i.e. incompletely  
74 crystallized cumulates (Sinton and Dietrick, 1992). More recent seismic reflection  
75 studies have shown a series of melt lenses in the lower crust below the AML both on  
76 and off-axis (e.g. Marjanovic et al., 2014). In addition, melt in the lower crust and/or the  
77 crust-mantle transition zone was also inferred by seafloor compliance studies  
78 (Crawford and Webb, 2002). Thus, there is an increasing set of arguments for a multi-  
79 level complex of melt lenses beneath the ridge axis (Marjanovic et al., 2014).

80 However, how these melt lenses contribute to the formation of both the upper and  
81 lower crust and what accretion processes are operating in the lower crust remain  
82 unclear. Two end-member models for crustal accretion have emerged from  
83 geophysical observations at fast-spreading ridges and more largely from field evidence  
84 in the Oman and other ophiolites (Kelemen et al., 1997; Marjanovic et al., 2014; Nicolas  
85 and Boudier, 2015). In the 'gabbro glacier' model, most crystal growth occurs within  
86 the AML, which subsides by ductile flow to form the entire gabbro section (e.g. Quick  
87 and Delinger, 1993). The 'sheeted sill' model, where gabbro formation occurs *in situ* in  
88 small magma bodies throughout the lower oceanic crust, better fits with the occurrence  
89 and structure of the interlayered mafic and ultramafic cumulates in ophiolites (Kelemen  
90 et al., 1997). In the Oman ophiolite, recent studies of the crust-mantle transition zone  
91 have shown that faults, enabling water introduction at depth, may be a more common  
92 feature than previously expected in the formation of the lowermost oceanic crust in a

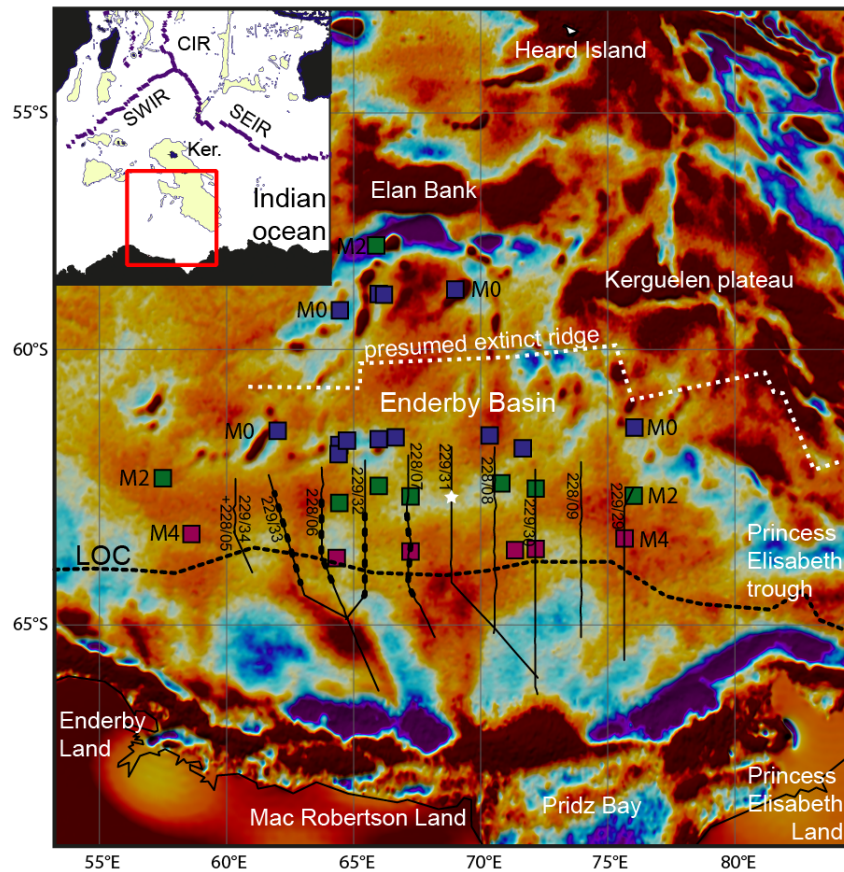
93 context of high melt supply (Abily et al., 2011; Rospabé et al., 2019). Such faults have  
94 not been documented yet in seismic reflection profiles at fast-spreading ridges.  
95 However, lower crustal dipping reflectors have been observed on ridge flanks within  
96 both slow- and fast-spreading crust (see Bécel et al. (2015) for a review) while they  
97 are not imaged along the ridge axis itself. Such lower crustal dipping reflections within  
98 fast-spread crust have been interpreted as arising from shear zones that form near the  
99 spreading center in the region with interstitial melt, and result from shear at the base  
100 of the crust (Bécel et al., 2015). It has been further suggested that such differential  
101 motion at the base of the crust could result from plate reorganizations (Bécel et al.,  
102 2015).

103 While lower crustal events dipping toward the paleo-ridge axis have been  
104 predominantly described until now (Bécel et al., 2015; Ding et al., 2018; Reston et al.,  
105 1999), here we identify numerous both ridgeward and continentward dipping high-  
106 amplitude reflectors in the lower oceanic crust of the Enderby Basin, between the  
107 Kerguelen Plateau and the Antarctic margin. Thanks to high-quality seismic reflection  
108 profiles, we are able to document the occurrence of such dipping reflections in two  
109 different but juxtaposed domains: typical oceanic crust and the ocean-continent  
110 transition. We relate these lower crustal dipping reflectors to syn-magmatic faulting  
111 described recently in the Oman ophiolite (Abily et al., 2011; Rospabé et al., 2019).  
112 These observations give some clues for the sub-axial tectono-magmatic processes  
113 that may occur within the oceanic crust.

## 114 **2. Geological background**

### 115 **2.1. The Enderby Basin**

116 Here, we focus on the oceanic domain and the ocean-continent transition within the  
117 central part of the Enderby Basin. It is bounded by the Enderby Land to the southwest,  
118 by the Elan Bank to the north and the southern Kerguelen Plateau to the northeast, by  
119 the Princess Elizabeth Trough to the east and by the Antarctic margin and the Mac  
120 Robertson Land to the south (Fig. 1). The Enderby Basin is thought to be formed during  
121 the Early Cretaceous as East Antarctica and India rifted apart (McElhinny, 1970). An  
122 intermediate spreading rate of ~60 km/Ma has been inferred from east-west trending  
123 magnetic anomalies M4 (126.7 Ma), M2 (124.1 Ma), and M0 (120.4 Ma) (Gibbons et  
124 al., 2013). These anomalies have been identified north and south of an extinct ridge  
125 running parallel to the Elan Bank (Gaina et al., 2007) (Fig. 1). However, this extinct  
126 ridge is poorly constrained and, contrasting with many other extinct ridges, it is not  
127 linked to a gravity low (MacLeod et al., 2017). Moreover, magnetic anomaly profiles in  
128 the Enderby Basin are scarce and, due to the absence of clear and continuous  
129 magnetic anomalies, their identification is debated (e.g. Golynsky et al., 2013). It has  
130 been suggested that the lack of clear magnetic anomalies may result from seafloor  
131 spreading during the Cretaceous Normal Superchron (Jokat et al., 2010). Therefore,  
132 no consensus about the spreading history of the Enderby Basin has been reached yet  
133 (e.g. Davis et al., 2018).



134 **Fig. 1:** Map of the eastern Enderby Basin. The background image is the free air gravity anomaly grid  
 135 derived from satellite altimetry data (Sandwell et al., 2014). The black dashed line indicates the landward  
 136 edge of the oceanic crust (LOC) after Gaina et al. (2007). The white dashed line indicates the presumed  
 137 extinct ridge axis after Gibbons et al. (2013). The squares show the magnetic anomaly picks from  
 138 Gibbons et al. (2013). The black lines indicate the seismic profiles from Geoscience Australia used in  
 139 this paper. Their thickened and dashed parts correspond to the sections shown in Fig. 3. The white star  
 140 indicates the location of Fig. 6. Ker., Kerguelen Island; CIR, Central Indian Ridge; SEIR, Southeast  
 141 Indian Ridge; SWIR, Southwest Indian Ridge.

142 By contrast, there is a consensus about the location of the inboard edge of unequivocal  
 143 oceanic crust (LOC) (Fig. 1). It typically coincides with: (1) a prominent oceanward  
 144 step-up in the basement level of 500-1000 m, (2) the continentward abrupt termination  
 145 of a well-marked oceanic Moho in the seismic reflection profiles (Stagg et al., 2005),  
 146 and (3) the Enderby Basin Anomaly (EBA; (Golynsky et al., 2013), a high-amplitude  
 147 (350–500 nT) magnetic anomaly which is interpreted to mark the contact between  
 148 strongly magnetized oceanic crust and less magnetized continental rocks (Golynsky et  
 149 al., 2013). The domain to the north of the LOC is described as unambiguous oceanic  
 150 crust (Stagg et al., 2005). The domain immediately to the south, within the ocean-  
 151 continent transition, is referred to as transitional crust on the basis of seismic reflection  
 152 profiles and limited refraction data (sonobuoys) (Stagg et al., 2005). It is thought to be  
 153 made of stretched continental crust or exhumed mantle that was subsequently  
 154 modified by magmatic intrusions during the formation of the initial- or proto-oceanic  
 155 crust (Gaina et al., 2007; Gillard et al., 2019).

156 We use 10 high-resolution and deep-penetrating seismic reflection profiles from the  
 157 GA-228 and GA-229 surveys collected by Geoscience Australia in 2000 and 2001,  
 158 respectively (Stagg et al., 2005). During these surveys, 36-fold stacked and migrated  
 159 deep seismic data (60 l airgun array source; 3600 m streamer; 288 channels; 16 s



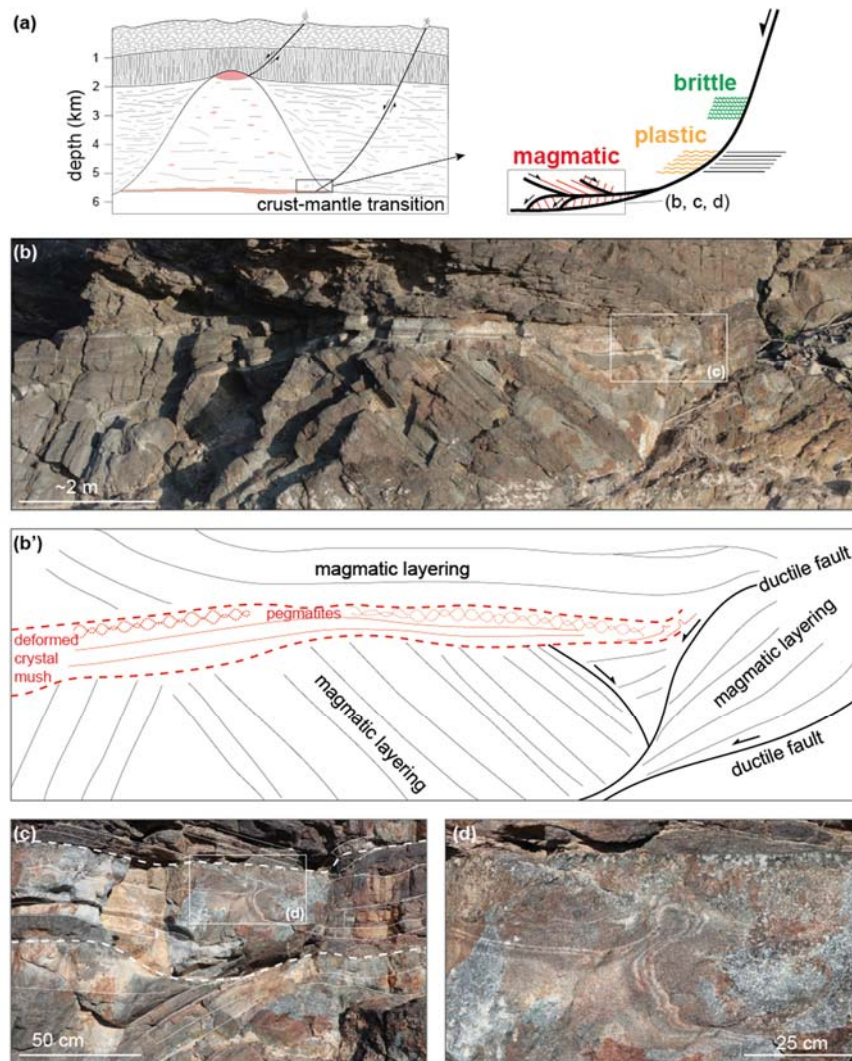
160 record length) were recorded between offshore western Enderby Land and the  
161 southern Kerguelen Plateau (Fig. 1) (Stagg et al., 2005). The seismic profiles are  
162 trending North-South, perpendicular to the LOC and the magnetic lineations of the  
163 Enderby Basin. They are thus thought to be collected along a flow line of the Enderby  
164 Basin spreading center, although the geometry and segmentation of this ridge is poorly  
165 known. This data set was used by Stagg et al. (2005) to map and describe distinct  
166 sectors along the Antarctic margin and the adjacent oceanic crust.

## 167       2.2.       The Oman ophiolite

168 The Oman ophiolite is the largest coherent remaining fragment of the Tethyan oceanic  
169 lithosphere. It is interpreted as formed along a highly productive (Ceuleneer et al.,  
170 1996; Pallister and Hopson, 1981) and possibly fast-spreading center ~95-97 million  
171 years ago (Boudier et al., 1985; Rioux et al., 2012). Major ductile shear zones were  
172 recognized as common features in the mantle and crustal sections of the Oman  
173 ophiolite since pioneer structural studies (Amri et al., 1996; Boudier et al., 1985;  
174 Boudier et al., 1988; Jousselin and Nicolas, 2000; Jousselin et al., 1998). They are  
175 characterized by intense deformation with the development of peridotite mylonites and  
176 flaser gabbros on thicknesses ranging from a few meters to several hundred meters.  
177 The main ones can be followed along strike over distances of several tens of  
178 kilometres. Shearing initiated at very high temperature, close or above the solidus of  
179 peridotites and gabbros, frequently in the presence of melt, and usually stopped before  
180 the rock cooled down significantly, although most of these shear zones were still active  
181 at greenschist facies metamorphic conditions.

182 The shear zones revealed by the early structural mapping of the Oman ophiolite show  
183 a clear continuity with the metamorphic sole and, hence, have been attributed to  
184 emplacement tectonics (intra-oceanic thrusting close to the ridge axis) (Boudier et al.,  
185 1985; Boudier et al., 1988). Until recently, this interpretation was extended by most  
186 geologists to all kinds of ductile and brittle fault zones affecting the mantle and the  
187 deep crustal section of the Oman ophiolite, apart from minor ones interpreted in terms  
188 of oceanic spreading (e.g. Dijkstra et al., 2002). Circularity in the way of reasoning  
189 maintained the confusion: Oman ophiolite being supposed to derive from a fast-  
190 spreading centre where faulting (at least down to deep levels of the crust) was  
191 supposed to play an anecdotic role relative to igneous accretion, faults observed in  
192 Oman were *a priori* attributed to later events, among other the intra-oceanic thrusting.  
193 However, more detailed studies have revealed the existence of high temperature shear  
194 zones, which did not record strike slip or inverse kinematics calling for convergent  
195 tectonics. A normal shear sense is actually recorded by many faults among those  
196 which have an azimuth subparallel to the one of paleo-ridge axis, including high  
197 temperature ductile faults (Abily et al., 2011; Rospabé et al., 2019).

198 Moreover, our structural observations and petrological data from the Maqsad area  
199 highlight that faults were active early at Moho level, since the magmatic stage, and that  
200 they contributed to the petrological and geochemical organization of the lower crust.  
201 Due to the deep introduction of water they triggered, these faults exerted a strong  
202 control on the reaction leading to the transformation of mantle harzburgite into dunite  
203 at the Moho and on melts migration and crystallization paths, and continued to serve  
204 as major avenues for hydrothermal fluids down to lower temperatures (Abily et al.,  
205 2011; Rospabé et al., 2017). These faults are either parallel to the strike of the sheeted  
206 dike complex (*i.e.* parallel to the regional orientation of the inferred paleo-ridge axis) or



207 **Fig. 2:** Evidence of syn-magmatic normal faulting and block rotation at Moho level in the Oman ophiolite,  
 208 Maqсад area (see also Abily et al. (2011)). (a) Simplistic sketches illustrating the possible context of  
 209 acquisition of the structures observed in the field (left) and the evolution in the conditions of deformation  
 210 along the fault (right). (b) Main structural elements observed on this outcrop: magmatic layering (thin  
 211 black lines); ductile faults (thick black lines and arrows), deformed crystal mush layer (red symbols). (c)  
 212 Closer view on the zone of former crystal mush with complex modal layering induced by crystal sorting  
 213 and melt injection during viscous deformation. (d) Detail on a ptygmatic fold and on the upper horizon  
 214 of pegmatite (former melt layer that made possible the mechanical decoupling between the tilted blocks  
 215 of layered cumulates and the overlying cumulates).

216 slightly oblique to it (Rospabé et al., 2019). They mostly have a ridgeward dip ranging  
 217 from 65° to 10° and some are clearly listric, with dips progressively shallowing as the  
 218 crust-mantle boundary is approached, inducing early tilting of blocks of hardly  
 219 consolidated layered cumulates (Fig. 2). Normal syn-accretion faults highly altered in  
 220 a wide temperature range have been identified in other massifs of the Oman ophiolite  
 221 (e.g. Zihlmann et al., 2018) and seem to be the rule rather than the exception. In the  
 222 case of the fault studied in detail by Abily et al. (2011), the rotation of these blocks of  
 223 layered cumulates, at high angles relative to the Moho, was accommodated by an  
 224 anastomosing fault network connected to the main fault plane. It is locally underlined  
 225 by thin screens of gabbroic micropegmatites, which represent former hydrated evolved  
 226 melts crystallizing as amphibole-bearing gabbros and by ptygmatic folds, pointing to  
 227 viscous deformation of a sheared and compacting crystal mush (Abily et al., 2011)  
 228 (Fig. 2). Flat-lying undeformed cumulate layers, in the same differentiation stage as

229 the deformed ones, settled directly over the tilted blocks, which is the main evidence  
230 for syn-magmatic block rotation (Fig. 2). In this example, outcrops witnessing syn-  
231 magmatic deformation exceptionally escaped lower temperature deformation and  
232 alteration. This evidences a remarkable lateral evolution in the deformation style on a  
233 distance of a few hundred meters. Moving away from the zone where syn-magmatic  
234 structures are preserved, i.e. moving toward the main fault that was active down to  
235 greenschist facies conditions, shearing continued at sub-solidus temperatures along  
236 some fault planes, and brittle deformation structures become more and more prevalent  
237 (Abily et al., 2011).

238 Lower crustal gabbros from Oman generally present a quite regular igneous (modal)  
239 layering sub-parallel to the crust-mantle boundary ("paleo-Moho"). This monotonous  
240 orientation is totally disturbed within several hundred meters from these syn-magmatic  
241 normal faults. Minor faults are spaced by a characteristic distance of ~250 m on  
242 average, but the major ones may be several kilometers apart. Moving from the top to  
243 the base of the crust-mantle transition zone, the deformation conditions evolved from  
244 brittle to ductile. Most of these faults were active in a broad temperature interval, with  
245 the development of serpentine and carbonate breccias that can be intruded by  
246 gabbroic dikes altered in greenschist facies conditions. These brecciated zones reach  
247 up to 10 m in thickness in the few major faults and have been zones of intense fluid  
248 circulation (Rospabé et al., 2019). The fact that water penetration occurred early during  
249 the development of these faults is attested by geochemical gradients continuous on  
250 distances reaching a few dozen of meters away from the faults (Rospabé et al., 2019).  
251 Concerning the lower temperature water circulation and greenschist facies alteration,  
252 the connection with former seafloor hydrothermal vents is attested by the occurrence  
253 of Fe, Ni and Cu sulfide mineralizations within these faults (Abily et al., 2011).

254 A recent survey showed that the Moho steepens in the massifs located close to the  
255 front of the Oman ophiolite. This unusual dipping is attributed to a ductile shear zone  
256 that was active in very high temperature conditions, close to the gabbro solidus  
257 (Ceuleneer et al., 2020). The lower crustal cumulates are affected by plastic  
258 deformation on a thickness reaching 2 km and the along strike extent of the fault  
259 reaches 100 km subparallel to the paleo-ridge axis. The curvature of this mega-fault  
260 was continentward at the time of accretion. Away from the Moho, the decrease in the  
261 deformation intensity is correlated with a progressive flattening of the layering and  
262 foliation of the gabbros (listric fault kinematics). This major feature, of regional extent,  
263 is interpreted in terms of syn-accretion tectonics (Ceuleneer et al., 2020).

### 264 **3. Description of the seismic reflection profiles in the Enderby Basin**

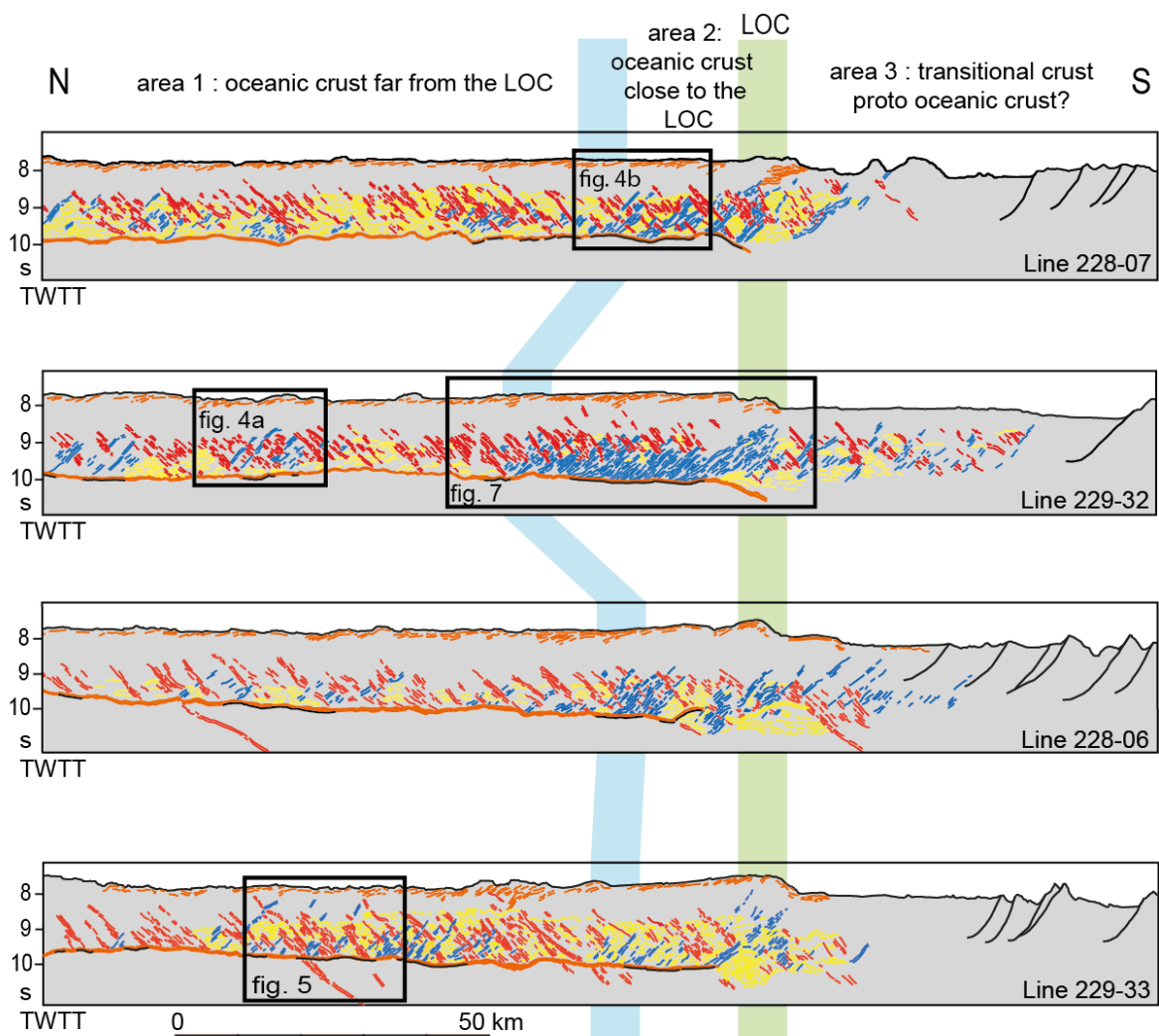
265 Here we gather several examples from different seismic profiles to get an all-  
266 encompassing view of the typical seismic structures from the unambiguous oceanic  
267 crust in the northern part of the survey area to the ocean-continent transition zone to  
268 the south.

#### 269 *3.1. The northernmost part of the survey area*

270 In the northernmost end of the seismic sections we observe a well-defined oceanic  
271 crust characterized by: (1) a smooth flat and reflective top basement, (2) some short  
272 reflections in the shallowest part of the crust, (3) a transparent unit in the upper crust



273 located above, (4) a more reflective lower crust, and (5) a set of horizontal reflectors at  
 274 the base of the crust. We interpret this latter as the oceanic Moho, although various  
 275 geological structures at the base of the crust may generate high-amplitude reflections  
 276 (e.g. Collins et al., 1986). The thickness of the oceanic crust is usually 2-2.2 s TWTT  
 277 corresponding to ~6.4-7 km (using Canales et al. (2003) relationship between crustal  
 278 thickness and crustal reflection travel times), which is within the range of normal  
 279 oceanic crust thicknesses ( $6 \pm 1$  km; e.g. Christeson et al., 2019). In some places the  
 280 crust is thicker than the normal oceanic crustal thickness. This is the case south of the  
 281 Kerguelen plateau, where the crustal thickness reaches 3.2 s TWTT (~10 km) but also  
 282 at the western edge of the survey area where the crust reaches 2.5 s TWTT thickness  
 283 (7.9 km at 60°E) (Supplementary Fig. S1). Both the flat top basement and the  
 284 thickness of the oceanic crust argue for a formation at a magma-rich spreading center.



285 **Fig. 3:** Line drawing of 4 seismic profiles across the landward edge of the oceanic crust (LOC indicated  
 286 by the green band). Blue lines indicate oceanward dipping reflectors (ODRs); red ones indicate  
 287 continentward dipping reflectors (CDRs); yellow ones show nearly horizontal reflectors and orange ones  
 288 at the top basement indicate oceanic seawards dipping reflectors (OSDRs). The thick orange lines at  
 289 the bottom of the crust show the reflection Moho and the black lines beneath it show where the Moho is  
 290 continuous and highly reflective. The blue band indicates the rideward end of the dense network of  
 291 ODRs occurring close to the LOC. Vertical exaggeration is approximately x2. Uninterpreted and  
 292 interpreted versions of profiles 229/32 with no vertical exaggeration are shown in the **Electronic**  
 293 **Supplement 1**.

294 3.2. Oblique reflectors in the oceanic crust away of the LOC (area 1)

295 To the south, in area 1 (see Fig. 3), the most striking and intriguing features of the  
296 seismic reflection profiles are the numerous high-amplitude dipping reflectors in the  
297 lower oceanic crust. These deep reflectors occur along sections more than 150 km-  
298 long. They define a layer of almost constant thickness at the base of the oceanic crust  
299 (1.3 s TWTT on average that is ~4.6 km using a 7 km/s for the lower crust) (Electronic  
300 Supplement 1). A discontinuous upper horizontal reflector marks locally the top of this  
301 lower crustal layer (at 0.7-0.8 s TWTT depth below top basement that is ~1.9 km using  
302 a 5 km/s for the upper crust). At the base, the reflection Moho is well marked and  
303 defines an oceanic crust of normal thickness (~2-2.1 s TWTT on average) (Fig. 3).

304 The spacing between the deep reflectors is variable, reaching several kilometers.  
305 However, in sections where their distribution is more regular, the spacing is typically  
306 2 km. There, they are 5-6 km-long. Locally and rarely, they can reach 10 km-long  
307 where they reach the upper crust. While they dip either toward the continent or toward  
308 the ridge, they mostly occur as series of reflectors dipping in the same direction for  
309 several tens of kilometers before changing dip direction (Fig. 3). Such changes in the  
310 dip direction are not marked by any noticeable change neither at the top basement nor  
311 at the reflection Moho. Multiple changes of dip direction also occur locally such as in  
312 profile GA-229/32, where lower crustal reflectors are crossing each other (Fig. 4a).

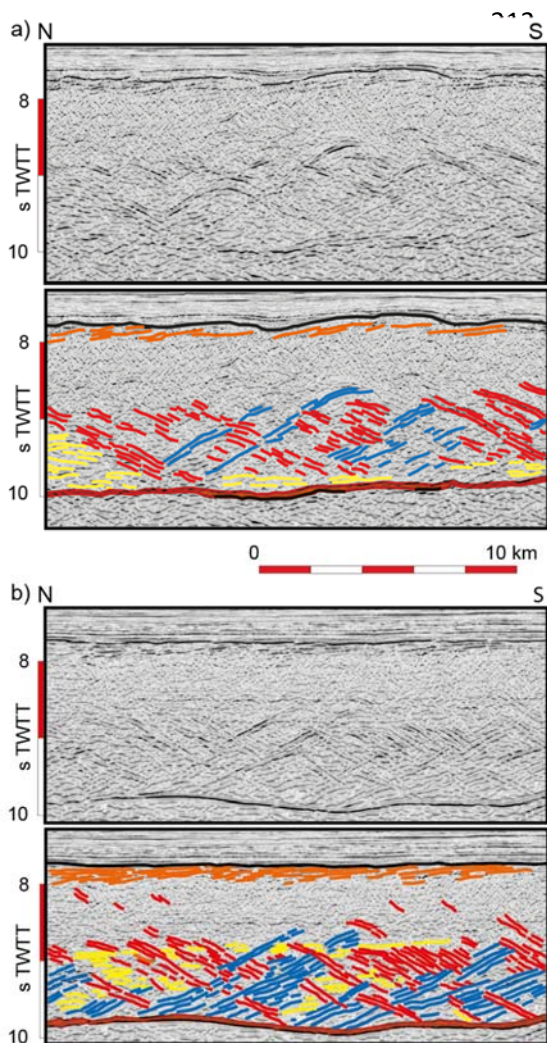


Fig. 4: Examples of dipping reflectors crossing each other (a: profile 229/32 and b: profile 228/07) defining a layer of almost constant thickness at the base of the oceanic crust. The reflection Moho is well marked almost all along the bottom of the layer. See figure caption and location in Fig. 3. Approximately no vertical exaggeration. Copyright Commonwealth of Australia (Geoscience Australia).

The deepest part of the lower crustal reflectors roots at the reflection Moho and their shallowest part flattens at the base of the transparent layer, giving them a general apparent sigmoidal shape (Fig. 4a and S2). Although the exact geometry of the reflectors is unknown (as we do not know the seismic velocity profile) we note that some of these reflectors merge with shallower horizontal ones (Supplementary Fig. S2). Rare deep reflectors are observed both in the crust and in the mantle as deep as 11.5 s TWTT (Fig. 5).

A few rising continentward dipping reflectors (CDRs) are observed in the upper crust but they do not reach the top basement. They are covered by long and continuous reflectors (reaching 4-5 km length), which are ubiquitous in the shallowest part of the crust (Figs. 4 and 5). The thickness of this

341 set of shallow reflectors is on average 0.5 s TWTT (1 km using a 4 km/s velocity for  
 342 the uppermost crust) but may reach 0.7-0.8 s TWTT locally (1.5 km at 4 km/s). These  
 343 shallow reflectors mostly dip gently toward the ridge at the base and then become  
 344 horizontal upward forming wedges, up to 10 km-long, in the uppermost part of the crust  
 345 (Fig. 6). Within these wedges, the CDRs that rise up from the lower crust are  
 346 discontinuous, distributed, short and almost perpendicular (on the time sections) to the  
 347 shallow reflectors dipping toward the ridge. Because these shallow reflectors remind  
 348 the seaward dipping reflectors (SDRs) observed at volcanic rifted margins, we have  
 349 call them oceanic seaward dipping reflectors (OSDRs). Despite the occurrence of  
 350 these OSDR wedges, the top basement is usually almost flat or very smooth and only  
 351 very rare volcanoes or faults can be inferred from the seismic reflection of the top  
 352 basement (Supplementary Fig. S3).

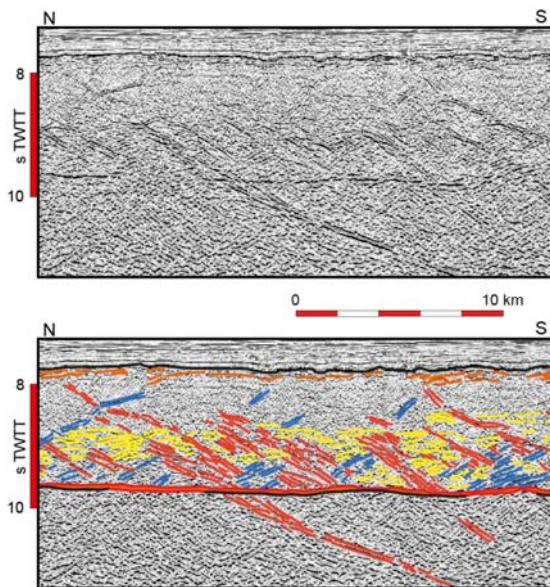


Fig. 5: Example of reflectors that are observed both in the crust and in the mantle as deep as 11.5 s TWTT (line 229/33). Note some rare examples of dipping reflectors that are shallowing but do not reach the top basement as they are covered by long and continuous reflectors. See figure caption and location in Fig. 3. Approximately no vertical exaggeration. Copyright Commonwealth of Australia (Geoscience Australia).

### 366 3.3. A specific network of lower crustal dipping reflectors close to the LOC (area 2)

367 In area 2, close to the LOC (see Fig. 3), some profiles show a 20-40 km-long denser  
 368 network of deep oceanward dipping reflectors (ODRs; 1 reflector every ~500 m), which  
 369 systematically sole out onto the reflection Moho. This is particularly well observed in  
 370 profile GA-229/32 (Figs. 3 and 7). There, a few ODRs reach the upper crust at the LOC  
 371 and are progressively replaced by CDRs with higher reflectivity (Fig. 7). Short CDRs  
 372 first observed in the mid-crust close to the LOC where the crust is thicker (2.4-  
 373 2.8 s TWTT), are lengthening and deepening oceanwards. The CDRs finally reach the  
 374 reflection Moho as the ODRs disappear at 30-40 km from the LOC.

375 This dense network of ODRs close to the LOC shows some variability from one profile  
 376 to the other: e.g. profile GA-228/07 displays triangular-shaped areas with groups of  
 377 deep reflectors dipping preferentially oceanwards or continentwards (Figs. 3 and 4b).  
 378 The top basement remains flat in area 2 except in profile GA-229/30. There, it is  
 379 associated with a wedge of shallow reflectors in the uppermost crust beneath a small  
 380 asymmetric basin at the seafloor (Supplementary Fig. S4). The ODRs systematically  
 381 sole out onto the Moho, which is particularly well marked by a single continuous bright  
 382 reflector (Figs. 3 and 7). In this area the Moho is nearly horizontal or slightly dipping  
 383 continentwards, defining a thicker oceanic crust (~2.4 s TWTT) than in area 1 (Fig. 7).



384 At the LOC the Moho branches out in a set of deep reflectors that shallow or deepen  
 385 parallel to the ODRs and CDRs, respectively (Figs. 7 and S5).

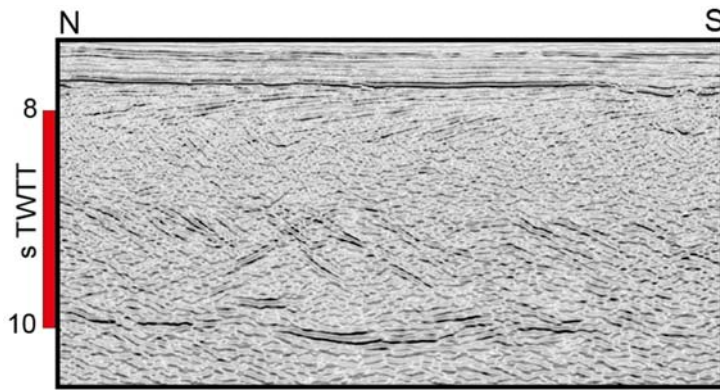
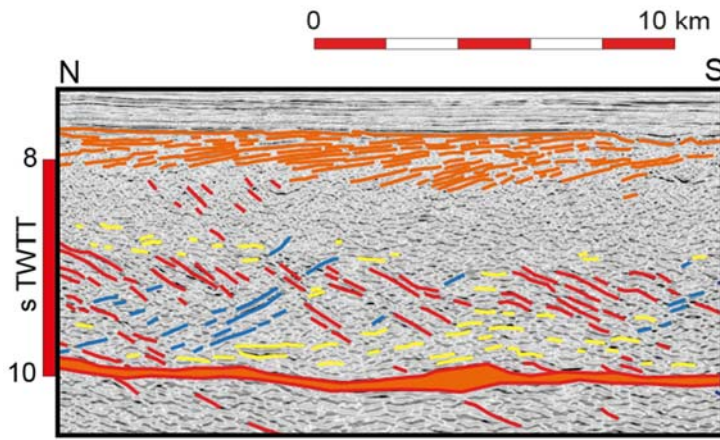


Fig. 6: Example of oceanic seawards dipping reflectors (OSDRs) forming up to ~10 km-long wedges in the uppermost part of the crust (profile 229/31). Same figure caption as Fig. 3. See location in Fig. 1. Approximately no vertical exaggeration. Copyright Commonwealth of Australia (Geoscience Australia).



402

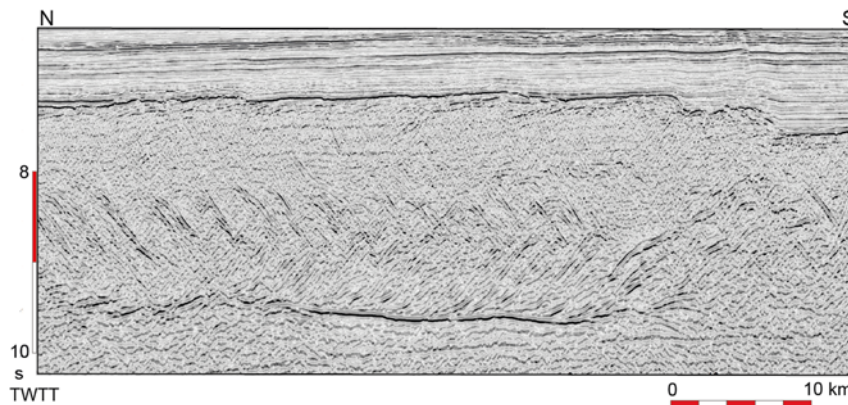
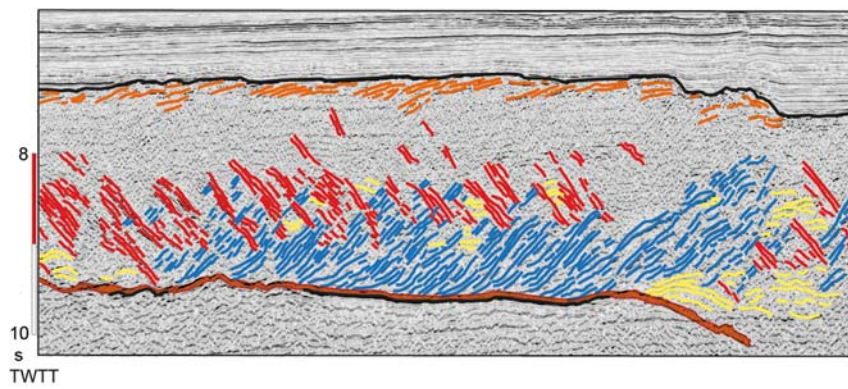


Fig. 7: Denser network of oceanward dipping reflectors (ODRs) and continentward dipping reflectors (CDRs) (1 reflector every ~500 m) close to the landward edge of the oceanic crust (profile 229/32). Vertical exaggeration is approximately 2x. See figure caption and location in Fig. 3. Copyright Commonwealth of Australia (Geoscience Australia).





423 Above the termination of the reflection Moho, an oceanward step-up in the top  
424 basement is systematically observed (Fig. 7). It is 0.5 TWTT high (~1000m at 4 km/s  
425 for the uppermost crust) on average. Locally, within this basement high, 2-3 shallow  
426 reflectors are slightly dipping oceanwards and are recovered progressively by flatter  
427 lying reflectors in a fan shape structure, similarly to the OSDRs observed in area 1  
428 (Supplementary Fig. S5).

### 429 3.4. *The transitional domain to the south of the LOC (area 3)*

430 The area 3 (see Fig. 3) to the south of the LOC shows a progressively deeper and  
431 rougher top basement reaching >8 s TWTT. Some parts of the top basement still show  
432 high reflectivity, but the top basement becomes less reflective continentwards as  
433 intense normal faulting results in numerous rotated blocks (see Electronic Supplement  
434 1). These normal faults, mainly dipping oceanwards, are rooting at a discontinuous  
435 horizontal reflector at ~1 s TWTT depth beneath the top basement. This reflector has  
436 been called UR (for upper reflector) by Gillard et al. (2019) in contrast to a  
437 discontinuous weaker lower reflector (LR) that is observed locally deeper at about  
438 10 s TWTT. Some of these normal faults are sealed by horizontal shallow reflectors in  
439 the uppermost basement. Deep reflectors are also observed in area 3 (see Figs. 3 and  
440 Electronic Supplement 1). Close to the LOC, one of these reflectors is observed  
441 dipping continentwards as deep as 11 s TWTT (Fig. 3).

## 442 4. Discussion

### 443 4.1. *Synthesis of observations and first order interpretation away of the LOC*

444 Both the alternating series of ODRs and CDRs and the local crosscutting relationships  
445 between these reflectors contrast with earlier observations of lower crustal reflectors  
446 dipping predominantly toward the paleo-ridge axis (e.g. Bécel et al., 2015; Ding et al.,  
447 2018; Reston et al., 1999). These new observations indicate that the ODRs and CDRs  
448 may locally be formed contemporaneously. We describe hereafter, from top to bottom  
449 of the oceanic crust, the various reflectors and infer their nature.

450 We interpret the CDRs that are locally reaching the upper crust as rotated dikes as  
451 they are distributed below, perpendicular to the OSDRs that we interpret as lava flows  
452 (Fig. 6). This systematic dipping of the shallowest lava flows toward the ridge and the  
453 rotation of the sheeted dike complex were described at fast-spreading centers by  
454 Karson (2002) on the basis of geological investigations of major fault scarps and  
455 DSDP/ODP Drill Holes. Evidence of shallow block rotation pre-dating the cessation of  
456 the magmatic activity along ridge parallel normal faults (i.e. with the same orientation  
457 as the deep faults) were also reported in Oman (MacLeod and Rothery, 1992).

458 The flat top basement above the wedges of OSDRs indicates that their formation  
459 occurred close enough to the paleo-ridge axis so that the latest lava flows within the  
460 neo-volcanic zone at the paleo-ridge axis sealed these wedges that were not deformed  
461 subsequently on the ridge flank. The neo-volcanic zone at fast-spreading ridges (zone  
462 of lava accumulation and dike intrusion at the ridge axis) is usually very narrow, few  
463 kilometers wide but the extent of these wedges within our study area shows that it may  
464 reach up to 10 km off-axis.

465 The rotation of the dikes and lava flows in the uppermost part of the crust must be  
466 accommodated below. The apparent sigmoid shape of the CDRs and ODRs and the  
467 local occurrence of a horizontal reflector marking the top of the layer of these dipping  
468 reflectors suggest a decoupling layer there that could serve both for the CDRs and  
469 ODRs in the lower crust and for the rotated dikes above (Figs. 4 and S2). It is located  
470 at 0.7-0.8 s TWTT below the top basement (~1.9 km at 5 km/s), which corresponds to  
471 the depth of the magma chamber at fast-spreading ridges and therefore to the base of  
472 the dike complex. A decoupling level at the base of the dike complex was already  
473 suggested by Varga et al. (2004).

474 At the base of the crust, the rooting of the dipping reflectors onto the Moho indicates  
475 that this latter corresponds to another decoupling level (Figs. 3 and 7). The nearly  
476 horizontal reflection Moho together with the smooth top basement suggest that the  
477 processes forming these dipping reflectors are restricted to the lower crust as neither  
478 the base nor the top of the crust are affected. Considering that water is unlikely to  
479 penetrate down to 11.5 s TWTT deep within the mantle beneath a relatively thick  
480 magmatic crust, we suggest that the local occurrence of dipping reflectors in the mantle  
481 (Fig. 5) is best explained at depth by melt intrusions.

#### 482 4.2. *Synthesis of observations and first order interpretation close to the LOC*

483 The dense network of ODRs close to the LOC is not observed elsewhere in the  
484 Enderby Basin, suggesting that it is a specific feature at the onset of spreading. The  
485 thicker oceanic crust (~0.3 s TWTT more that is ~1 km thicker than normal) closer to  
486 the LOC than away shows that the magma supply was up to 15% larger at the onset  
487 of spreading than afterwards. This increase of the magma supply was sudden as  
488 suggested by the 1 km-high step-up in the top basement above the termination of the  
489 reflection Moho. We interpret the pile of shallow reflectors within this step-up as a thick  
490 wedge of lavas flowing toward the continent (Supplementary Fig. S5). The base of this  
491 wedge could then correspond to the paleo-top basement of a pre-oceanic domain. The  
492 loading of volcanic material may have produced the flexure of this existing lithosphere.

493 The crustal thickness returned normal (2-2.1 s TWTT) after the onset of spreading. It  
494 decreased progressively as testified by a flat top basement and a ridgewards rising  
495 reflection Moho (see Fig. 3 and Electronic Supplement 1). There, starting from the LOC  
496 area, the ODRs become shorter, are progressively replaced by CDRs and finally  
497 terminate when the crustal thickness returns to normal. This suggests therefore a  
498 control of the occurrence ODRs vs. CDRs by the magma supply at the initial ridge.

499 This magma supply at the initial ridge may also display some variations. We have  
500 shown that locally the set of ODRs is replaced by CDRs just beneath a small  
501 asymmetric basin at the top basement and a wedge of lava flows underneath  
502 (Supplementary Fig. S4), which suggests a syn-tectonic volcanic building and thus a  
503 tectonic control. We therefore propose that there is a tradeoff between magma supply  
504 and extensional tectonics within the LOC area and that this tradeoff controlled the  
505 changes from ODRs to CDRs. For example, a basin at the top basement with a syn-  
506 tectonic wedge of lava flows underneath would indicate either less magma supply or a  
507 higher extensional rate that controls the termination of the set of ODRs. Alternating  
508 triangular-shaped areas with preferentially ODRs or CDRs (Fig. 3) would then show  
509 that this tradeoff could change over a short time scale. However, the nearly flat top

510 basement above these dipping reflectors, shows that the proximity to the ridge axis  
511 may allow the equalization of the overall magma supply on a longer time scale by  
512 leveling the relief by the latest lava flows. Without well constrained spreading rates for  
513 the Enderby Basin, we cannot estimate these time scales.

514 Close to the LOC, the dense network of deep oceanward dipping reflectors that  
515 systematically sole out onto a sharp and highly reflective Moho suggests that the Moho  
516 behaved as a decoupling layer. Moreover, the branching out of the reflection Moho at  
517 its continentward termination, following either ODRs or CDRs that are also observed  
518 in the transitional domain to the south of the LOC (Supplementary Fig. S5), also  
519 suggests a tectonic control of the deepest structures of the lower oceanic crust at the  
520 onset of spreading. Therefore we propose that, although the initial spreading center  
521 can be largely seen as a magmatic system like the EPR (where plate separation is  
522 accommodated by ~2% tectonic strain; Escartín et al., 2007) relative to the adjacent  
523 hyper-extended and intruded continental lithosphere (Gillard et al., 2019), the newly  
524 formed oceanic crust may be deformed. The denser network of dipping reflectors close  
525 to the LOC would then suggest that this tectonic deformation is slightly more intense  
526 at the onset of spreading than later, once the oceanic ridge is more mature.

527 The progressively deeper and rougher top basement to the south of the LOC (Fig. 3)  
528 was interpreted as exhumed mantle with increasing magmatic addition toward the LOC  
529 (Gillard et al., 2019). This is also shown by normal faults that are sealed by lava flows  
530 close to the LOC but that offset the top basement far away from it. Such increasing  
531 magma volume from the continent toward the ocean with magma addition both on the  
532 top and within the basement together with complex magma-fault relationships have  
533 already been described in other magma-poor rifted margins (Gillard et al., 2017).

534 *4.3. How do observations in the Oman ophiolite help to understand the nature and*  
535 *the origin of the lower crustal dipping reflectors?*

536 Bécel et al. (2015) proposed that the lower crustal dipping reflections within the fast  
537 spread crust offshore Alaska arise from shear zones that form near the spreading  
538 center. They extensively discuss the physical properties of tectonic and magmatic  
539 features that could ultimately be imaged in the lower oceanic crust. They conclude that  
540 either solidified melt that was segregated within the shear structures, mylonitization  
541 along shear zones, crystal alignment and/or a combination of these processes may  
542 result in the bright dipping reflections (Bécel et al., 2015). These authors noted,  
543 however, that shear zones with scales similar to the lower crustal reflections they  
544 imaged have not been observed to date in ophiolites, with special reference to the  
545 Oman ophiolite supposed to have formed in a similar tectonic setting than their study  
546 area. As seen above (section 2.2), this assertion is contradicted by recent observations  
547 in Oman that led to revisiting previous interpretations.

548 Accordingly, we suggest that syn-magmatic normal faulting revealed by new  
549 observations in the Oman ophiolite may correspond to the lower crustal dipping  
550 reflectors described in this study. We note similarities with the geometry of the dipping  
551 reflectors in the oceanic crust. They both dip either ridgeward or continentward within  
552 the lower crust and root at the crust-mantle transition zone. They also both occur within  
553 the hot ridge axial zone as evidenced by the latest lava flows sealing the top basement  
554 that remains almost flat and undeformed. It is important to note that the overall internal

555 deformation is quite variable in Oman, where we observed faults with small normal  
556 displacement and major shear zones with displacement reaching likely one or more  
557 kilometers. The thickness of these major shear zones may reach tens of meters and  
558 could thus be wide enough to be imaged by seismic reflection techniques. In Oman,  
559 the faults appear to be closer spaced than on the seismic reflection profiles but this is  
560 likely a question of spatial resolution.

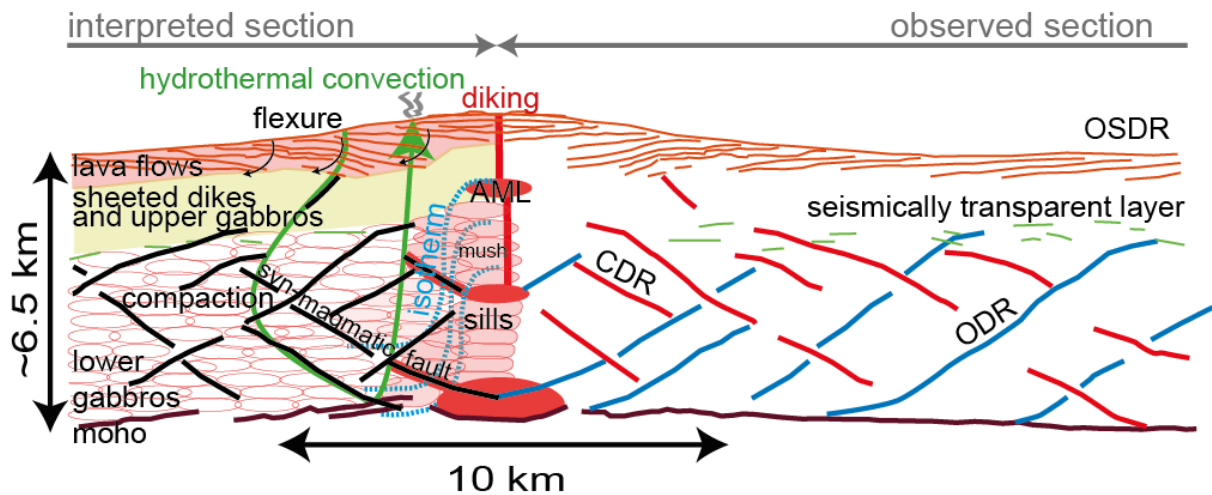
561 Following Bécel et al. (2015), we hypothesize that the bright reflections observed in  
562 our seismic data set might have a hybrid tectonic and magmatic origin. In Oman, both  
563 late magmatic intrusions and low-temperature water circulation occur within the syn-  
564 magmatic fault zones. The water introduction produced mineralogical reactions that  
565 were active down to greenschist facies and that are absent from gabbroic cumulates  
566 located away of the fault zone. We therefore suggest that these lithological  
567 modifications, restricted to the vicinity of syn-magmatic fault zones, may result in  
568 velocity and density contrasts sufficient enough to create an impedance contrast at the  
569 location of these faults. We further speculate that these processes could thus explain  
570 the brightness of the dipping reflectors observed in our seismic reflection profiles.  
571 Another possible interpretation might be looked for in the anisotropy/polarizing effects  
572 related to the igneous layering. Away from faults the bedding is quite regular but this  
573 regularity is totally lost in the vicinity (hundreds of meters) of syn-magmatic faults, as  
574 illustrated by our observations in Oman. This sudden lack of regularity (which goes  
575 along with an increase in alteration) might induce contrasts in the seismic wave  
576 propagation and be imaged as a reflector. More work is needed to reinforce the  
577 comparison between lower crustal dipping reflectors and syn-magmatic faults.

#### 578 *4.4. Toward a more complex model of magmatic accretion*

579 Summing up our observations of lower crustal dipping reflectors in the Enderby Basin  
580 and their comparison with syn-magmatic and high temperature ductile faults observed  
581 in the Oman ophiolite suggest that internal sub-axial deformation processes are more  
582 complicated than those shown in most current models of mid-ocean ridges. As a matter  
583 of fact, one of the main point revealed by studies in the Oman ophiolite is that very high  
584 temperature (up to syn-magmatic), high temperature (sub-solidus plastic deformation)  
585 and low temperature (brittle) deformation may coexist along the same fault over  
586 distances of several hundred meters at Moho depth. This huge temperature gradient  
587 likely results from the juxtaposition and interaction between crystallizing magmas and  
588 hydrothermal fluids induced by the episodic nucleation of faults in a context of  
589 continuous spreading (Rospabé et al., 2019).

590 A clear effect of crustal deformation is the rotation of originally horizontal lava flows  
591 and originally steeply dipping dikes to ridgeward and outward-dipping orientations,  
592 respectively (Fig. 8). These rotations are evident in outcrops of the upper crust at fast-  
593 spreading centers and in the Oman ophiolite (MacLeod and Rothery, 1992; Pallister  
594 and Hopson, 1981). Axial loading of lavas is generally considered to be the driving  
595 mechanism for this asymmetrical, subsidence of upper crustal units (Dewey and Kidd,  
596 1977). This sub-axial subsidence is rapid beneath the ridge axis and decreases up to  
597 the edge of the active volcanic zone, a few kilometers for fast-spreading ridges  
598 (Karson, 2002). However, our observations show that, within this axial zone,  
599 deformation may affect the underlying deeper gabbroic units as well.





600 **Fig. 8:** Cartoon of the structure of the oceanic ridge showing the formation of dipping reflectors by sub-  
 601 axial deformation (CDR, continentwards dipping reflectors; ODR, oceanwards dipping reflectors; OSDR,  
 602 oceanic seaward dipping reflectors). Oblique reflectors in the lower crust are syn-magmatic faults.  
 603 Isotherms (dotted blue lines) and hydrothermal circulation paths (green line) are schematic. AML: axial  
 604 melt lens. No vertical exaggeration.

605 Flexure of the upper crustal units in the brittle regime creates accommodation space.  
 606 At deeper levels, we suggest that early, syn- to sub-magmatic deformation as well as  
 607 later brittle deformation is accommodated by syn-magmatic faulting as evidenced by  
 608 the network of the dipping reflectors in the lower oceanic crust (Fig. 8). We infer a  
 609 decoupling level at the base of the dikes, as already suggested by Karson et al. (2002)  
 610 and Varga et al. (2004) for the fast-spreading East Pacific Rise, which results in a  
 611 partitioning of the deformation between the upper and lower crust. Gabbroic sills may  
 612 have been emplaced beneath the dike complex and not have fully crystallized when  
 613 the subsidence and deformation occurred in overlying units (Karson et al., 2015;  
 614 Yoshinobu and Harper, 2004).

615 Differences in melt supply along the axis of the fast-spreading East Pacific Rise have  
 616 been mapped by seismic reflection experiments with pure melt zones, inferred to  
 617 correspond to regions of fresh magma supply from the mantle asthenosphere, and  
 618 mush zones, inferred to have undergone cooling and crystallization and to be more  
 619 evolved (Singh et al., 1998). Significant temporal heterogeneities in the magma  
 620 plumbing system beneath this ridge were also suggested to account for the observed  
 621 differences between the geochemistry and petrology of the plutonic rocks recovered  
 622 from Hess Deep and Pito Deep (Perk et al., 2007). We suggest that such short  
 623 timescale changes of magma supply and subsequent thermal structure may influence  
 624 the lower crustal sub-axial deformation. The predominance of ODRs in the lower crust  
 625 during high magma delivery at the onset of seafloor spreading suggests that syn-  
 626 magmatic faults rooting at the Moho are a particularly efficient way for accommodating  
 627 space at the base of the crust in the hot axial zone in addition to new melt intrusions  
 628 (Fig. 8). The occurrence of CDRs on top of the ODRs and their progressive lengthening  
 629 and deepening up to the complete replacement of the ODRs while the magma supply  
 630 turns back to normal would then suggest that CDRs rather result from the compaction  
 631 and subsidence of the lower crust as it cools. This mode of spreading with somewhat  
 632 less magma supply is more likely to trigger vertical mass transport. Some of the CDRs  
 633 that reach locally the upper crust may thus indicate an episodic coupling of the upper  
 634 and lower crust when the magma budget/pressure is lower. Both ODRs and CDRs are  
 635 thus contemporaneous and participate to the hydrothermal cooling of the crust but their

636 extent could be related to the tradeoff between magma supply and tectonic  
637 deformation. This latter is probably relatively constant at the mature spreading center  
638 but may be variable at the onset of spreading.

## 639 **5. Conclusions**

640 The main results of our interpretation of high-quality seismic reflection profiles across  
641 the ocean-continent transition in the Enderby Basin, between the Kerguelen Plateau  
642 and the Antarctic margin, are as follows:

- 643 1. While lower crustal events dipping toward the paleo-ridge axis were  
644 predominantly described until now, we identified numerous both rideward and  
645 continentward dipping high-amplitude dipping reflectors in the lower oceanic  
646 crust;
- 647 2. We suggest that these lower crustal dipping reflectors correspond to syn-  
648 magmatic faults previously described in the Oman ophiolite;
- 649 3. Evidence for such syn-accretion tectonism at depth together with the systematic  
650 rotation of originally horizontal lava flows pre-dating the cessation of the  
651 magmatic activity argue for deformation within the axial zone of magmatic  
652 spreading centers.

653

## 654 **Acknowledgements**

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659 employees of Geoscience Australia. Gravity grid of Sandwell et al. (2014) is freely  
660 available from the website of the UCSD ([topex.ucsd.edu/cgi-bin/get\\_data.cgi](http://topex.ucsd.edu/cgi-bin/get_data.cgi)). We  
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664 National des Sciences de l'Univers INSU-CNRS.

## 665 **Figure captions:**

666 **Fig. 1:** Map of the eastern Enderby Basin. The background image is the free air gravity  
667 anomaly grid derived from satellite altimetry data (Sandwell et al., 2014). The black  
668 dashed line indicates the landward edge of the oceanic crust (LOC) after Gaina et al.  
669 (2007). The white dashed line indicates the presumed extinct ridge axis after Gibbons  
670 et al. (2013). The squares show the magnetic anomaly picks from Gibbons et al.  
671 (2013). The black lines indicate the seismic profiles from Geoscience Australia used in  
672 this paper. Their thickened and dashed parts correspond to the sections shown in  
673 **Fig. 3**. The white star indicates the location of **Fig. 6**. Ker., Kerguelen Island; CIR,  
674 Central Indian Ridge; SEIR, Southeast Indian Ridge; SWIR, Southwest Indian Ridge.

675 **Fig. 2:** Evidence of syn-magmatic normal faulting and block rotation at Moho level in  
676 the Oman ophiolite, Maqсад area (see also Abily et al. (2011)). (a) Simplistic sketches

677 illustrating the possible context of acquisition of the structures observed in the field  
678 (left) and the evolution in the conditions of deformation along the fault (right). (b) Main  
679 structural elements observed on this outcrop: magmatic layering (thin black lines);  
680 ductile faults (thick black lines and arrows), deformed crystal mush layer (red symbols).  
681 (c) Closer view on the zone of former crystal mush with complex modal layering  
682 induced by crystal sorting and melt injection during viscous deformation. (d) Detail on  
683 a pygmatic fold and on the upper horizon of pegmatite (former melt layer that made  
684 possible the mechanical decoupling between the tilted blocks of layered cumulates and  
685 the overlying cumulates).

686 **Fig. 3:** Line drawing of 4 seismic profiles across the landward edge of the oceanic crust  
687 (LOC indicated by the green band). Blue lines indicate oceanward dipping reflectors  
688 (ODRs); red ones indicate continentward dipping reflectors (CDRs); yellow ones show  
689 nearly horizontal reflectors and orange ones at the top basement indicate oceanic  
690 seawards dipping reflectors (OSDRs). The thick orange lines at the bottom of the crust  
691 show the reflection Moho and the black lines beneath it show where the Moho is  
692 continuous and highly reflective. The blue band indicates the ridgeward end of the  
693 dense network of ODRs occurring close to the LOC. Vertical exaggeration is  
694 approximately x2. Uninterpreted and interpreted versions of profiles 229/32 with no  
695 vertical exaggeration are shown in the **Electronic Supplement 1**.

696 **Fig. 4:** Examples of dipping reflectors crossing each other (a: profile 229/32 and b:  
697 profile 228/07) defining a layer of almost constant thickness at the base of the oceanic  
698 crust. The reflection Moho is well marked almost all along the bottom of the layer. See  
699 figure caption and location **in Fig. 3**. Approximately no vertical exaggeration. Copyright  
700 Commonwealth of Australia (Geoscience Australia).

701 **Fig. 5:** Example of reflectors that are observed both in the crust and in the mantle as  
702 deep as 11.5 s TWTT (line 229/33). Note some rare examples of dipping reflectors that  
703 are shallowing but do not reach the top basement as they are covered by long and  
704 continuous reflectors. See figure caption and location in **Fig. 3**. Approximately no  
705 vertical exaggeration. Copyright Commonwealth of Australia (Geoscience Australia).

706 **Fig. 6:** Example of oceanic seawards dipping reflectors (OSDRs) forming up to  
707 ~10 km-long wedges in the uppermost part of the crust (profile 229/31). Same figure  
708 caption as **Fig. 3**. See location in **Fig. 1**. Approximately no vertical exaggeration.  
709 Copyright Commonwealth of Australia (Geoscience Australia).

710 **Fig. 7:** Denser network of oceanward dipping reflectors (ODRs) and continentward  
711 dipping reflectors (CDRs) (1 reflector every ~500 m) close to the landward edge of the  
712 oceanic crust (profile 229/32). Vertical exaggeration is approximately 2x. See figure  
713 caption and location in **Fig. 3**. Copyright Commonwealth of Australia (Geoscience  
714 Australia).

715 **Fig. 8:** Cartoon of the structure of the oceanic ridge showing the formation of dipping  
716 reflectors by sub-axial deformation (CDR, continentwards dipping reflectors; ODR,  
717 oceanwards dipping reflectors; OSDR, oceanic seaward dipping reflectors). Oblique  
718 reflectors in the lower crust are syn-magmatic faults. Isotherms (dotted blue lines) and  
719 hydrothermal circulation paths (green line) are schematic. AML: axial melt lens. No  
720 vertical exaggeration.

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