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► **To cite this version:**

A. Corbalán, M. Nedimović, K. Louden, M. Cannat, I. Grevemeyer, et al.. Seismic Velocity Structure Along and Across the Ultraslow-Spreading Southwest Indian Ridge at 64°30'E Showcases Flipping Detachment Faults. *Journal of Geophysical Research: Solid Earth*, 2021, 126 (10), 10.1029/2021JB022177 . hal-03359315

HAL Id: hal-03359315

<https://hal.science/hal-03359315v1>

Submitted on 4 Oct 2021

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1 **Seismic Velocity Structure Along and Across the Ultraslow-Spreading Southwest**
2 **Indian Ridge at 64°30'E Showcases Flipping Detachment Faults**

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16 **Key Points:**

- 17
- 18 • First detailed 2D regional P-wave velocity models across and along an ultraslow-
19 spreading Southwest Indian Ridge amagmatic segment
 - 20 • A system of flipping detachments is imaged in the subsurface for the first time
21 constrained by the velocity structure
 - 22 • Lithosphere gradually transitions from highly fractured and fully serpentinized peridotites
at the top to unaltered peridotites at depth

23 **Abstract**

24 We present two ~150-km-long orthogonal 2-D P-wave tomographic velocity models across and
25 along the ridge axis of the ultraslow-spreading Southwest Indian Ridge at 64°30'E. Here,
26 detachment faults largely accommodate seafloor accretion by mantle exhumation. The velocity
27 models are constructed by inverting first arrival traveltimes recorded by 32 ocean bottom
28 seismometers placed on the two profiles. The velocities increase rapidly with depth, from 3–3.5
29 km/s at the seafloor to 7 km/s at depths ranging from 1.5–6 km below the seafloor. The vertical
30 gradient decreases for velocities >7 km/s. We suggest that changes in velocity with depth are
31 related to changes in the degree of serpentinization and interpret the lithosphere to be composed
32 of highly fractured and fully serpentinized peridotites at the top with a gradual downward
33 decrease in serpentinization and pore space to unaltered peridotites. One active and five
34 abandoned detachment faults are identified on the ridge-perpendicular profile. The active axial
35 detachment fault (*DI*) shows the sharpest lateral change (horizontal gradient of $\sim 1 \text{ s}^{-1}$) and
36 highest vertical gradient ($\sim 2 \text{ s}^{-1}$) in the velocities. In the western section of the ridge-parallel
37 profile, the lithosphere transitions from non-volcanic to volcanic over a distance of ~ 10 km. The
38 depth extent of serpentinization on the ridge-perpendicular profile ranges from ~ 2 -5 km, with the
39 deepest penetration at the *DI* hanging wall. On the ridge-parallel profile, this depth (~ 2.5 -4 km)
40 varies less as the profile crosses the *DI* hanging wall at ~ 5 -9 km south of the ridge axis.

41 **Plain Language Summary**

42 We investigate the Southwest Indian Ridge lithosphere at 64°30'E, where the Somalian and
43 Antarctic plates move slowly away from each other at less than 14 mm/year. This is one of a
44 limited number of places on Earth where mantle is currently being exhumed to the seafloor. We
45 use seismic sensors, placed across and along the ridge axis, to analyze how seismic waves travel
46 from the energy sources, through the lithosphere, to these sensors. Our results, in the form of
47 two-dimensional velocity models, show that the rock velocities increase rapidly with depth.
48 Lateral and vertical velocity changes delimit a system of detachment faults on the ridge-
49 perpendicular profile, responsible for bringing mantle-derived rocks, peridotites, up to the
50 seafloor. Based on the modeled velocities and velocity changes, and previous extensive seafloor
51 sampling, we suggest that $\sim 75\%$ of the lithosphere in the study area is composed of highly
52 fractured and fully hydrothermally altered peridotites at the top with a gradual downward
53 decrease in alteration and pore space to unaltered peridotites at depth. We also locate the
54 transition to lithosphere with a magmatic component in the western section of the ridge-parallel
55 profile.

56 **1 Introduction**

57 The global mid-ocean ridge system consists of spreading centres that greatly differ from
58 each other in their spreading rate, spreading obliquity, melt supply and modes of seafloor
59 accretion. Oceanic ridges are normally classified by their full-spreading rate as fast- (~ 80 –180
60 mm/yr), intermediate- (~ 55 –70 mm/yr), slow- (20-55mm/yr), and ultraslow-spreading (< 20
61 mm/yr) (Dick et al., 2003). The scientific community has invested significant effort into studying
62 the oceanic crust formed at fast- (e.g. Aghaei et al., 2014; Canales et al., 2003; Detrick et al.,
63 1993; Dunn & Toomey, 2001; Grevemeyer et al., 1998; Han et al., 2014; Vera & Diebold, 1994),
64 intermediate- (e.g. Canales et al., 2005; Carbotte et al., 2006, 2008; Nedimović et al., 2005,
65 2008; Newman et al., 2011; Weekly et al., 2014) and slow-spreading rates (e.g. Arnulf et al.,

66 2012; Barclay et al., 1998; Christeson et al., 2020; Dannowski et al., 2010; Escartín & Canales,
67 2011; Estep et al., 2019; Kardell et al., 2019; Seher et al., 2010, Xu et al., 2020). Less effort has
68 been directed toward studying the lithosphere formed at ultraslow-spreading ridges, which thus
69 remains relatively less well understood. Yet, the ultraslow-spreading centers constitute about
70 35% of the global ridge system (Dick et al., 2003). The comparatively smaller effort put toward
71 understanding the lithosphere at ultra-slow ridges is partially a consequence of their remoteness
72 and inaccessibility, as these ridges are located in the Arctic (Gakkell Ridge, Knipovich Ridge,
73 Mohns Ridge, and Kolbeinsey Ridge) and Indian Oceans (Southwest Indian Ridge - SWIR)
74 (Argus et al., 2011; Bird, 2003; Kreemer et al., 2014; Müller et al., 2008).

75 Early controlled-source seismic surveys (e.g. Ewing & Ewing, 1959; Houtz & Ewing,
76 1976; Peterson et al., 1974; Raitt, 1963; Talwani et al., 1965, 1971), in situ rock investigations
77 and laboratory velocity measurements on rock samples (e.g. Carlson & Miller, 1997, 2003;
78 Christensen, 1972; Christensen & Salisbury, 1975; Miller & Christensen, 1997), and ophiolite
79 studies (e.g. Christensen, 1978; Christensen & Smewing, 1981) suggest an oceanic crustal
80 structure composed of three seismically identifiable layers that often correspond, from top to
81 bottom, to an extrusive basaltic lava layer (Layer 2A), a sheeted diabase dike layer (Layer 2B),
82 and a Layer 3 comprised of isotropic gabbros at the top and layered gabbros at the bottom
83 topping the uppermost mantle. However, the seismic boundaries do not necessarily correspond to
84 lithological boundaries. For instance, the layer 2A/2B boundary, which is thought to be an
85 alteration front or a major change in porosity, may or may not correspond to a change in
86 lithology (e.g. Berge et al., 1992; Carbotte and Scheirer, 2004; Christeson et al., 2007; Wilcock
87 et al., 1992). Igneous mafic layers 2A, 2B and 3 are often distinguished according to their
88 commonly associated velocity and thickness ranges, as well as their vertical velocity gradients
89 (Christeson et al., 2019; Grevemeyer et al., 2018a; White et al., 1992). However, identified
90 outcrops of exposed mantle-derived peridotites on the seafloor at slow- and ultraslow-spreading
91 ridges (e.g. Blackman et al., 2002; Cannat et al., 2006; Dick et al., 2008; Ildefonse et al., 2007)
92 have challenged the 3-layer paradigm at slower spreading rates. Moreover, sampling of the
93 seafloor at the SWIR has nearly exclusively (~90%) recovered serpentinized peridotites (Sauter
94 et al., 2013) suggesting the total absence of continuous igneous mafic layers at the sampled
95 locations.

96 Exhumed mantle seafloor exposures are generally associated with detachment faults (e.g.
97 Canales et al., 2004; Cannat, 1993; Sauter et al., 2013; Tucholke & Lin, 1994) and Oceanic Core
98 Complexes (OCCs) at slow- and ultraslow-spreading ridges (e.g. Dick et al., 2019; Escartín et
99 al., 2003; Sauter et al., 2013; Smith et al., 2006; Zhao et al., 2013; Zhou & Dick, 2013).
100 Widespread detachment faulting indeed plays a central role in oceanic lithosphere accretion and
101 plate divergence accommodation at melt-poor ridge sections of slow- and ultraslow-spreading
102 ridges (Cann et al., 1997; Cannat et al., 2006; Escartín et al., 2008; Sauter et al., 2013; Smith et
103 al., 2006), particularly at segment ends as magma is focused toward the segment centers (Lin et
104 al., 1990) and thus is scarce at the ends. At the slow-spreading Mid-Atlantic Ridge (MAR), the
105 mode of asymmetrical accretion along detachment faults can last for 1–3 Myr (Tucholke et al.,
106 1998) while at the SWIR continuous exhumation of mantle-derived rocks has been occurring
107 during the last ~11 Myr in a flip-flop detachment faulting mode (Sauter et al., 2013). Steep long-
108 offset normal faults rotate and flatten as footwall flexural bending occurs exposing the ultramafic
109 mantle peridotites on the detachment surface (deMartin et al., 2007; Dick et al., 2010; Escartín et
110 al., 2003; Ildefonse et al., 2007; Smith et al., 2006; Tucholke et al., 1998). These long-offset

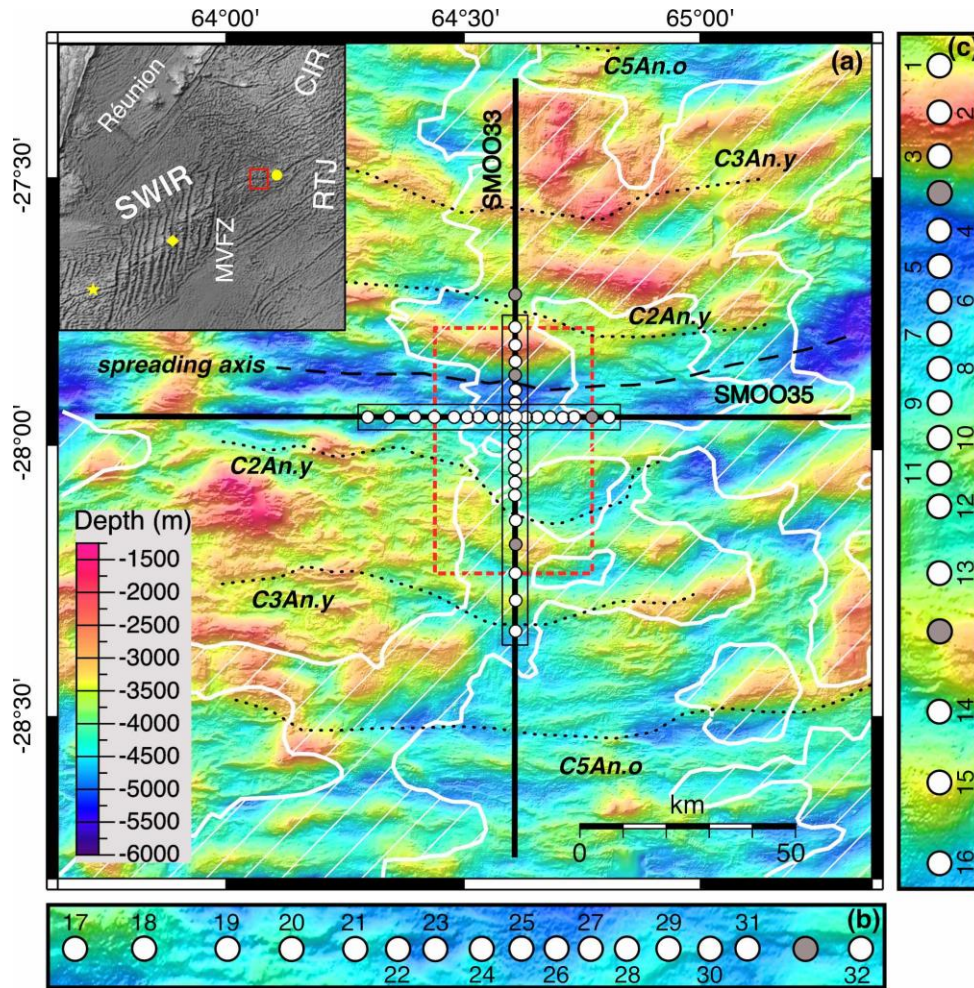
111 normal faults root on a steeply dipping ($\sim 70^\circ$) interface (deMartin et al., 2007; Parnell-Turner et
112 al., 2017) at depths up to 20 km (Bickert et al., 2020; Schlindwein & Schmid, 2016).

113 The exhumed peridotites become hydrothermally altered when in contact with seawater.
114 Peridotite-seawater interactions release large amounts of methane and hydrogen to the water
115 column (Alt et al., 2009; Mével, 2003) making serpentinization relevant to the emergence and
116 thriving of unique microbial communities (e.g. Früh-Green et al., 2018; Kelley et al., 2005;
117 Schrenk et al., 2004). Serpentinization also plays a crucial role in the detachment faulting and
118 favors the development of large-offset low-angle detachment faults (Ildefonse et al., 2007;
119 Lavier et al., 1999; Tucholke et al., 1998). New steep normal faults may initiate and become the
120 new master detachment faults with the same or reverse polarity (e.g. Reston & McDermott,
121 2011; Sauter et al., 2013). Successive detachment faults that change polarity develop a flip-flop
122 fault mode (Bickert et al., 2020; Reston, 2018; Sauter et al., 2013) and reveal exhumed mantle
123 domains in this process on both sides of the spreading axis (Cannat et al., 2019; Reston, 2018;
124 Sauter et al., 2013). What causes the abandonment of a fault and the initiation of a new master
125 fault with opposite polarity is still under debate.

126 Coincident multichannel seismic (MCS) reflection and wide-angle ocean bottom
127 seismometer (OBS) refraction surveys at ultraslow-spreading ridges are critical to understanding
128 the crustal and uppermost mantle structure, the faulting dynamics associated with divergence,
129 and the mechanisms of seafloor accretion. Seismic surveys at ultraslow-spreading ridges beyond
130 the SWIR include work done at the Knipovich (Kandilarov et al., 2008, 2010), Mohns
131 (Klingelhöfer et al., 2000), Gakkel (Jokat & Schmidt-Aursch, 2007), and Mid-Cayman (Van
132 Avendonk et al., 2017; Grevemeyer et al., 2018b) spreading centers. At the SWIR, large efforts
133 have been focused on the Dragon Flag OCC at $49^\circ 39' E$ (e.g. Zhao et al., 2013), the anomalously
134 thick magmatic crust inferred at $50^\circ 28' E$ (e.g. Jian et al., 2017; Li et al., 2015), the Atlantis II
135 Fracture Zone at $57^\circ E$ (e.g. Muller et al., 1997, 2000), the non-volcanic seafloor exposures at
136 $64^\circ 30' E$ (e.g. Momoh et al., 2017), and the mafic crustal structure at $66^\circ E$ (e.g. Minshull et al.,
137 2006).

138 In the Fall of 2014, French and Canadian scientists collaborated on the marine
139 geophysical project SISMO-SMOOTH (Leroy & Cannat, 2014) aboard the R/V Marion-
140 Dufresne to carry out a major 2D and 3D MCS and OBS survey across the SWIR at $64^\circ 30' E$
141 (Fig. 1), one of the geologically most sampled areas of the ultra-slow spreading seafloor. This
142 location was also selected because, albeit remote, it does not have ice floes like the ridges in the
143 Arctic Ocean, which allows for low-risk use of long MCS streamers and large groups of OBSs.
144 The main goal of the SISMO-SMOOTH project was to determine the seismic reflection and
145 velocity structure of an ultraslow-spreading ridge to investigate the geophysical fingerprints of
146 variably serpentinized mantle peridotites, map the lithospheric fabric, and better understand the
147 mantle exhumation dynamics, all in an area where the mode of oceanic lithosphere accretion has
148 been interpreted to form broad exposures of exhumed mantle (Cannat et al., 2006). The first
149 results from the analysis of the collected data were focused on the 2D and 3D MCS reflection
150 imaging (Momoh et al., 2017, 2020). Here, we present the results from a tomographic analysis of
151 two orthogonal ~ 150 -km-long OBS profiles, the north-south (NS) profile that is perpendicular to
152 the spreading axis (SMOO33; Figs. 1a and 1c) and the east-west (EW) that is subparallel to it
153 (SMOO35; Figs. 1a and 1b). The seismic velocity structure imaged along these two profiles
154 provides new information on the subsurface expression of the detachment fault system, including
155 the distribution of the detachment faults, the degree of exhumed mantle serpentinization and its

156 anisotropy, and the east-west transition from predominantly exhumed mantle to more magma-
 157 rich lithosphere.



158
 159 **Figure 1.** (a) Two regional orthogonal OBS profiles NS (SMOO33) and EW (SMOO35) from
 160 the SISMO SMOOTH Survey (Leroy et al., 2015) overlay a bathymetry map (color background;
 161 Cannat et al., 2006; Momoh et al., 2017). Thick black lines outline shot locations, and white and
 162 gray circles with black outlines are the positions of OBS instruments that did and did not provide
 163 useful data, respectively. The shooting distance inside the dashed red rectangle is 150 m and
 164 outside 300 m. Dashed black line shows the spreading axis location. Dotted black lines indicate
 165 the magnetic anomalies isochrons C2An.y (2.581 Ma), C3An.y (5.894 Ma), and C5An.o (10.949
 166 Ma) (Cande & Kent, 1995; Cannat et al., 2006; Sauter et al., 2008; Reston, 2018). Areas filled
 167 with inclined thin white lines and bounded by thick white lines delimit the smooth non-volcanic
 168 seafloor (Cannat et al., 2019). Inset in the top left shows the location of the Southwest Indian
 169 Ridge (SWIR) relative to the Réunion Island, the Central Indian Ridge (CIR), the Melville
 170 Fracture Zone (MVFZ), and the Rodriguez Triple Junction (RTJ). Red rectangle shows the limits
 171 of the study area presented in the main figure. The yellow star, diamond and circle indicate the
 172 locations of earlier SWIR investigations at 50°E, 57°E and 66°E, respectively. (b, c)
 173 Magnifications of the main map within thin black rectangles show positions of the OBS

174 instruments along the EW (b) and NS (c) profiles. Only the OBS with useful data are
175 sequentially numbered, first in NS and then EW direction.

176 **2 Study area**

177 The SWIR is an ultraslow-spreading center (Dick et al., 2003; Sauter & Cannat, 2010)
178 with a full spreading rate of <14 mm/year (Kreemer et al., 2014). Variations in melt-supply,
179 mantle thermal and compositional heterogeneities, and changes in spreading obliquity along this
180 ridge result in significant large-scale variations of the accreted lithosphere (Cannat et al., 2008).
181 For instance, the easternmost SWIR, east of the Melville Fracture Zone (61°E) and west of the
182 Rodriguez Triple Junction (70°E), is considered to be an endmember in the global ridge system
183 where the interplay between plate- and mantle-driven processes results in a thin or absent mafic
184 igneous crust with a complex relationship between intermittent volcanic edifices, corrugated
185 volcanic seafloor and extensive exhumed mantle domains (Cannat et al., 2003, 2006). At 66°E
186 the mafic igneous crust is estimated to be 2.2-5.4 km thick (Minshull et al., 2006), less than the
187 global average of ~6 km (Chen, 1992; Christeson et al., 2019), while the SWIR at 50°28'E shows
188 an anomalously thick (~9.5 km) crust (Jian et al., 2016). At 64°30'E, which is at the center of our
189 study area (Fig. 1), the SWIR exhibits the widest non-volcanic seafloor documented thus far
190 (Cannat et al., 2006) with on-axis volcanic centres inferred to the east and west (Cannat et al.,
191 2003; Schlindwein & Schmid, 2016).

192 In the last two decades, several surveys have focused on studying the SWIR at 64°30'E
193 and have used gravity (Cannat et al., 2006), magnetics (Sauter et al., 2008) and side-scan sonar
194 (Sauter et al., 2013) to identify and map the extension of these non-volcanic seafloor domains
195 (Fig. 1a) known as “smooth-seafloor” (Cannat et al., 2006). Variably serpentinized mantle-
196 derived rocks, peridotites, are the dominant lithology at the “smooth-seafloor” (Sauter et al.,
197 2013) and coincide with high residual mantle Bouguer gravity anomaly (RMBA; 30–50 mGal)
198 (Cannat et al., 2006). The seafloor topography is characterized by rounded broad ridges with a
199 height ranging from 500 to 2000 m and a length ranging from 15 to 90 km (Cannat et al., 2006,
200 2019). Sixteen dredges collected across-axis in the amagmatic corridor of the SWIR at 64°30'E
201 nearly exclusively recovered variably serpentinized peridotites with a minor amount (<5%) of
202 basalts and gabbros (Sauter et al., 2013). Oxygen isotope analyses on these samples suggest
203 relatively high serpentinization temperatures (271–366°C) and in-situ and bulk-rock analyses of
204 the samples support seawater as the serpentinizing fluid, ruling out leaching of basalts or gabbros
205 (Rouméjon et al., 2014). Moreover, the scarcity of melt products is expected as a result of the
206 very low melt supply inferred in the area based on large axial depth and high mean basalt sodium
207 content (Cannat et al., 2008; Meyzen et al., 2003; Seyler et al., 2003).

208 Momoh et al. (2017) studied the 3D seismic reflection structure at the SWIR at 64°30'E
209 and suggested that the uppermost lithosphere consists of a 4–5 km thick layer mostly composed
210 of serpentinized peridotites with a small proportion of igneous rocks derived from occasional and
211 incipient magmatism. Two main packages of seismic reflectors are imaged across the ridge axis:
212 (1) a group of subparallel reflectors dipping south at 50–60° in the footwall and (2) a group of
213 north dipping reflectors in the hanging wall of the active detachment fault (Momoh et al., 2017).
214 The former are interpreted to be related to the damage zone of the active axial fault, and the latter
215 are suggested to represent either the damage zone of a previously active fault's footwall or to be
216 related to recent tectonic extension occurring on the hanging wall. Similarly, Momoh et al.
217 (2020) proposed that the crustal-type seismic velocities are related to extensive tectonic damage

218 and hydrothermal alteration of both peridotites and occasional intruding gabbros.
219 Serpentinization and incipient magmatism are thought to occur in two successive phases: first
220 when mantle-rocks are exhumed on the active detachment fault footwall and later when these
221 rocks constitute the hanging wall of the next detachment fault (Cannat et al., 2019; Momoh et al.,
222 2020).

223 Microseismicity studies have constrained a thick (20–25 km) brittle lithosphere in the
224 vicinity of our study area (Schlindwein & Schmid, 2016). As a consequence of the virtually-zero
225 melt supply, the seafloor is largely created by successive, flipping polarity, detachment faults
226 that form broad unroofed mantle domains both north and south of the spreading axis (Cannat et
227 al., 2006, 2019; Sauter et al., 2013; Reston, 2018). Active and abandoned detachment fault
228 surfaces have been imaged with side-scan sonar at the SWIR at 64°30'E (Sauter et al., 2013) and
229 seismic reflectors associated with the currently active axial detachment fault have been observed
230 in 3D MCS data (Momoh et al., 2017). Numerical models have demonstrated that a combination
231 of serpentinization and grain size reduction in thick brittle lithosphere can generate flip-flop
232 detachment faulting (Bickert et al., 2020). Detailed bathymetric and kinematic analysis have
233 been carried out to investigate the emergence and breakaway of the interpreted faults and explain
234 the mantle exhumation dynamics at detachment-dominated spreading ridges (Cannat et al., 2019;
235 Reston, 2018). Still lacking, however, is a well-resolved regional-scale velocity model capturing
236 these detachment faults, active and abandoned, to back up or rebut the proposed lithospheric
237 accretion models.

238 **3 Data acquisition and analysis**

239 **3.1 Seismic experiment**

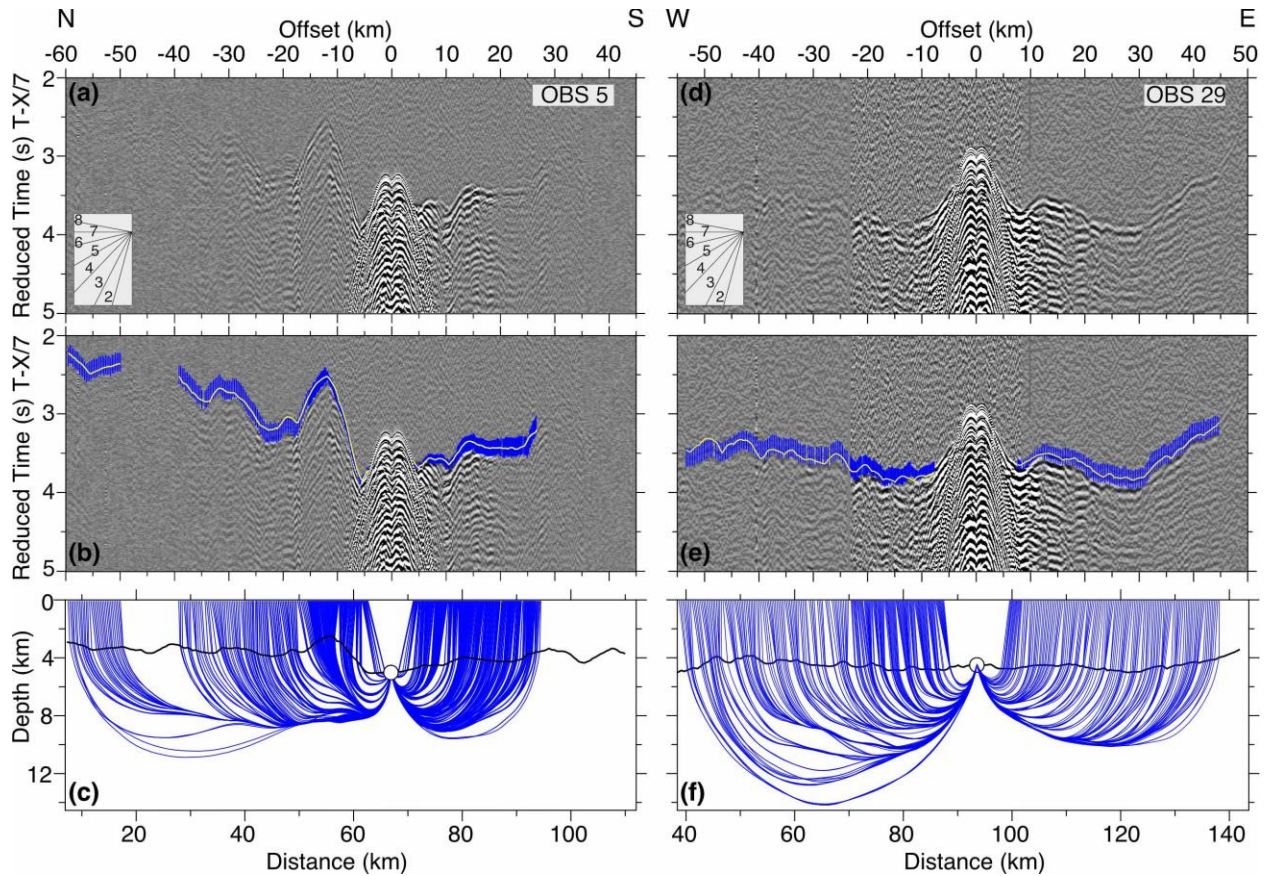
240 The MD 199 - SISMO-SMOOTH Cruise 2014 (Leroy & Cannat, 2014; Leroy et al.,
241 2015) in the easternmost SWIR collected a variety of datasets including pseudo-3D MCS
242 (Momoh et al., 2017), 2D MCS (Momoh et al., 2020), 3D wide-angle OBS, and 2D wide-angle
243 OBS. The 3D MCS and 3D OBS data are focused in narrow (1.8x24 km and 20x30 km,
244 respectively) rectangles at the ridge axis, while the 2D profiles extend ~150 km across and along
245 the spreading axis. In this paper, we show and interpret the results from analysis of the regional
246 2D OBS wide-angle data set (Fig. 1). Shots for the 3D MCS survey recorded by OBSs 4-13 on
247 the NS profile (Fig. 1) were used by Momoh et al. (2017) to form a simple velocity model for
248 migration of the reflection signal. However, none of the regional 2D OBS shots recorded by the
249 32 OBSs on the NS and the EW profile (Fig. 1), which provide a far greater source-receiver
250 offset range and crossing ray area that are needed for extracting high-quality detailed velocity
251 information, have been analyzed prior to this study.

252 The seismic source consisted of two linear arrays of 7 air guns towed at an average depth
253 of 14 m with a total nominal volume of 6790 in³. Three different types of short-period OBS were
254 used to record the wide-angle data: 16 Canadian OBSs from Dalhousie University, 7 French
255 OBSs from the Institut National des Sciences de l'Univers du CNRS, and 9 micro OBSs from the
256 National Central University of Taiwan. All the OBSs recorded continuously at a sampling rate of
257 250 Hz (4 ms) with one hydrophone and a 3 orthogonal component geophone. The OBS spacing
258 ranges from 3 to 10 km. For presentation purposes, OBS names used during the survey were
259 converted to sequential numbers (Fig. 1; Table S1). OBSs north of OBS 1, and between OBSs 3
260 and 4, OBSs 13 and 14, and OBSs 31 and 32 were lost during the survey or recorded unusable

261 data. The white circles in Figure 1 are the 32 OBS instruments used for the modeling. These
262 OBSs form the two ~150 km long wide-angle seismic profiles. The EW profile (SMOO35) lies
263 in the spreading axis direction, and the NS profile (SMOO33) is orthogonal to and crosses the
264 spreading axis (Fig. 1a). The NS profile cuts through the inferred detachment faults and
265 practically all of its OBSs lie within the previously mapped smooth seafloor. The EW profile is
266 presumed to transition from volcanic seafloor in the west to exhumed mantle at the seafloor in
267 the east.

268 3.2 Data processing

269 The OBSs were relocated to their true positions on the seafloor (more information in
270 Supporting Information) and the data were bandpass filtered using a minimum phase trapezoidal
271 band-pass filter with corner frequencies 1-5-18-25 Hz. PASTEUP software (Fujie et al., 2008)
272 was used to manually pick the first break of arrivals on the OBS records. Two examples of OBS
273 gathers for the NS and the EW profiles, with and without picks, are shown in Figure 2. More
274 examples are shown in Supporting Information (Figs. S1-S4). The picking was carried out on
275 unfiltered data as much as possible, with the filtered data used only to extend the picks to further
276 offsets. Where first arrivals are not clear at long offsets, arrivals of the first water multiple were
277 picked where possible and then time-shifted until picks from the multiple for near and/or mid
278 offsets coincided with equivalent picks for the first arrivals. The 2D bathymetry from a previous
279 multibeam survey (Cannat et al., 2006) was plotted in a separate window above the OBS data
280 window as a function of model distance and source-receiver offset to help guide the picking
281 process and identify seafloor diffractions. First arrivals were picked to offsets of up to ~90 km
282 along the NS profile, and ~60 km along the EW profile. Assigned pick uncertainty is offset
283 dependent as follows: 30 ms for high-quality waveforms at offsets <6.5 km; 60 ms for offsets
284 between 6.5 km and 12 km; 100 ms for offsets between 12 km and 20 km; 120 ms for offsets
285 >20 km; and 150 ms for time-shifted multiple arrival picks. A total of 6,523 and 4,193 first
286 arrival picks were made for the NS and the EW profile, respectively. Secondary arrivals, such as
287 Moho reflections, were not found in the OBS records, and sediment arrivals were negligible.



288

289 **Figure 2.** Example OBS gathers for the NS and EW profiles (a and d) are shown together with
 290 related first arrival traveltimes picks (b and e) and calculated ray paths (c and f). (a) Hydrophone
 291 data for OBS 5 on the NS profile and (d) vertical geophone data for OBS 29 on EW profile after
 292 application of a reduction velocity of 7 km/s and band-pass filtering (1-5-18-25 Hz). Insets show
 293 the linear moveout of different phase velocities in km/s. (b and e) Same as a and b but with
 294 picked (centers of blue error bars) and modeled (yellow curves) first arrival traveltimes
 295 superimposed. Synthetic traveltimes and raypaths were computed by ray tracing through the final
 296 velocity model. (c and f) Raypath diagram for the modeled first arrival traveltimes in b and e.
 297 Black thick line is the seafloor and white circles with thin black outlines show the OBS
 298 locations.

299

3.3 Traveltime tomography

300

We performed P-wave traveltime tomography using TOMO2D (Korenaga et al., 2000).
 301 Traveltimes of P-wave first refracted arrivals and later Moho reflection arrivals (*PmP*) are
 302 commonly used for joint inversion of the regional 2D velocity structure in a sheared mesh model
 303 hung from the seafloor (e.g. Watremez et al., 2015). We, however, do not model the Moho
 304 reflector because of the lack of *PmP* arrivals in the data. In the TOMO2D method, forward
 305 modeling is first applied to find the shortest raypath from the shot to the receiver for each arrival,
 306 followed by a least-squares regularized inversion, in which the starting velocity model is
 307 perturbed and updated until the targeted chi-squared (χ^2) or the set number of maximum
 308 iterations is reached (Korenaga et al., 2000). Application of smoothing and optional damping
 309 constraints is used to regularize the iterative inversion process (Korenaga et al., 2000). Thus,

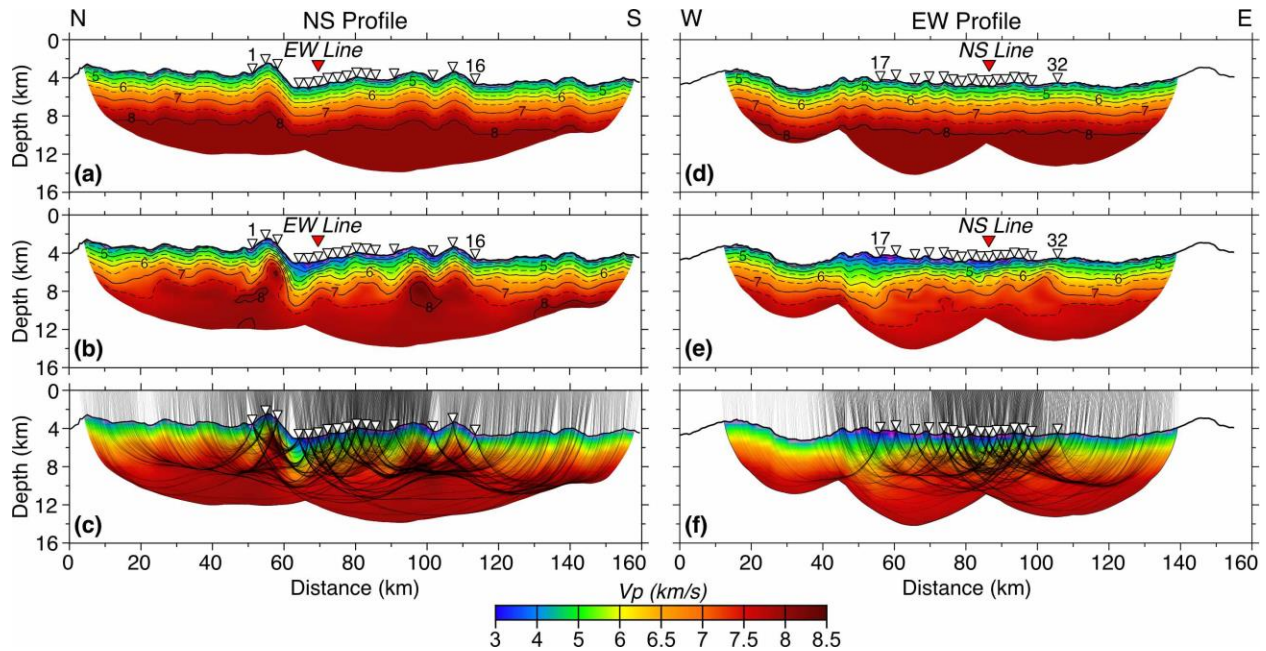
310 damping and smoothing weighting factors control the data fitting and the smoothness of the
311 model, and similarly, the correlation lengths for the velocity nodes control the inversion stability.
312 The final TOMO2D product is a minimum-structure smooth velocity model, meaning that
313 minimum a priori information is used to resolve the minimum or simplest structure needed to
314 explain the data. This approach reduces subjective input from the interpreter in the development
315 of the final tomographic model.

316 Cells in our models, which are 160 km long and 30 km deep, are 1 km wide and 500 m
317 high. The starting 1D velocity model is based on the 1D average velocity of Momoh et al. (2017)
318 and the average velocity structure reported at other ultraslow-spreading centers bearing
319 serpentinized mantle domains (e.g. Grevemeyer et al., 2018b; Van Avendonk et al., 2017). We
320 opted for simplicity and, after taking into consideration the expected geology, settled on a 1D
321 starting velocity model with 3 velocity-depth points: 4 km/s velocity at the seafloor, 6.5 km/s at 2
322 km depth below the seafloor (dbsf), and 8.0 km/s at 5 km dbsf. For consistency, the same 1D
323 starting velocity model extended in 2D by hanging it off the seafloor was used for both
324 orthogonal profiles. Figures 3a and 3d show the starting velocity model extended in 2D for both
325 the NS and EW profile, respectively. For the NS profile, the starting velocity model produced a
326 χ^2 of 11.97 and an RMS traveltimes residual of 208 ms. For the EW profile, it produced a χ^2 of
327 15.37 and an RMS traveltimes residual of 261 ms. We set our inversion to run 5 iterations and use
328 the same parametrization values for both profiles to prevent modeling inconsistencies (more
329 information in Supporting Information).

330 **4 Results**

331 4.1 Velocity models

332 Figure 3b shows the final velocity model for the NS profile. The model is shown over the
333 areas with ray coverage and the calculated raypaths are shown in Figure 3c overlaying the final
334 velocity model. The model converges to an RMS traveltimes residual of 53 ms and a χ^2 of 1.10.
335 Similarly, the final velocity model of the EW profile is shown in Figure 3e and the calculated
336 raypaths are shown in Figure 3f. The EW model converges to an RMS traveltimes residual of 55
337 ms and a χ^2 of 0.86. Figure S5 shows the evolution of χ^2 as a function of iteration number for
338 both models. Most of the lateral and vertical velocity variations are found in the central parts of
339 the models, below the areas covered by the OBSs, and therefore in the areas where there are
340 crossing raypaths (Figs. 3c and 3f). Toward the profile ends, which are sections covered by shots
341 but no OBSs, or sections with no crossing raypaths, the velocity structure in the final models
342 mostly follows the seafloor topography and the starting velocity models.



343

344 **Figure 3.** Results from first arrival traveltimes tomographic inversion of the NS and EW profiles:
 345 (a, d) Starting velocity models; (b, e) final tomographic models; (c, f) raypaths (black lines) of
 346 the first arrivals traced through the final velocity models (b, e), for the NS and EW profiles,
 347 respectively. Iso-velocity contours are shown every 0.5 km/s in (a, b, d and e); solid black at
 348 every km/s and dashed in between. White inverted triangles show the positions of the OBSs on
 349 the seafloor. Red triangles show the location at which the profiles cross each other.

350 Traveltimes are well fitted at all model distances (Figs. S6a and S6b) with the majority of
 351 traveltimes residuals, calculated as the difference between the observed and calculated
 352 traveltimes, reduced by the inversion to ± 60 ms (Figs. S6c and S6d).

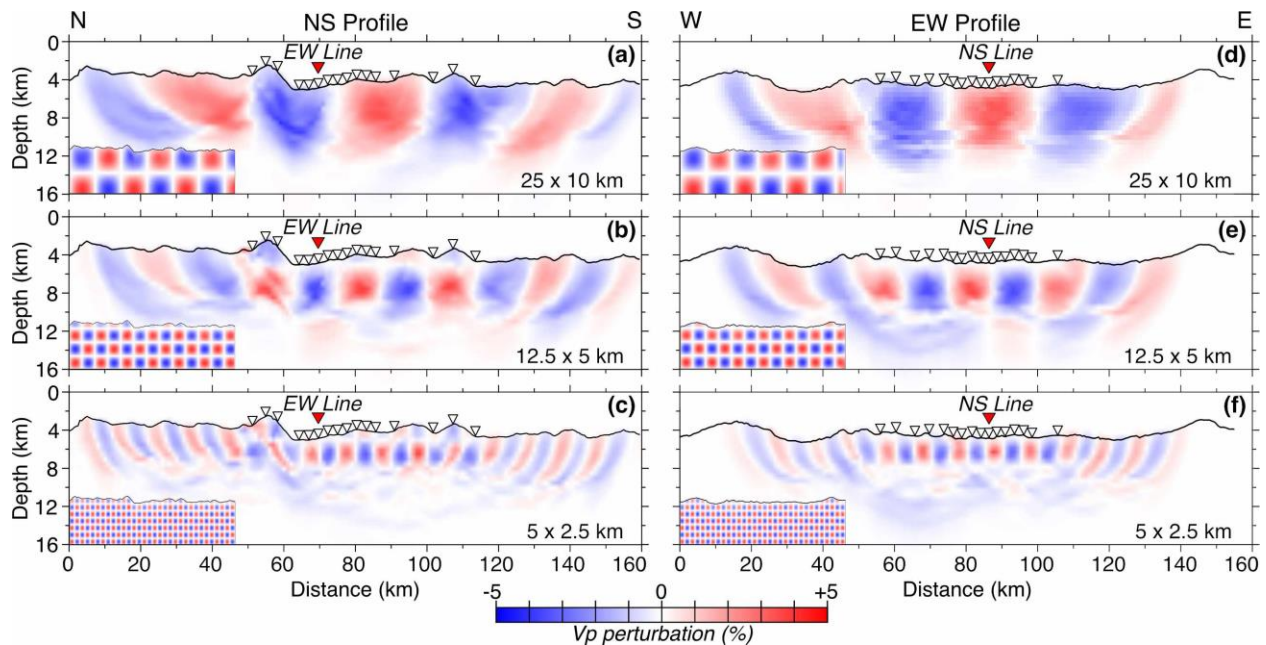
353 The final velocity models (Figs. 3b and 3e) show that seismic velocities increase rapidly
 354 with depth with velocities ranging from ~ 3.5 km/s at the seafloor to 7 km/s at 1.5–5.5 km dbfsf at
 355 the NS profile, and from ~ 3 km/s at the seafloor to 7 km/s at 2–6 km dbfsf at the EW profile. The
 356 NS profile reaches velocities in the range of 7.8–8.4 km/s, while the EW profile only reaches
 357 velocities in the range of 7.6–7.8 km/s. The NS profile shows greater lateral changes in the
 358 velocities than the EW profile, including a sharp lateral change (horizontal gradient of ~ 1 s $^{-1}$ at
 359 ~ 62 km model distance) at the highest topographic feature. Within the area of OBS coverage, the
 360 EW profile also shows a smooth trend of increasing velocities toward the East, which is
 361 accentuated between OBSs 30 and 32. Similarly, a distinct increase in the velocities is observed
 362 between OBSs 17 and 18. Both profiles show high vertical velocity gradient (velocity contours
 363 closely spaced) in upper sections of the models (velocities < 7 km/s) and a considerably lower
 364 vertical gradient (sparse velocity contours) in deeper sections (velocities > 7 km/s).

365 4.2 Uncertainty assessment

366 4.2.1 Checkerboard Tests

367 We assess the resolution of our models with checkerboard tests as follows. Checkerboard
 368 patterns for a set of different horizontal and vertical cycle lengths with a $\pm 5\%$ periodic velocity
 369 perturbation are added to our two final velocity models. The chosen cell widths and heights are:

370 25x10 km (Figs. 4a and 4d), 12.5x5 km (Figs. 4b and 4e), and 5x2.5 km (Figs. 4c and 4f). The
 371 perturbed velocity models are used as the starting velocity models for the inversions. The
 372 recovered perturbations are obtained by subtracting the input velocity models from the
 373 corresponding final inverted velocity models for different cell sizes. The extent of perturbation
 374 recovery at any particular section of our models is a measure of resolvability of corresponding
 375 velocity anomalies for that model area. The input and inverted perturbation models are compared
 376 for the two profiles in Figure 4. Full-size checkerboard test figure is included in the SI (Fig. S7).
 377 Large structures are resolved across the profiles where there is any ray coverage (Figs. 4a and
 378 4d). Structures 12.5 km wide and 5 km high are resolved in the areas below the seafloor
 379 encompassing the first and last OBS location to depths of ~ 5 km. In these central areas,
 380 structures as small as 5x2.5 km are also resolved but the depth or resolvability below the seafloor
 381 is reduced to ~ 2 – 3 km. In all the checkerboard tests, the resolved cells are smeared toward
 382 profile ends and with increasing depth, with the resolution progressively declining.

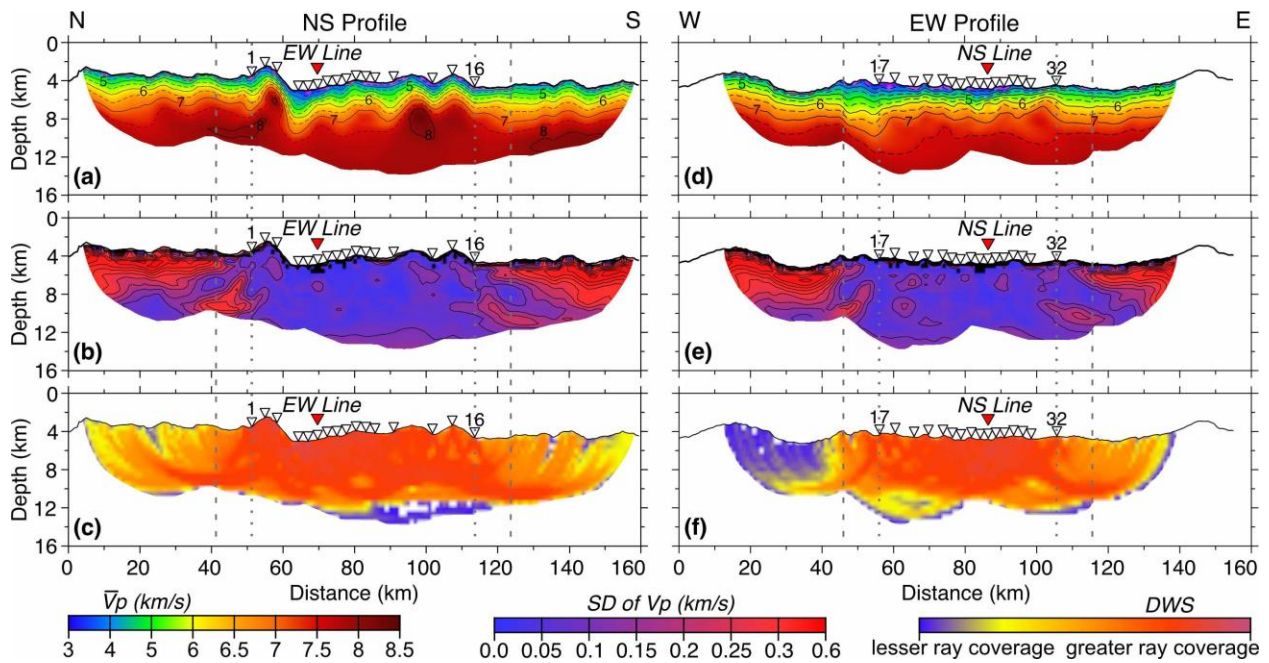


383
 384 **Figure 4.** Checkerboard resolution tests for the NS (left column) and EW (right column) profiles
 385 for perturbation cells: 25 km wide x 10 km high (a and d), 12.5 km wide x 5 km high (b and e), 5
 386 km wide x 2.5 km high (c and f). The input perturbed model is shown in the bottom left inset and
 387 the recovered perturbed model is the full-size figure. White and red inverted triangles as in
 388 Figure 3 caption.

389 4.2.2 Monte Carlo Analysis

390 We run a nonlinear Monte Carlo analysis (e.g. Tarantola, 1987) to estimate velocity
 391 uncertainty across our models following the strategy of Korenaga et al. (2000). For this analysis,
 392 the input velocity model (or starting velocity model) is randomized to create a set of 100
 393 different input models (Fig. S8). This is done by randomizing the velocities of the three nodes of
 394 the starting velocity model within a $\pm 6\%$ range and by randomizing the depths to the two sub-
 395 seafloor layer interfaces or inflection points within a ± 1.1 km range. The 100 randomized 1D
 396 starting velocity models are used to form 100 randomized 2D starting velocity models and run

397 100 inversions (for both NS and EW profiles) using the same inversion parameters applied to
 398 calculate the final velocity models (Figs. 3b and 3e). The resulting tomographic models are
 399 averaged to produce average velocity models for the NS and EW profiles (Figs. 5a and 5d) and
 400 compute standard deviations of the P-wave velocities across these models (Figs. 5b and 5e). The
 401 results show that the inversion process is stable as the average velocity models (Figs. 5a and 5d)
 402 are very similar to the final velocity models (Figs. 3a and 3d) for both profiles. The standard
 403 deviation of seismic velocities for most of the lithosphere at central parts of the models is ~ 0.1
 404 km/s (Figs. 5b and 5e). Larger standard deviations are observed in the areas that are less well
 405 resolved as indicated by the checkerboard patterns (Fig. 4), in areas with lower ray density (Figs.
 406 5c and 5f) and especially where there are no crossing rays (Figs. 3c and 3f), and below the
 407 seafloor where no instruments were deployed. The ray density is presented by the derivative
 408 weight sum (DWS; Toomey & Foulger, 1989), a nondimensional relative indicator of ray
 409 coverage.



410

411 **Figure 5.** Results from the Monte Carlo analysis. Averaged final velocity models for the NS (a)
 412 and EW (d) profiles. Iso-velocity contours are shown every 0.5 km/s in (a and d); solid black at
 413 every km/s and dashed in between. Standard deviation of the P-wave velocity calculated via the
 414 Monte Carlo analysis for the NS (b) and EW (e) profiles. Solid black contours are shown every
 415 0.05 km/s in (b and e). Derivative weight sums (DWS) indicating the ray coverage for the NS (c)
 416 and EW (f) profiles. In all panels, the dotted light grey vertical lines mark the end of the best
 417 resolved areas, and the dashed light grey vertical lines mark the ends of the well resolved areas.
 418 White and red inverted triangles as in Figure 3 caption.

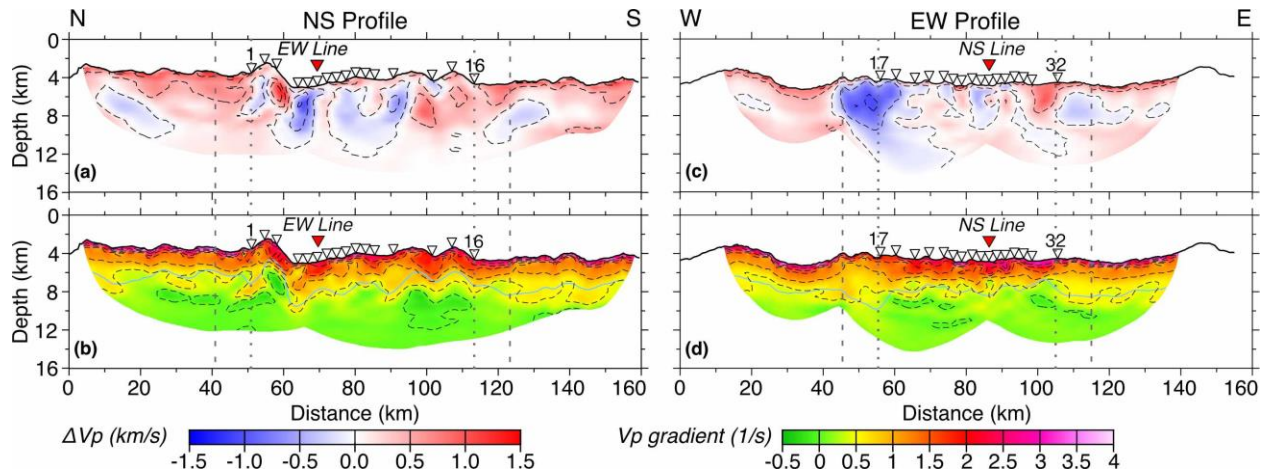
419

4.3 Derivatives of the velocity models

420

421 To aid the discussion, we plot 1D velocity-depth functions (Fig. S9) extracted at every 1
 422 km distance within the best resolved areas of the two average velocity models (Figs. 5a and 5d).
 423 We use these functions to determine the average 1D velocity-depth functions and the extent of
 the velocity-depth envelopes for both profiles (Fig. S9). We further augment our interpretation

424 by computing and plotting velocity anomalies (Figs. 6a and 6c) and vertical velocity gradients
 425 (Figs. 6b and 6d) for both the NS and EW profile. The 2D velocity anomalies are calculated as
 426 the difference between the average velocity models (Fig. 5a and 5b) and the respective average
 427 1D velocity-depth functions (Fig. S9). The vertical velocity gradients are calculated by
 428 computing the central first derivative of the average velocity models (Fig. 5a and 5b).



429

430 **Figure 6.** Velocity anomaly (top panels) and velocity gradient (bottom panels) results for the NS
 431 and EW profiles, respectively. Dashed black contours are shown every 0.5 km/s in (a and c) and
 432 every 0.5 s⁻¹ in (b and d). The depth to the 7 km/s velocity contour is shown in (b) and (d) in a
 433 solid light blue line. White and red inverted triangles as in Figure 3 caption. Vertical dotted and
 434 dashed light grey lines as in Figure 5 caption.

435 5 Discussion

436 The final and average P-wave tomographic velocity models for the NS and EW profiles
 437 give insight into the subsurface structure of the SWIR at 64°30'E. In the following subsections,
 438 we discuss (1) the ridge structure and the distribution of the active fault and the older and now
 439 inert detachment faults; (2) the inferred lithospheric composition and its anisotropy; and (3) the
 440 velocity structure in our study area in the context of the known velocity structure elsewhere at
 441 the SWIR. We limit our discussion only to the geological structures that can be resolved as
 442 indicated by the checkerboard tests, and the areas of the velocity models that show standard
 443 deviations of <~0.1 km/s (Figs. 5b and 5e) and/or high ray coverage (Figs. 5c and 5f). This
 444 effectively limits our detailed interpretation to the best resolved areas (within the dotted light
 445 grey vertical lines in Fig. 5) with crossing rays and OBSs on the seafloor (51 to 114 km model
 446 distance for the NS profile and 55 to 106 km for the EW profile), with the regional interpretation
 447 extended to include the well resolved areas (within the dashed light grey vertical lines in Fig. 5)
 448 found up to ~10 km away from the first/last OBS on both profiles, as indicated by the Monte
 449 Carlo analysis results (Fig. 5).

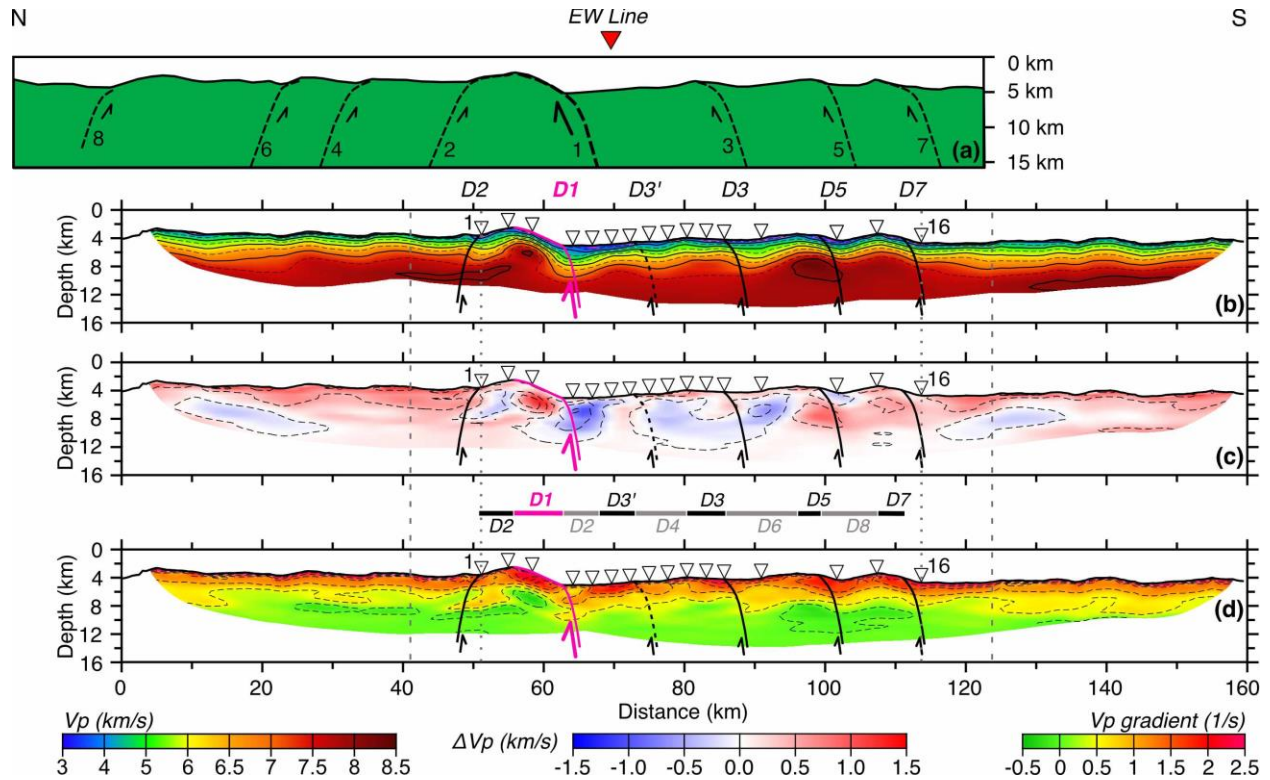
450 5.1 Ridge structure

451 5.1.1 Delineation of detachment faults on the NS profile

452 The information extracted from the NS profile (Figs. 5a, 6a and 6b), which cuts across
 453 the SWIR at 64°30'E, is particularly useful for subsurface identification of the active and

454 abandoned detachment faults. We first interpret a sharp lateral change in the velocities (a
455 horizontal gradient of $\sim 1 \text{ s}^{-1}$ at $\sim 62 \text{ km}$ model distance; Figs. 5a and 6a) and a high vertical
456 velocity gradient ($1.5\text{--}2.5 \text{ s}^{-1}$; Fig. 6b) coincident with the shallow section (top 2 km, i.e. depth 0-
457 2 km below seafloor) of the highest topographic feature ($\sim 51\text{--}62 \text{ km}$ model distance) as the
458 seismic expression of an active axial detachment fault (hereafter *D1*; Fig. 7). This bathymetric
459 high is characterized by higher velocity than the surrounding regions (Fig. 5a) and its top surface
460 has previously been interpreted as an active axial detachment fault based on side-scan sonar
461 (Sauter et al., 2013), bathymetric and kinematic analysis (Cannat et al., 2019; Reston, 2018), and
462 seismic reflection data (Momoh et al., 2017, 2020). Therefore, our velocity model supports these
463 earlier interpretations as it shows the footwall exhuming (or bringing up to shallow depth) rocks
464 of high velocities, those corresponding to lithologies typically found at greater depths, which
465 become superimposed by the lower velocity rocks of the hanging wall at the topographic low
466 immediately south. This north-south transition at $\sim 62 \text{ km}$ model distance from the detachment
467 footwall to the detachment hanging wall is characterized by an abrupt decrease in the vertical
468 gradient, from a high of $1.5\text{--}2.5 \text{ s}^{-1}$ to a low of $0.5\text{--}1.0 \text{ s}^{-1}$, as well as by a switch in polarity of
469 the largest velocity anomaly, from 1.5 km/s to -1.5 km/s .

470 Elsewhere, the NS profile exhibits smoothly varying low to moderate vertical velocity
471 gradient values ($< 1.5 \text{ s}^{-1}$), except for several locations that show similar lateral changes in the
472 vertical velocity gradient to *D1*, with higher vertical gradients ($1.5\text{--}2.0 \text{ s}^{-1}$) juxtaposed with lower
473 gradients ($0\text{--}1.0 \text{ s}^{-1}$) at alike depths (\sim top 2 km). These are found at model distances of about 50
474 km, 74 km, 87 km, 101 km, and 113 km (Fig. 6b). The velocity anomalies (Fig. 6a) at these
475 model distances also show a similar change to *D1*, with a switch in the polarity from positive to
476 negative anomaly, except at 50 km where the switch in polarity is reversed. Additionally, the
477 velocities (Fig. 5a) across the profile show a repeat drop pattern that coincides with the changes
478 observed in the vertical velocity gradient and velocity anomalies. While the identified vertical
479 velocity gradient, velocity, and velocity anomaly changes are not as pronounced as for the
480 interpreted active detachment fault *D1*, they are clearly recognizable and we interpret them to
481 indicate the subsurface location of the abandoned detachment faults (*D2* at $\sim 50 \text{ km}$, *D3'* at ~ 74
482 km, *D3* at $\sim 87 \text{ km}$, *D5* at $\sim 101 \text{ km}$, and *D7* at $\sim 113 \text{ km}$; Fig. 7b).



483

484 **Figure 7.** Comparison of a (a) conceptual model based on previous interpretations (Cannat et al.,
 485 2019; Reston, 2018; Sauter et al., 2013) depicting the sequence of flipping rolling-hinge faults
 486 (black dashed lines) along the NS profile and (b) the average velocity model from Figure 5a, (c)
 487 velocity anomalies from Figure 6a, and (d) vertical gradient from Figure 6b, with interpreted
 488 locations of corresponding faults (solid lines) for the best resolved area (51-114 km). In (a),
 489 previously interpreted faults are numbered 1–8 from youngest to oldest. In (b, c, and d) the
 490 identified faults are named *D2*, *D1*, *D3'*, *D3*, *D5*, *D7*, and are equivalent to faults 2, 1, 3, 5, and 7
 491 in (a) omitting *D3'* that is not inferred in (a). *D* stands for detachment. *D1* is the active
 492 detachment fault (solid pink line) and the fault numbers increase sequentially to describe older
 493 abandoned faults (solid black lines). Inset between (c) and (d) shows the interpreted extension of
 494 each detachment footwall surface located on the seafloor. The thin rectangle in pink limits the
 495 extension of *D1* footwall surface, the black rectangles limit the extension of *D2*, *D3'*, *D3*, *D5* and
 496 *D7* footwall surfaces, and the grey rectangles limit the extension of *D2*, *D4*, *D6*, and *D8* hanging
 497 wall surfaces. Iso-velocity contours are shown every 0.5 km/s in (b); solid black at every km/s
 498 and dashed in between. Dashed black contours are shown every 0.5 km/s in (c) and every 0.5 s⁻¹
 499 in (d). White and red inverted triangles as in Figure 3 caption. Vertical dotted and dashed light
 500 grey lines as in Figure 5 caption.

501

5.1.2 Comparison with earlier interpretations

502 In Figure 7, we compare our interpretation on the location of the detachment faults with
 503 that of previous interpretations (Cannat et al., 2019; Reston, 2018; Sauter et al., 2013), which are
 504 primarily based on observed bathymetric features, i.e. the location of the breakaway and
 505 emergence points on the fault surfaces. For simplicity, we list the detachment faults previously
 506 inferred from 1 to 8, with 1 being the youngest and 8 being the oldest fault (Fig 7a). Our velocity

507 model (Fig. 7b), the velocity anomalies (Fig. 7c), and the vertical velocity gradient (Fig. 7d),
 508 provide supporting evidence for the existence of faults 1–3, 5 and 7. The reverse polarity in the
 509 pattern observed in the velocity anomalies at ~50 km model distance (Fig 7c), at the interpreted
 510 location of *D2*, coincides with the previously interpreted location of fault 2 (Cannat et al., 2019;
 511 Reston, 2018; Sauter et al., 2013), only offset by ~1 km south. Fault *D2* was active prior to *D1*
 512 and thus it shows opposite polarity. Similarly, the interpreted location for fault *D1* is comparable
 513 to the location of the previously interpreted fault 1, only offset by ~1 km north (Fig. 7).
 514 Previously interpreted locations of faults 5 and 7 are identical to the interpreted locations of *D5*
 515 and *D7* in this work, respectively, while fault 3 is offset by ~4 km north from *D3* (Fig. 11). The
 516 locations of faults *D1* and *D3* are also consistent with previously identified south dipping
 517 reflectors in MCS data (Momoh et al., 2017, 2020) interpreted to be related to fault damage in
 518 the footwall. The results presented here also demarcate an abandoned detachment *D3'* that has
 519 not been inferred previously. Detachment *D3'* may have been missed in other models (Cannat et
 520 al., 2019; Reston, 2018; Sauter et al., 2013) because its seafloor expression shows a smoother
 521 emergence topography in comparison to the other interpreted faults based on bathymetry. One
 522 possible cause for this is a relatively short lifespan of the *D3'* fault, which precluded full
 523 development of the characteristic seafloor geometry of a detachment fault. Alternatively, the
 524 velocity signature observed at ~74 km model distance may possibly be related to recent
 525 extensional damage occurring in the hanging wall of *D1* as proposed by Momoh et al. (2020),
 526 since no south dipping reflectors related to this fault are imaged in MCS data (Momoh et al.,
 527 2017). However, given the resolution of our model, the presence of fault *D3'* provides an
 528 explanation that is more consistent with the velocity, velocity anomaly, and vertical gradient
 529 patterns observed at the locations of other interpreted faults (Figs. 7b, 7c, and 7d).

530 For our study area, Cannat et al. (2019) estimated the duration of the active deformation
 531 period for each detachment fault. The active life for these detachments ranges from 0.6 Myr to
 532 2.8 Myr, with an average life of 1.35 Myr. Our interpretation of an additional detachment fault
 533 (*D3'*; Fig. 7) combined with the adjustment in the location of *D3* calls for a reevaluation of these
 534 age numbers. However, we can only estimate total fault longevity for detachments *D1* and *D2*,
 535 and partial longevity for faults south of *D1* since our NS velocity model does not resolve the
 536 location of the faults north of *D2* (Table 1). Like Cannat et al. (2019), we estimate the partial and
 537 total fault lifespans based on the horizontal distance between faults' emergence and breakaway
 538 points (Table 1). The inset shown in between Figures 7c and 7d illustrates the interpreted
 539 extension of each detachment footwall surface on the seafloor used for our calculations. Portions
 540 of each abandoned fault footwall are located both north and south of the spreading axis, except
 541 for the active detachment (*D1*) that has not yet been cut off by a new master fault and carried
 542 away from the axis. Portions of *D4*, *D6* and *D8*, the faults inferred further north of *D2* but not
 543 resolved by our velocity model, are also considered based on earlier interpretations of seafloor
 544 data (Cannat et al., 2019; Reston 2018; Sauter et al., 2013) to estimate the ages in Table 1. Our
 545 calculations point to a duration of ~0.7 Myr for *D2*, half the previously suggested age, and ~0.5
 546 Myr for *D1*, larger than the previously suggested age (0.3 Myr).

547

Detachment # <i>(Youngest to oldest)</i>	Dip	Horizontal distance from fault emergence to	Horizontal distance from fault breakaway	Estimated partial fault duration	Estimated total fault duration (Myr)
--	------------	--	---	---	---

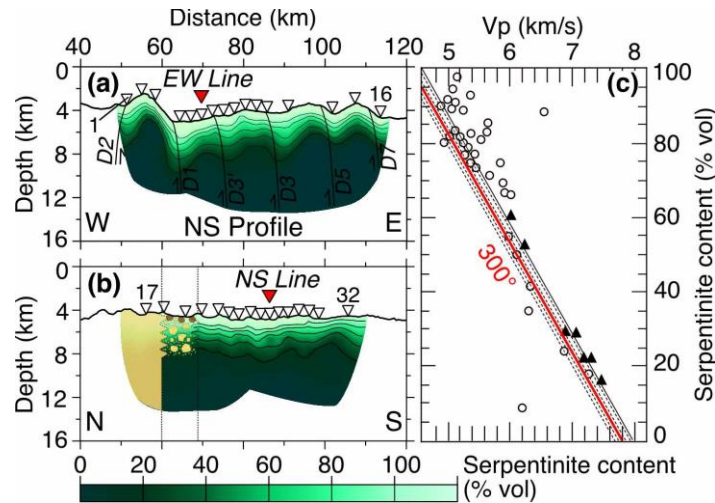
		adjacent fault breakaway (km)	to adjacent fault emergence (km)	based on distance (Myr)	
D1 (<i>active</i>)	South	7.1	0	0.51	0.51
D2 (<i>North of D1</i>)	North	5.0	-	0.36	0.72
D2 (<i>South of D1</i>)	North	-	5.1	0.36	
D3'	South	5.1	<i>Unknown</i>	0.36	<i>Unknown</i>
D4	North	<i>Unknown</i>	7.3	0.52	<i>Unknown</i>
D3	South	5.5	<i>Unknown</i>	0.39	<i>Unknown</i>
D6	North	<i>Unknown</i>	10.2	0.73	<i>Unknown</i>
D5	South	3.4	<i>Unknown</i>	0.24	<i>Unknown</i>
D8	North	<i>Unknown</i>	8.0	0.57	<i>Unknown</i>
D7	South	3.9	<i>Unknown</i>	0.28	<i>Unknown</i>

548 **Table 1.** Estimated detachment fault longevity based on the horizontal distance between faults'
549 emergence and breakaway locations of the inferred faults across the profile SMOO33 (NS
550 profile).

551 5.2 Lithospheric composition

552 5.2.1 Exhumed mantle area

553 In order to relate the modeled velocities to the subsurface lithology, we assume that the
554 investigated area is composed of exhumed mantle rocks ranging from variably serpentinized and
555 fractured peridotites at shallower depths, to unaltered peridotites at greater depths. This is
556 followed by conversion of the seismic velocities along the NS and EW profiles (Figs. 5a and 5d)
557 to degree of serpentinization (Figs. 8a and 8b) using a linear relationship for partially-
558 serpentinized peridotites (Fig. 8c) from Carlson & Miller (2003). These authors used empirical
559 data (Christensen, 1978, 1996; Miller & Christensen, 1997) to evaluate how the relationship
560 between P-wave velocities and the degree of serpentinization changes with different confining
561 pressure and temperature. We choose the relationship for a temperature of 300°C, in agreement
562 with the high serpentinization temperatures suggested for the rock samples analyzed along the
563 NS profile (Rouméjon et al., 2014). Albeit converting seismic velocities to degree of
564 serpentinization is a simplification of the causes for the velocity heterogeneities, especially at the
565 top of the model, it allows us to discuss how deep serpentinization may extend and what may
566 control such depth.



567

568 **Figure 8.** Estimated degree of serpentinization for the NS (a) and EW (b) profiles based on their
 569 tomographic velocities (Figs. 5a and 5d) and the linear relationship (c) of serpentinite content
 570 with P-wave velocity from Carlson and Miller (2003) for a temperature of 300°C, in agreement
 571 with oxygen isotopes studies in the area (Rouméjon et al., 2015). Black triangles in (c) are
 572 laboratory measurements of P-wave velocities in serpentinized peridotites at 25°C and at 200
 573 MPa and open circles are velocity measurement at other confining pressure (up to a 1000 MPa).
 574 Carlson & Miller (2003) collected data points from several studies (Christensen, 1978, 1996;
 575 Miller & Christensen, 1997). Dashed lines show the approximate relationships at temperatures of
 576 100, 200, 300, 400, and 500°C corrected from the best fitting relationship measured at 200 MPa
 577 (solid black line). In (a) the solid black lines show the detachment faults' locations interpreted in
 578 Fig. 7. In (b) the dotted lines show the location at which there is a change in the lithosphere
 579 (volcanic before 59 km, non-volcanic after 69 km, and transitional in between) as discussed in
 580 the text. Solid black contours in (a and b) show serpentinite content at every 20% vol. White and
 581 red inverted triangles in (a) and (b) as in Figure 3 caption.

582 While our assumption of the exhumed mantle domains throughout the study area is a
 583 simplification of the true geology, it is supported by several lines of evidence and justified by our
 584 intent of carrying out a first-order interpretation of the subsurface geology. First, earlier rock
 585 sampling of the seafloor in our study area (Rouméjon et al., 2014; Sauter et al., 2013) has
 586 predominately retrieved peridotites and the extent of the mapped smooth seafloor (Cannat et al.,
 587 2006) (Fig. 1), interpreted to represent exhumed mantle domains, covers majority (~3/4) of the
 588 area along the NS and EW profiles contained by the OBS instruments. Second, no reflection
 589 Moho has been identified in the pseudo-3D MCS dataset by Momoh et al. (2017), which
 590 indicates the lack of a distinct and seismically-well characterized Moho in our study area.
 591 Reflection Moho is often well imaged in upper oceanic lithosphere formed at faster spreading
 592 mid-ocean ridges where a 3-layer mafic oceanic crust tops the ultramafic uppermost mantle (e.g.
 593 Aghaei et al., 2014; Bouhalanis et al., 2020). Third, no wide-angle Moho reflected arrivals
 594 (*PmP*) are identified in the OBS data examined in this work, and these arrivals are routinely
 595 observed and picked in data collected worldwide in oceanic lithosphere formed at faster
 596 spreading rates (e.g. Canales et al., 2000; Horning et al., 2016). Furthermore, the lack of *PmP*
 597 arrivals in our study area is consistent with observations from other ultraslow spreading ridges
 598 dominated by magma starved spreading conditions (Grevemeyer et al., 2018b).

599 We interpret the uppermost lithosphere to be composed of highly fractured and fully
600 serpentinized peridotites at the top with a gradual decrease in pore space volume and
601 serpentinization degree to unaltered peridotites at depth (Figs. 8a and 8b). The velocities lower
602 than 4.5 km/s at the top of the model may be representative of peridotites that are fully
603 serpentinized and heavily fractured. Geologically, these low velocities could also be
604 representative of basalts. However, this possibility is highly unlikely because, whereas scattered
605 low-volumetric basalts may be found across the study area (Sauter et al., 2013), the results of the
606 extensive seafloor studies and the lack of Moho reflections in both wide-angle OBS and MCS
607 data (e.g. Cannat et al., 2006; Sauter et al., 2013; Momoh et al., 2015) clearly indicate that a
608 continuous basaltic top layer is not present.

609 While our first order interpretation is comparable to that of Momoh et al. (2017), the
610 higher resolution and lateral variability of the new results presented in this work make it possible
611 to carry out a detailed interpretation. Serpentinization seems more extensive and penetrates
612 deeper along the NS profile than the EW profile. For example, 20% serpentinization extends to
613 up to ~5 km dbf on the NS profile and up to ~3–4 km dbf on the EW profile, with the anomaly
614 being the location of the active detachment fault (*DI*) footwall where the 20% serpentinization
615 contour is found at the shallowest depths of ~1.5–2 km dbf (Figs. 8a and 8b).

616 The change from relatively large and quickly decreasing vertical velocity gradients (1.5-
617 2.5 s^{-1}) at velocities <7 km/s, to relatively low and gradually decreasing vertical velocity
618 gradients (<0.5 s^{-1}) at velocities >7 km/s (Figs. 6b and 6d) likely illustrates a change in the
619 porosity and permeability regime that impacts the serpentinization process for the upper and
620 lower sections of the profiles. These low and gradually decreasing vertical velocity gradients
621 within deeper sections of the models also indicate that the Moho transition is not an abrupt
622 serpentinization or alteration front, as has been suggested for the study area and elsewhere along
623 the SWIR (e.g. Dick et al., 2019; Mével, 2003; Minshull et al., 1998, 2006), but rather a gradual
624 transition from hydrated peridotites to unaltered peridotites. The smoother gradient of seismic
625 velocities above 7 km/s in the EW profile suggests a more uniform upper mantle in comparison
626 to the NS profile.

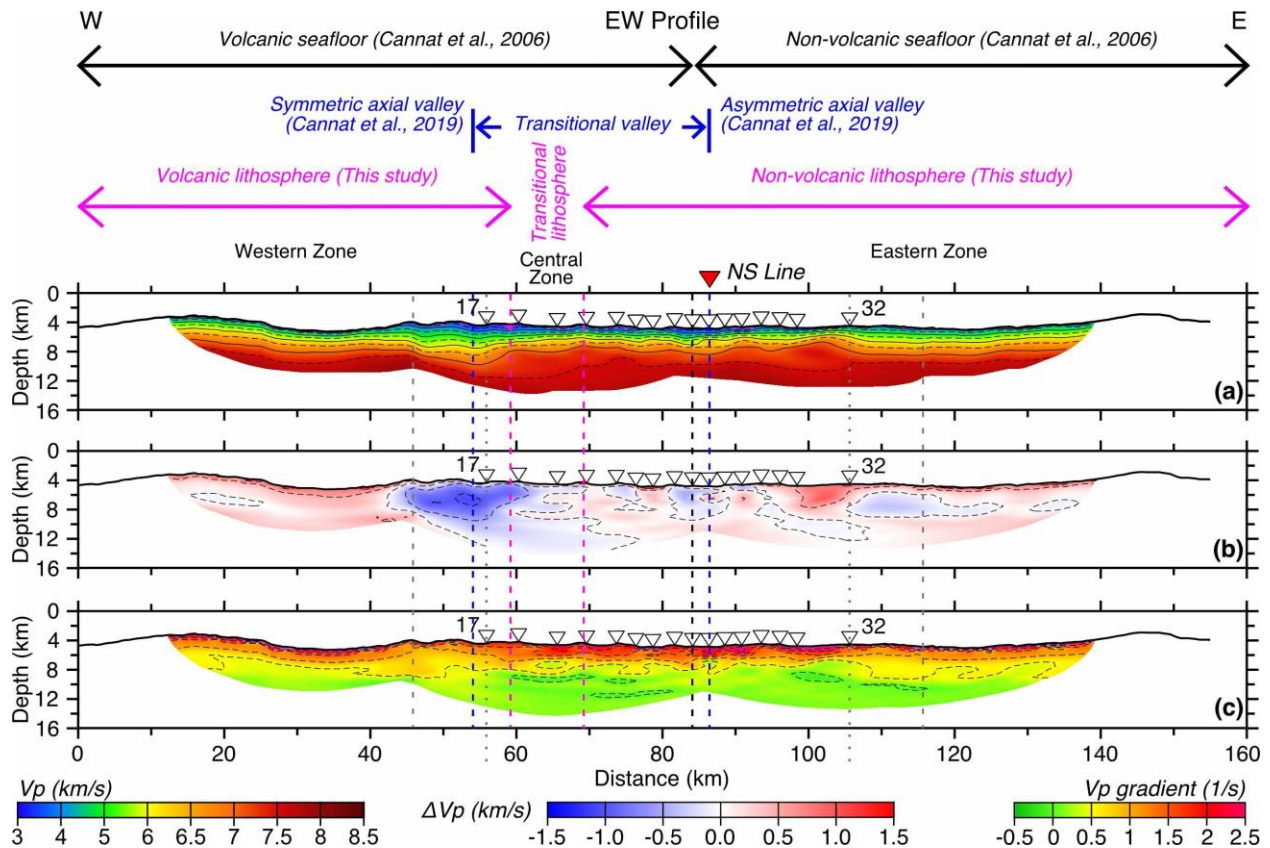
627 From Figure 8a, we further decipher the following: (i) Despite the similar penetration
628 depth of serpentinization on both sides of individual detachment faults, for similar depths on
629 both sides of the detachment, serpentinization is more pervasive in the hanging walls than in the
630 footwalls. This is possibly due to the continuous exhumation of the footwalls that leaves hanging
631 walls longer exposed to water at temperatures that are more optimal for the serpentinization to
632 take place (e.g. *DI*, Fig. 8a); (ii) The depth and degree of serpentinization depends on the length
633 of time the detachments were active. For example, amongst the abandoned detachments south of
634 *DI*, the 20% serpentinization contour reaches deeper levels around faults *D3'* and *D3* than
635 around *D5* and *D7*, which agrees with the estimated longer active life for faults *D3'* and *D3*
636 (Table 1). Therefore, we suggest that the bulk of the serpentinization occurs while detachment
637 faults are active, with much diminished alteration after the lithosphere migrates off-axis. The
638 longer a particular detachment is active, the deeper serpentinization reaches due to both more
639 extensive deformation of the fault walls resulting in greater porosity and permeability and longer
640 exposure to seawater. The overall increase in velocity and, therefore, decrease in estimated
641 degree of serpentinization from the active to abandoned detachment faults is possibly caused by
642 a reduction in porosity by closure of cracks and fractures once fault activity stops and the fault
643 moves away from the ridge axis.

644

5.2.2 EW transition from exhumed mantle to volcanic seafloor

645 Earlier work on seafloor mapping in the study area (Cannat et al., 2006) indicated that the
 646 EW profile crosses a transition within the uppermost lithosphere from exhumed and
 647 serpentinized ultramafic mantle domains in the east to volcanic and magmatic mafic domains in
 648 the west (Fig. 1). This transition was initially interpreted to occur at the OBS 25 location (model
 649 distance ~ 84 km; Fig. 1) (Cannat et al., 2006). Cannat et al. (2019) later proposed a wider
 650 transitional domain from the detachment-dominated asymmetric topography, characteristic of
 651 non-volcanic seafloor, to the magmatic symmetric topography, characteristic of volcanic
 652 seafloor. The authors examined four ridge-perpendicular bathymetric profiles spread over a
 653 distance of ~ 50 km and observed a change in the seafloor topography across the profiles from
 654 ridge-asymmetric topography, indicative of non-volcanic seafloor, to ridge-symmetric
 655 topography, indicative of volcanic seafloor. The distance between the profile showing
 656 asymmetric topography and the closest profile showing ridge-symmetric topography is 32.6 km.
 657 A profile showing transitional bathymetry is found in between these two profiles, which led the
 658 authors to interpret that the transitional region occurs over a 20-30 km distance.

659 Our velocity, velocity anomaly, and vertical velocity gradient models (Fig. 9) also
 660 suggest a major change in the lithospheric structure and composition along the profile. This
 661 change occurs over a distance of ~ 10 km between OBSs 18 and 20 (model distance ~ 59 -69 km;
 662 Fig. 9). In Figure 9 we plot the limits of the interpreted volcanic and non-volcanic seafloor as
 663 proposed by Cannat et al. (2006, 2019) and in this study. The recent interpretation by Cannat et
 664 al. (2019) put the transitional area at model distance of ~ 54 -86 km, which is wider but in broad
 665 agreement with the results from this work.



666

667 **Figure 9.** Comparison of the (a) average velocity model from Figure 5d, (b) velocity anomalies
 668 from Figure 6c, and (c) vertical gradient from Figure 6d, along the EW profile. Arrows in the top
 669 of the figure show the different interpretations of the proposed transition from volcanic to non-
 670 volcanic lithosphere: Cannat et al. (2006) in black, Cannat et al. (2019) in blue, and this study in
 671 pink. The blue short straight lines indicate the location of Cannat et al. (2019) bathymetric
 672 profiles that show contrasting symmetric and asymmetric axial valleys and constrain the
 673 transitional zone. The black, blue, and pink dashed lines extend the limits of the different
 674 interpretations across (a, b, and c). The pink arrows also delimit the three zones in the EW
 675 model: western, central, and eastern. White and red inverted triangles as in Figure 3 caption.
 676 Vertical dotted and dashed light grey lines as in Figure 5 caption.

677 The observed changes in velocity, velocity anomaly, and vertical velocity gradient divide
 678 the EW profile into three distinctive zones: eastern (model distance >69 km), central (model
 679 distance from 59 to 69 km), and western (model distance <59 km). The eastern zone shows high
 680 and laterally variable seismic velocities at shallow depths, reaching 4–4.5 km/s within 0.5 km
 681 dbsf and 7 km/s at depths 2–3.5 km dbsf (Fig. 9a), an overall positive velocity anomaly including
 682 a larger positive anomaly (0.5–1 km/s) at model distances 99–106 km (Fig. 9b), and a high
 683 vertical velocity gradient of 1–2 s⁻¹ (Fig. 9c). These characteristics are consistent with exhumed
 684 and variably serpentized mantle peridotites, where serpentization extent diminishes as a
 685 function of depth. A low in the velocities that corresponds with a low velocity anomaly (Fig. 9b)
 686 and a more moderate vertical gradient than for the neighboring areas (Fig. 9c) is observed within
 687 model distances 81–86 km (below OBSs 24–26; Fig. 9a). We speculate that this is indicative of a
 688 ~5km-wide volcanic dike injection, a feature resolvable in our model (Fig. 4f), that could be
 689 responsible for the lower RMBA values (10–0 mGal) that led to the interpretation of this area
 690 and the area further west as volcanic seafloor (Cannat et al., 2006). Other smaller low velocity
 691 anomalies, e.g. below OBSs 21 and 22 (model distances 73–76 km; Fig. 9b) and below OBS 28
 692 (model distances 90–92 km; Fig. 9b) may suggest the presence of additional smaller dikes that
 693 are not fully resolvable by our data. Detailed seafloor mapping in our study area with side-scan
 694 sonar shows small sparse lava patches on top of the exhumation surfaces (Sauter et al., 2013).
 695 Our results bolster the argument that the lava patches are erupted directly onto the exhumed
 696 surface by small offset high-angle normal faults (Cannat et al., 2019; Sauter et al., 2013), as
 697 opposed to being allochthonous rafted volcanic blocks transported to the surface off-axis by
 698 successive detachments (Reston, 2018). Furthermore, the presented evidence of volcanic dike
 699 injections within the “smooth-seafloor” favors the interpretation by Sauter et al. (2013) that the
 700 abandonment of the active axial detachment fault and consequent activation of the successive
 701 detachment fault may be a consequence of increased diking.

702 The western zone shows sharply lower seismic velocities that reach 3.5 km/s at 0.5 km
 703 dbsf and 7 km/s at 4–5.3 km dbsf (Fig. 9a), a large negative velocity anomaly of -1.5–1 km/s
 704 (Fig. 9b), and a moderate to low vertical velocity gradient of 0.5–1 s⁻¹ (Fig. 9c). These
 705 characteristics are consistent with top of the lithosphere being partially constructed by mafic
 706 magmatic rocks. This interpretation is further supported by analysis of the ray coverage or the
 707 DWS (Fig. 5e). Although the ray density at all ends of the seismic profiles is gradually reduced
 708 with increasing shot distance from the last OBS (Figs. 5c and 5e), the reduction at the west end
 709 of the EW profile (Fig. 5f) is considerably greater than at the three other profile ends, which is
 710 indicative of a major change in the nature of the lithosphere. This more rapid drop in ray density
 711 also coincides in an apparent westward velocity increase at the western limit of the well resolved
 712 area (Fig. 9a), but this is an artifact. The inverted velocity model follows the starting velocity

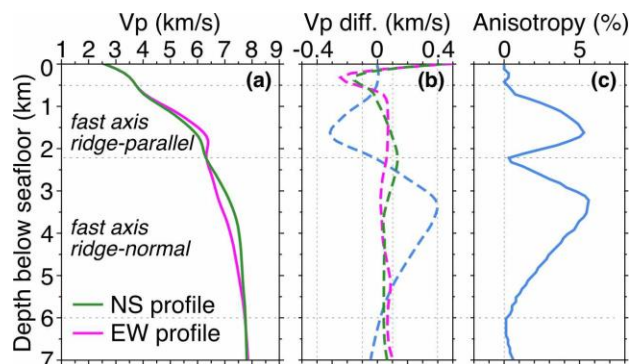
713 model in areas of low ray coverage (i.e. outside the well resolved area), and in the well resolved
 714 section of the western zone seismic velocities are considerably slower than the starting velocity
 715 model. This forces a gradual lateral change from the well resolved area. On the contrary, in the
 716 east the starting and the average velocity models have similar velocities and no lateral change is
 717 observed across the limit of the well resolved area.

718 In between the eastern and western zones is the central zone, which displays gradual
 719 westward changes in the velocities (decreasing; Fig. 9a), velocity anomaly (from low positive to
 720 low negative Fig. 9b), and vertical velocity gradient (vertically less variable, Fig. 9c). We
 721 interpret this as indicative of a transition from the amagmatic upper lithosphere of the eastern
 722 zone to the mafic magmatic rocks toping the lithosphere of the western zone and also likely an
 723 indicator of a transitional lithosphere that is heterogeneous in its composition with layers of
 724 mafic extrusive and intrusive rocks laterally intertwined with layers of fully and partially
 725 serpentinized ultramafic rocks (Fig. 8b).

726 5.2.3 Anisotropy

727 We extract 1D velocity-depth functions at the crossing point between the NS and EW
 728 velocity profiles (Fig. 10a) to evaluate if there is directional dependence in seismic velocities or
 729 seismic anisotropy (Fig. 10). The difference between these two 1D velocity-depth functions is
 730 shown in Figure 10b (dashed blue line), and the corresponding anisotropy is shown in Figure
 731 10c. Both velocity functions are nearly coincident for the first 0.5 km dbsf. At greater depth,
 732 from ~ 0.5 to ~ 2.2 km dbsf, velocities on the EW profile are faster (up to $\sim 5\%$ difference) than on
 733 the NS profile. The velocity relationship reverses from ~ 2.2 to ~ 6 km dbsf, with the NS profile
 734 being faster (up to $\sim 5\%$ difference). At depths greater than 6 km dbsf, the two velocity-depth
 735 functions are again nearly coincident.

736 Figure 10b also compares the difference in the two velocity-depth functions to the
 737 standard deviation (SD) estimated for the NS and EW velocity models at their crossing point.
 738 The SD-depth functions are similar for both profiles at the crossing point, with most SD values
 739 being $< \pm 0.1$ km/s. The P-wave velocity difference near the function peaks reaches or approaches
 740 ± 0.4 km/s, which is at least several times greater than the SD of the both velocity models
 741 indicating that the difference in velocities we observe falls well within the estimated uncertainty.
 742 While some of the differences in velocities at the two crossing profiles may be due to the
 743 limitations of modeling wave propagation in 2D, most of the observed differences can be
 744 attributed to seismic anisotropy thus rendering our results a useful first-order approximation.



745

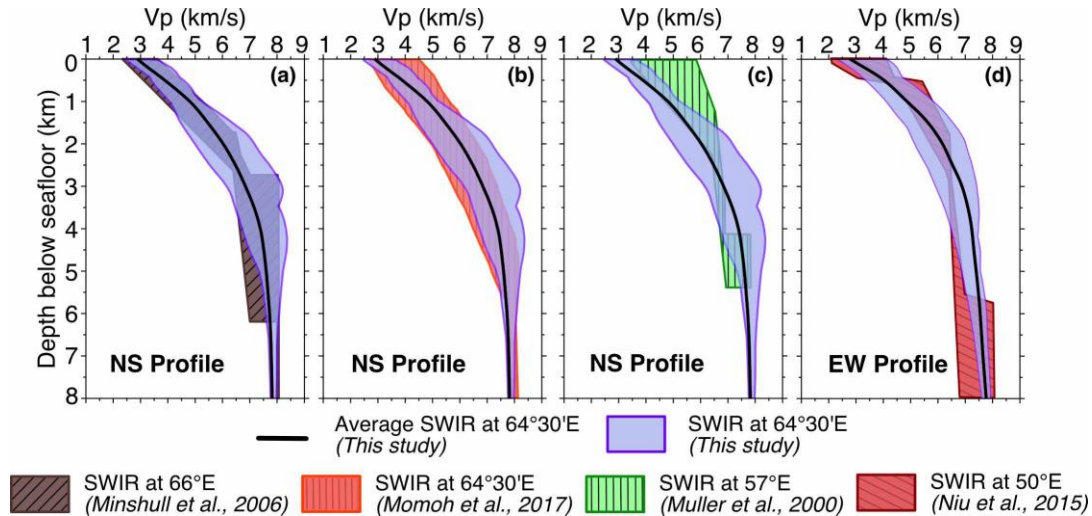
746 **Figure 10.** (a) Comparison of the 1D velocity-depth functions extracted from the NS (green) and
 747 EW (pink) profiles at their crossing point. (b) Dashed blue line shows the difference between NS
 748 and EW velocities presented in (a), and green and pink dashed lines show the standard deviation
 749 of the velocities presented in (a) (from Figs. 5b and 5e). (c) Functional fit of % of anisotropy
 750 with depth in light blue. The horizontal dashed grey lines in (a, b and c) indicate the depths for
 751 the anisotropy consistent with a fast axis aligned in a ridge-parallel direction (~ 0.5 to ~ 2.2 km
 752 dbsf) and for the anisotropy consistent with a fast axis aligned in a ridge-normal direction (~ 2.2
 753 to 6 km dbsf).

754 The velocity differences in the shallower zone (~ 0.5 to ~ 2.2 km dbsf) are consistent with
 755 the anisotropy reported at other ridges near the spreading axis of 1%–12% at shallow to
 756 intermediate depths (0–3 km) and with the fast axis aligned in a ridge-parallel direction (e.g.
 757 Seher et al., 2010; Weekly et al., 2014). This anisotropy is associated with the alignment of
 758 vertical cracks within the crust in the ridge axis direction (Dunn & Toomey, 2001). Christeson et
 759 al. (2019) synthesized the oceanic crustal structure formed at spreading ridges with half-
 760 spreading velocities greater than 5 mm/yr from 2D seismic profiles and documented that
 761 anisotropy may be restricted to the upper crust in areas near the ridge axis. Cracks induced by
 762 stresses related to the footwall exhumation and bending at shallow to intermediate levels both in
 763 the footwall and the hanging wall, as well as extensive extensional damage on the hanging wall,
 764 have been suggested in our study area (Cannat et al., 2019; Momoh et al., 2017, 2020).
 765 Therefore, we suggest the uppermost anisotropy is due to the preferential distribution of cracks
 766 parallel or subparallel to the axis at depths from ~ 0.5 to ~ 2.2 km dbsf. We expect that the top 0.5
 767 km dbsf are also characterized by axis parallel or subparallel cracks and the resulting anisotropy
 768 but, due to the discussed limitations of our data and velocity models, this anisotropy was not
 769 possible to resolve.

770 With greater depth, the increasing lithospheric pressure gradually closes the cracks thus
 771 removing the source of the ridge-parallel anisotropy. Serpentinization also diminishes with
 772 increasing depth leading to increased ratio of olivine minerals versus serpentine or other
 773 alteration minerals, thus generating anisotropy with the ridge-normal fast direction that starts to
 774 prevail at ~ 2.2 km dbsf. Our data can resolve the ridge-normal fast anisotropy to 6 km dbsf, after
 775 which the model resolution is insufficient for this purpose. Velocities from 6– ~ 7 km dbsf have
 776 diminished resolution and are already influenced by the starting velocity model through
 777 smoothing. This uppermost mantle, ridge-normal anisotropy is related to the lattice-preference
 778 orientation of olivine minerals in the direction of lithospheric strain (Hess 1964), which is
 779 consistent with the near-orthogonal spreading direction attributed to our study area (Cannat et al.,
 780 2008), and has been reported for older oceanic crust (e.g. Ismail and Mainprice, 1998;
 781 VanderBeek et al., 2016).

782 5.3 Comparison of velocity-depth fields

783 We compare the average 1D velocities and velocity field envelopes of the NS and EW
 784 profiles (Fig. S9) with corresponding results from previously published ridge-normal and ridge-
 785 parallel seismic profiles, respectively, at other locations along the SWIR.



786

787 **Figure 11.** Comparison of the average 1D velocity-depth profiles (thick black line) and 1D
 788 velocity-depth fields (light purple areas bounded by dark purple lines) from this study with the
 789 velocity fields from earlier studies of the SWIR at the following locations: (a) 66°E (Minshull et
 790 al., 2006); (b) 64°30'E (Momoh et al., 2017); (c) 57°E (Muller et al., 2000); and (d) 50°E (Niu et
 791 al., 2015). Note that the locations of the earlier work done at 66°, 57° and 50°E are shown in the
 792 Figure 1 inset with yellow circle, diamond and star, respectively, while the work done at 64°30'E
 793 coincides with our study area.

794 Figure 11 displays a comparison of our results at 64°30'E with velocity fields from earlier
 795 work at the SWIR. From East to West, shown are velocity fields at 66°E (Minshull et al., 2006)
 796 (Fig. 11a), 64°30'E (Momoh et al., 2017) (Fig. 11b), 57°E (Muller et al., 2000) (Fig. 11c), and
 797 50°E (Niu et al., 2015) (Fig. 11d).

798 Our NS profile velocity envelope and that of Momoh et al. (2017) (Fig. 11b), both from
 799 64°30'E, are mostly in general agreement. Momoh et al. (2017) shows little structure with
 800 velocities smoothly increasing with depth, from ~ 2.7 km/s at the seafloor to ~ 7 – 8
 801 km/s at 5 km dbfs. The NS velocity model constrains the velocities at the seafloor to a narrower
 802 and slower range (~ 2.5 – 3.7 km/s), increasing to a similar range by about 1.4 km dbfs, and
 803 becoming overall higher for depths up to ~ 5 km dbfs. Momoh et al.'s (2017) velocities show
 804 smooth vertical velocity gradient changes with depth, while the NS velocities indicate a more
 805 complex structure for how the velocity gradient changes with depth and show a higher vertical
 806 velocity gradient at the top that it is reduced to a lower velocity gradient for depths greater than
 807 ~ 2 km dbfs. While our interpretation is broadly similar to that of Momoh et al. (2017), the NS
 808 velocity model has recovered deeper and more detailed velocity information thus providing more
 809 constraints on the lithospheric structure. This is likely because the NS profile is longer (150 km
 810 vs. 43 km) and has more OBSs (16 vs. 8) than the profiles used by Momoh et al. (2017),
 811 resulting in denser and deeper ray coverage with a larger range of source-receiver offsets.

812 Minshull et al. (2006) at 66°E (Fig. 11a) show velocities at the seafloor ranging from
 813 ~ 2.3 – 3.5 km/s and increasing at a high vertical velocity gradient up to ~ 6.4 – 7 km/s at ~ 2.7 km
 814 dbfs. At depths greater than ~ 2.7 km dbfs, the velocities increase at a low-velocity gradient and
 815 range from ~ 6.5 – 7 to 8 km/s. The average velocities for the NS profile fit well with the velocity
 816 field of Minshull et al. (2006). The NS velocity field also presents a similar range and vertical
 817 gradient for depths up to 1 km dbfs but it has a lower low and a higher high velocity for depths

818 of 1–3.5 km dbf. At greater depths, the NS profile velocities are overall higher than the
819 velocities at 66°E. Despite the significant similarities in velocities between the two models, large
820 differences exist on the lithospheric structure interpretation in these two study areas that are only
821 ~150–200 km apart. Minshull et al. (2006) suggested a crustal structure composed of mafic
822 oceanic layers 2 and 3, with a mean crustal thickness of 4.2 km, and constrained the Moho with
823 *PmP* arrivals and complementary gravity data. They interpreted that serpentinized peridotites do
824 not form the dominant lithology in the seismic lower crust and instead they suggested a Layer 3
825 with a variable thickness (0.5–3 km) governed by melt focusing toward segment centers.

826 The presence of Segment-8 volcano at ~65°40'E (Cannat et al., 2006; Schindwein &
827 Schmid, 2016) could explain some of the differences between the two results and interpretations.
828 Velocity structure of Minshull et al. (2006) shows a higher gradient for the top and lower
829 gradient for the bottom of the model than the NS profile, which is consistent with a high-gradient
830 Layer 2 on top of a low-gradient Layer 3, while the SWIR at 64°30'E has a gradual decrease in
831 the vertical velocity gradient consistent with a gradual decrease in serpentinization and pore
832 pressure with depth. However, Minshull et al. (2006) used a layered modeling and inversion
833 procedure constrained by model parametrization of two crustal layers. The wide-angle data were
834 collected on 8 OBSs (~10–30 km spacing) with no coincident MCS data to guide the layered
835 inversion. Therefore, we speculate that a fair amount of variably serpentinized peridotites may be
836 present in the subsurface at the SWIR at 66°E based on the overlap of the NS profile velocity
837 envelope with Minshull et al. (2006) velocities, and that a denser seismic survey followed by
838 first arrival traveltimes tomography for a single model layer would provide a better and more
839 detailed comparison.

840 The SWIR at 57°E (Fig. 11c), across the Atlantic Bank, shows velocities ranging from
841 3.5 km/s to ~5.8 km/s at the seafloor (Muller et al., 2000). This velocity range gradually narrows
842 to 6.4–6.9 km/s for depths ~2.2–4.1 km dbf as the vertical velocity gradient decreases. For
843 depths greater than 4.1 km dbf the velocities range from ~6.8–7.8 km/s. The authors interpreted
844 magmatic oceanic crust composed of layers 2 and 3 on top of the uppermost mantle rocks. The
845 NS profile velocities are overall in disagreement showing slower velocities for depths up to ~2.6
846 km dbf and higher velocities for greater depths. We interpret the topmost ~2.6 km dbf on the
847 NS profile, characterized by lower velocities than those from Muller et al. (2000), to represent
848 fully serpentinized and highly fractured peridotites at the top that gradually transition to ~40%
849 serpentinized peridotites with minor fractures at the bottom. The NS profile velocities continue
850 to increase with increasing depth, though at a reduced gradient, due to continued fracture closure
851 and further diminishing serpentinization. The Moho at the SWIR at 57°E is constrained by *PmP*
852 reflections and gravity modeling, in contrast to our study area where the amagmatic seismic crust
853 lacks any shreds of evidence of a Moho. However, the results from Muller et al. (2000) likely
854 have greater uncertainties than our results since they use only 8 OBSs (~5–15 km spacing) and
855 do not have coincident reflection data, which are used to guide layered modeling and inversion.

856 The velocity field at the segment center at 50°E (Fig. 11d, Niu et al., 2015) can be
857 divided in 4 sections: (1) top one (0–0.6 km dbf), with a mostly moderate gradient and
858 velocities ranging from ~2 km/s to ~4 km/s; (2) a high gradient section underneath (0.6–2.8 km
859 dbf) with velocities of ~4.4–6.5 km/s; (3) a low gradient section (2.8–5.5 km dbf) further down
860 with a narrow range of velocities (6.5–7 km/s); and (4) a low gradient section (depth > 5.5 km
861 dbf) at the bottom with velocities ranging from 6.6 km/s to 8.1 km/s. The NS profile velocities
862 are mostly in agreement within the top section, lower than velocities of Niu et al. (2015) in the

863 top part and in agreement with the bottom part of the second section, are significantly higher in
 864 the third section, and somewhat higher in the fourth section. Niu et al. (2015) interpreted layers
 865 2A, 2B, and 3 overlying the uppermost mantle. The investigated segment center at 50°E has an
 866 anomalously thick crust, ranging from ~5.5 km to 10.2 km, and a robust and well-imaged axial
 867 magma chamber (Niu et al., 2015; Jian et al., 2016, 2017). This interpretation is consistent with a
 868 magma-rich spreading center and, as such, it differs from magma-starved spreading interpreted at
 869 64°30'E.

870 **6 Conclusions**

871 We constrain tomographic velocity structure across- and along-axis the ultraslow-
 872 spreading SWIR at 64°30'E by inverting first arrivals from two ~150-km-long orthogonal wide-
 873 angle OBS profiles. Our major findings and conclusions are the following:

- 874 1. About 75% of the investigated uppermost lithosphere appears to be composed of highly
 875 fractured and fully serpentinized peridotites at the top, with a gradual decrease in pore
 876 space volume and serpentinization degree to unaltered peridotites at depth. Key evidence
 877 for this are seismic velocities that increase rapidly with depth, changing from 3–4 km/s at
 878 the seafloor to 7 km/s at depths ranging from 1.5–6 km dbfs, much lower vertical velocity
 879 gradient for velocities >7 km/s that gradually reduces with increasing depth, and no
 880 distinct and seismically well-characterized Moho observable in the data.
- 881 2. A system of detachment faults is imaged in the subsurface for the first time in our study
 882 area by the profile that crosses the ridge axis. We interpret a sharp lateral change
 883 (horizontal gradient $\sim 1 \text{ s}^{-1}$) in velocities, switch in polarity of the largest velocity
 884 anomaly, from 1.5 km/s to -1.5 km/s, and high vertical gradient ($\sim 2 \text{ s}^{-1}$) in the velocities
 885 coincident with the shallow section (top 2 km) of the highest topographic feature as the
 886 seismic expression of an active axial detachment fault. Five abandoned detachment faults
 887 are also identified based on anomalously high velocities and vertical gradients that
 888 characterize the footwalls on all identified detachment faults, with the opposite
 889 characterizing the hanging walls. Serpentinization across-axis is controlled by the
 890 longevity of detachments and fault block movement, with longer-lived faults showing
 891 deeper serpentinization extent and footwalls showing less pervasive serpentinization due
 892 to continuous exhumation.
- 893 3. Comparison of the 1D velocity-depth functions at their crossing point between the two
 894 orthogonal profiles suggests an up to 5% ridge-parallel fast-axis anisotropy from ~0.5 to
 895 ~2.2 km dbfs attributed to the preferential distribution of cracks parallel to the ridge, and
 896 a similar magnitude but reversed polarity ridge-normal fast-axis anisotropy at >~2.2 km
 897 dbfs that we attribute to the lattice-preference orientation of olivine minerals in the less
 898 serpentinized peridotites.
- 899 4. Upper lithospheric composition along the western half of the axis-parallel profile seems
 900 to transition over a distance of ~10 km from the variably serpentinized peridotites
 901 domains in the East to predominately mafic magmatic domains in the West. The
 902 exhumed mantle domains show high and laterally variable seismic velocities at shallow
 903 depths, reaching 4–4.5 km/s within the first 0.5 km dbfs and 7 km/s at depths 2–3.5 km
 904 dbfs, a high vertical velocity gradient of $1\text{--}2 \text{ s}^{-1}$, and an overall positive velocity anomaly
 905 (up to 0.5-1 km/s). The mafic domains show sharply lower seismic velocities that reach

906 3.5 km/s at 0.5 km dbf and 7 km/s only at 4–5.3 km dbf, a moderate to low and
 907 smoother vertical velocity gradient of $0.5\text{--}1\text{ s}^{-1}$, and a large negative velocity anomaly of
 908 $-1.5\text{--}1\text{ km/s}$. We suggest that the change in the seafloor accretion mode is propelled by a
 909 westward increase in melt supply.

910 5. Comparison of velocity structure from our results at the ultraslow-spreading SWIR at
 911 $64^{\circ}30'E$ with the velocity structure elsewhere at the SWIR has shown an overall
 912 agreement of our results with studies at amagmatic segments, a disagreement with
 913 identified anomalously magma-rich segments, and mixed results for magma-starved
 914 segments, such as the SWIR at 66° and 57° E. This work has also demonstrated the
 915 challenges in carrying out meaningful velocity structure comparisons when the data
 916 resolution and techniques used to determine the velocities are not the same (e.g. layered
 917 modeling vs. tomography).

918 **Acknowledgments and data**

919 AC was supported by “la Caixa” Foundation [Scholarship LCF/BQ/AN15/10380004],
 920 NSERC CREATE TOSST (NSERC Collaborative Research and Training Experience for the
 921 Transatlantic Ocean System Science and Technology), and an NSERC Discovery Grant to MRN.
 922 AC also thanks HOSST and GEOMAR for their support and training experience during her
 923 research exchange. The authors are grateful to the Flotte Océanographique Française (FOF) and
 924 an NSERC Ship Time grants that funded the SISMOSMOOTH cruise, and CNRS-INSU Tellus,
 925 ANR Rift2Ridge NT09-48546 and RidgeFactory-Slow 18-CE01-0002-01 for providing support
 926 for the cruise. We also thank Captain Thierry Dudouit (CMO-CGM) and the crew of the R/V
 927 Marion-Dufresne, and Erwan Nedelec and Jean-Charles Guedes (Genavir) for the seismic
 928 deployment. Raw data are available on request from SISMER
 929 (<https://doi.org/10.17600/14003300>). Velocity models are available on request from the National
 930 Facility for Seismic Imaging (www.nfsi.ca). Figures were produced using the Generic Mapping
 931 Tools (GMT) software (Wessel and Smith, 1998).

932 **References**

- 933 Aghaei, O., Nedimović, M.R., Carton, H., Carbotte, S.M., Canales, J.P., & Mutter, J.C. (2014).
 934 Crustal thickness and Moho character of the fast-spreading East Pacific Rise from $9^{\circ} 42' N$ to 9°
 935 $57' N$ from poststack-migrated 3-D MCS data. *Geochemistry, Geophysics, Geosystems*, *15*(3),
 936 634-657. <https://doi.org/10.1002/2013GC005069>
- 937 Alt, J., Bach, W., Edwards, K., Frost, R., Früh-Green, G., Godard, M., et al. (2009). Drilling in
 938 Serpentine Sea. In *White Paper “Serpentine Sea” presented at the INVEST conference, Bremen*,
 939 23-25.
- 940 Argus, D.F., Gordon, R.G., & DeMets, C. (2011). Geologically current motion of 56 plates
 941 relative to the no-net-rotation reference frame. *Geochemistry, Geophysics, Geosystems*, *12*(11).
- 942 Arnulf, A.F., Harding, A.J., Singh, S.C., Kent, G.M. & Crawford, W. (2012). Fine-scale velocity
 943 structure of upper oceanic crust from full waveform inversion of downward continued seismic
 944 reflection data at the Lucky Strike Volcano, Mid-Atlantic Ridge. *Geophysical Research Letters*,
 945 *39*(8).

- 946 Barclay, A.H., Toomey, D.R., & Solomon, S.C. (1998). Seismic structure and crustal magmatism
947 at the Mid-Atlantic Ridge, 35° N. *Journal of Geophysical Research: Solid Earth*, 103(B8),
948 17827-17844.
- 949 Berge, P.A., Fryer, G.J., & Wilkens, R.H. (1992). Velocity-porosity relationships in the upper
950 oceanic crust: Theoretical considerations. *Journal of Geophysical Research: Solid Earth*,
951 97(B11), 15239-15254.
- 952 Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics,*
953 *Geosystems*, 4(3).
- 954 Bickert, M., Lavier, L., & Cannat, M. (2020). How do detachment faults form at ultraslow mid-
955 ocean ridges in a thick axial lithosphere? *Earth and Planetary Science Letters*, 533.
956 <https://doi.org/10.1016/j.epsl.2019.116048>
- 957 Blackman, D.K., Karson, J.A., Kelley, D.S., Cann, J.R., Früh-Green, G.L., Gee, J.S., et al.
958 (2002). Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30 N): Implications for the
959 evolution of an ultramafic oceanic core complex. *Marine Geophysical Researches*, 23(5), 443-
960 469.
- 961 Boulahanis, B., Carbotte, S.M., Huybers, P.J., Nedimović, M.R., Aghaei, O., Canales, J.P., &
962 Langmuir, C.H. (2020). Do sea level variations influence mid-ocean ridge magma supply? A test
963 using crustal thickness and bathymetry data from the East Pacific Rise. *Earth and Planetary*
964 *Science Letters*, 535. <https://doi.org/10.1016/j.epsl.2020.116121>
- 965 Bratt, S. R., & Purdy, G. M. (1984). Structure and variability of oceanic crust on the flanks of the
966 East Pacific Rise between 11° and 13°N. *Journal of Geophysical Research: Solid Earth*, 89,
967 6111–6125.
- 968 Canales, J.P., Detrick, R. S., Toomey, D. R., & Wilcock, W. S. D. (2003). Segment-scale
969 variations in the crustal structure of 150-300 kyr old fast spreading oceanic crust (East Pacific
970 rise, 8°15'N-10°5'N) from wide-angle seismic refraction profiles. *Geophysical Journal*
971 *International*, 152(3), 766–794. <https://doi.org/10.1046/j.1365-246X.2003.01885.x>
- 972 Canales, J.P., Detrick, R.S., Lin, J., Collins, J. A., & Toomey, D.R. (2000). Crustal and upper
973 mantle seismic structure beneath the rift. *Journal of Geophysical Research*, 105(B2), 2699–2719.
- 974 Canales, J.P., Tucholke, B.E. & Collins, J.A. (2004). Seismic reflection imaging of an oceanic
975 detachment fault: Atlantis megamullion (Mid-Atlantic Ridge, 30 10' N). *Earth and Planetary*
976 *Science Letters*, 222(2), 543-560.
- 977 Canales, J.P., Detrick, R.S., Carbotte, S.M., Kent, G.M., Diebold, J.B., Harding, A., et al. (2005).
978 Upper crustal structure and axial topography at intermediate spreading ridges: Seismic
979 constraints from the southern Juan de Fuca Ridge. *Journal of Geophysical Research: Solid*
980 *Earth*, 110(B12).
- 981 Cann, J.R., Blackman, D.K., Smith, D.K., McAllister, E., Janssen, B., Mello, S., et al. (1997).
982 Corrugated slip surfaces formed at ridge–transform intersections on the Mid-Atlantic Ridge.
983 *Nature* 385, 329–332. <https://doi.org/10.1038/385329a0>
- 984 Cannat, M. (1993). Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *Journal of*
985 *Geophysical Research: Solid Earth*, 98(B3), 4163-4172.

- 986 Cannat, M., Céline, R.J., & Fujimoto, H. (2003). Melt supply variations to a magma-poor ultra-
987 slow spreading ridge (Southwest Indian Ridge 61° to 69°E). *Geochemistry, Geophysics,*
988 *Geosystems*, 4(8), 1–21. <https://doi.org/10.1029/2002GC000480>
- 989 Cannat, M., Sauter, D., Mendel, V., Ruellan, E., Okino, K., Escartin, J., et al. (2006). Modes of
990 seafloor generation at a melt-poor ultraslow-spreading ridge. *Geology*, 34(7), 605–608.
991 <https://doi.org/10.1130/G22486.1>
- 992 Cannat, M., Sauter, D., Bezos, A., Meyzen, C., Humler, E., & Le Rigoleur, M. (2008). Spreading
993 rate, spreading obliquity, and melt supply at the ultraslow spreading Southwest Indian Ridge.
994 *Geochemistry, Geophysics, Geosystems*, 9(4), 1–26. <https://doi.org/10.1029/2007GC001676>
- 995 Cannat, M., Sauter, D., Lavier, L., Bickert, M., Momoh, E., & Leroy, S. (2019). On spreading
996 modes and magma supply at slow and ultraslow mid-ocean ridges. *Earth and Planetary Science*
997 *Letters*, 519, 223–233. <https://doi.org/10.1016/j.epsl.2019.05.012>
- 998 Carbotte, S.M. & Scheirer, D.S. (2004). Variability of ocean crustal structure created along the
999 global mid-ocean ridge. *Hydrogeology of the oceanic lithosphere*, 59-107.
- 1000 Carbotte, S.M., Detrick, R.S., Harding, A., Canales, J.P., Babcock, J., Kent, G., et al. (2006). Rift
1001 topography linked to magmatism at the intermediate spreading Juan de Fuca Ridge. *Geology*,
1002 34(3), 209-212.
- 1003 Carbotte, S.M., Nedimović, M.R., Canales, J.P., Kent, G.M., Harding, A.J. & Marjanović, M.
1004 (2008). Variable crustal structure along the Juan de Fuca Ridge: Influence of on-axis hot spots
1005 and absolute plate motions. *Geochemistry, Geophysics, Geosystems*, 9(8).
- 1006 Carlson, R.L. & Miller, D.J. (1997). A new assessment of the abundance of serpentinite in the
1007 oceanic crust. *Geophysical Research Letters*, 24(4), 457-460.
- 1008 Carlson, R.L., & Miller, D.J. (2003). Mantle wedge water contents estimated from seismic
1009 velocities in partially serpentinitized peridotites. *Geophysical Research Letters*, 30(5).
1010 <https://doi.org/10.1029/2002gl016600>
- 1011 Carter, D.J.T. (1980). Echosounding correction tables (formerly Matthews tables), Hydrographic
1012 Department, Ministry of Defenoe, Taunton, UK.
- 1013 Chen, Y.J. (1992). Oceanic crustal thickness versus spreading rate. *Geophysical Research*
1014 *Letters*, 19(8), 753-756.
- 1015 Christensen, N.I. (1972). The abundance of serpentinites in the oceanic crust. *The Journal of*
1016 *Geology*, 80(6), 709-719.
- 1017 Christensen, N.I. & Salisbury, M.H. (1975). Structure and constitution of the lower oceanic
1018 crust. *Reviews of Geophysics*, 13(1), 57-86.
- 1019 Christensen, N.I. (1978). Ophiolites, seismic velocities and oceanic crustal structure.
1020 *Tectonophysics*, 47(1-2), 131-157.
- 1021 Christensen, N.I. & Smewing, J.D. (1981). Geology and seismic structure of the northern section
1022 of the Oman ophiolite. *Journal of Geophysical Research: Solid Earth*, 86(B4), 2545-2555.
- 1023 Christensen, N.I. (1996). Poisson's ratio and crustal seismology. *Journal of Geophysical*
1024 *Research: Solid Earth*, 101(B2), 3139-3156.

- 1025 Christeson, G.L., McIntosh, K.D., & Karson, J.A. (2007). Inconsistent correlation of seismic
1026 layer 2a and lava layer thickness in oceanic crust. *Nature*, 445(7126), 418–421.
- 1027 Christeson, G.L., Goff, J.A., & Reece, R.S. (2019). Synthesis of oceanic crustal structure from
1028 two-dimensional seismic profiles. *Reviews of Geophysics*, 57, 504– 529.
1029 <https://doi.org/10.1029/2019RG000641>
- 1030 Christeson, G.L., Reece, R.S., Kardell, D.A., Estep, J.D., Fedotova, A. & Goff, J.A. (2020).
1031 South Atlantic Transect: Variations in Oceanic Crustal Structure at 31° S. *Geochemistry,*
1032 *Geophysics, Geosystems*, 21(7).<https://doi.org/10.1038/nature05517>
- 1033 deMartin, B.J., Sohn, R.A., Canales, J.P. & Humphris, S.E. (2007), Kinematics and geometry of
1034 active detachment faulting beneath the Trans-Atlantic Geotraverse (TAG) hydrothermal field on
1035 the Mid-Atlantic Ridge. *Geology*, 35, 711– 714.
- 1036 Dannowski, A., Grevemeyer, I., Ranero, C.R., Ceuleneer, G., Maia, M., Morgan, J.P. & Gente,
1037 P. (2010). Seismic structure of an oceanic core complex at the Mid-Atlantic Ridge, 22 19' N.
1038 *Journal of Geophysical Research: Solid Earth*, 115(B7).
- 1039 Detrick, R.S., Harding, A.J., Kent, G.M., Orcutt, J.A., Mutter, J.C. & Buhl, P. (1993). Seismic
1040 structure of the southern East Pacific Rise. *Science*, 259(5094), 499-503.
- 1041 Dick, H.J.B., Lin, J., & Schouten, H. (2003). An ultraslow-spreading class of ocean ridge.
1042 *Nature*, 426(6965), 405–412. <https://doi.org/10.1038/nature02128>
- 1043 Dick, H.J.B., Tivey, M.A. & Tucholke, B.E. (2008). Plutonic foundation of a slow-spreading
1044 ridge segment: Oceanic core complex at Kane Megamullion, 23 30' N, 45 20' W. *Geochemistry,*
1045 *Geophysics, Geosystems*, 9(5).
- 1046 Dick, H.J.B., Lissenberg, C.J., & Warren, J.M. (2010). Mantle Melting, Melt Transport, and
1047 Delivery Beneath a Slow-Spreading Ridge: The Paleo-MAR from 23°15'N to 23°45'N. *Journal*
1048 *of Petrology*, 51(1-2), 425–467. <https://doi.org/10.1093/petrology/egp088>
- 1049 Dick, H.J.B., Macleod, C.J., Blum, P., Abe, N., Blackman, D.K., Bowles, J.A., et al. (2019).
1050 Dynamic accretion beneath a slow-spreading ridge segment: IODP Hole 1473A and the Atlantis
1051 Bank Oceanic Core Complex. *Journal of Geophysical Research: Solid Earth*, 124(12), 12631-
1052 12659.
- 1053 Dunn, R.A., & Toomey, D.R. (2001). Crack-induced seismic anisotropy in the oceanic crust
1054 across the East Pacific Rise (9°30'N). *Earth and Planetary Science Letters*, 189(1–2), 9–17.
1055 [https://doi.org/10.1016/S0012-821X\(01\)00353-3](https://doi.org/10.1016/S0012-821X(01)00353-3)
- 1056 Escartín, J., Mével, C., MacLeod, C.J. & McCaig, A.M. (2003). Constraints on deformation
1057 conditions and the origin of oceanic detachments: The Mid-Atlantic Ridge core complex at 15
1058 45' N. *Geochemistry, Geophysics, Geosystems*, 4(8).
- 1059 Escartín, J., Smith, D.K., Cann, J., Schouten, H., Langmuir, C.H. & Escrig, S. (2008). Central
1060 role of detachment faults in accretion of slow-spreading oceanic lithosphere. *Nature*, 455(7214),
1061 790-794.
- 1062 Escartín, J. & Canales, J. P., (2011), Detachments in Oceanic Lithosphere: Deformation,
1063 Magmatism, Fluid Flow, and Ecosystems. *Eos Trans. AGU*, 92(4), 31.

- 1064 Estep, J., Reece, R., Kardell, D.A., Christeson, G.L. & Carlson, R.L. (2019). Seismic layer 2A:
1065 Evolution and thickness from 0-to 70-Ma crust in the slow-intermediate spreading South
1066 Atlantic. *Journal of Geophysical Research: Solid Earth*, 124(8), 7633-7651.
- 1067 Ewing, J. & Ewing, M. (1959). Seismic-refraction measurements in the Atlantic Ocean basins, in
1068 the Mediterranean Sea, on the Mid-Atlantic Ridge, and in the Norwegian Sea. *Geological Society
1069 of America Bulletin*, 70(3), 291-318.
- 1070 Früh-Green, G.L., Orcutt, B.N., Rouméjon, S., Lilley, M.D., Morono, Y., Cotterill, C., et al.
1071 (2018). Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif
1072 (IODP Expedition 357). *Lithos*, 323, 137-155.
- 1073 Fujie, G., Kasahara, J., Murase, K., Mochizuki, K. & Kaneda, Y. (2008). Interactive analysis
1074 tools for the wide-angle seismic data for crustal structure study (Technical Report). *Exploration
1075 Geophysics*, 39(1), 26-33.
- 1076 Grevemeyer, I., Weigel, W., & Jennrich, C. (1998). Structure and ageing of oceanic crust at 14 °
1077 S on the East Pacific Rise. *Geophysical Journal International*, 135, 573–584.
- 1078 Grevemeyer, I., Hayman, N. W., Peirce, C., Schwardt, M., Avendonk, H. J. A. Van, Dannowski,
1079 A., & Papenberg, C. (2018b). exhumation at an ultraslow-spreading centre. *Nature Geoscience*,
1080 11, 444–449. <https://doi.org/10.1038/s41561-018-0124-6>
- 1081 Grevemeyer, I., Ranero, C. R., & Ivandic, M. (2018a). Structure of oceanic crust and
1082 serpentinization at subduction trenches. *Geosphere*, 14(2), 395–418.
1083 <https://doi.org/10.1130/GES01537.1>
- 1084 Han, S., Carbotte, S.M., Carton, H., Mutter, J.C., Aghaei, O., Nedimović, M.R. & Canales, J.P.
1085 (2014). Architecture of on-and off-axis magma bodies at EPR 9 37–40' N and implications for
1086 oceanic crustal accretion. *Earth and Planetary Science Letters*, 390, 31-44.
- 1087 Hess, H.H. (1964). Seismic anisotropy of the uppermost mantle under oceans. *Nature*,
1088 203(4945),629-631.
- 1089 Horning, G., Canales, J.P., Carbotte, S. M., Han, S., Carton, H., Nedimović, M.R., & Van
1090 Keken, P.E. (2016). A 2-D tomographic model of the Juan de Fuca plate from accretion at axial
1091 seamount to subduction at the Cascadia margin from an active source ocean bottom seismometer
1092 survey. *Journal of Geophysical Research: Solid Earth*, 121(8), 5859-5879.
1093 <https://doi.org/10.1002/2016JB013228>
- 1094 Houtz, R., & Ewing, J. (1976). Upper crustal structure as a function of plate age. *Journal of
1095 Geophysical Research*, 81(14), 2490-2498.
- 1096 Ildefonse, B., Blackman, D.K., John, B.E., Ohara, Y., Miller, D.J. & MacLeod, C.J. (2007).
1097 Oceanic core complexes and crustal accretion at slow-spreading ridges. *Geology*, 35(7), 623-626.
- 1098 Ismail, W.B., & Mainprice, D. (1998). An olivine fabric database: an overview of upper mantle
1099 fabrics and seismic anisotropy. *Tectonophysics*, 296(1–2), 145–157.
1100 [https://doi.org/10.1016/S0040-1951\(98\)00141-3](https://doi.org/10.1016/S0040-1951(98)00141-3)
- 1101 Jian, H., Chen, Y.J., Singh, S.C., Li, J., Zhao, M., Ruan, A., & Qiu, X. (2016). Seismic structure
1102 and magmatic construction of crust at the ultraslow-spreading Southwest Indian Ridge at
1103 50°28'E. *Journal of Geophysical Research : Solid Earth*, 121, 18–42.
1104 <https://doi.org/10.1002/2016JB013377>

- 1105 Jian, H., Singh, S. C., Chen, Y. J., & Li, J. (2017). Evidence of an axial magma chamber beneath
1106 the ultraslow-spreading Southwest Indian Ridge. *Geology*, *45*(2), 143–146.
1107 <https://doi.org/10.1130/G38356.1>
- 1108 Jokat, W., & Schmidt-Aursch, M. C. (2007). Geophysical characteristics of the ultraslow
1109 spreading Gakkel Ridge, Arctic Ocean. *Geophysical Journal International*, *168*(3), 983–998.
1110 <https://doi.org/10.1111/j.1365-246X.2006.03278.x>
- 1111 Kandilarov, A., Landa, H., Mjelde, R., Pedersen, R. B., Okino, K., & Murai, Y. (2010). Crustal
1112 structure of the ultra-slow spreading Knipovich Ridge, North Atlantic, along a presumed ridge
1113 segment center. *Marine Geophysical Research*, *31*(3), 173–195. [https://doi.org/10.1007/s11001-](https://doi.org/10.1007/s11001-010-9095-8)
1114 [010-9095-8](https://doi.org/10.1007/s11001-010-9095-8)
- 1115 Kandilarov, A., Mjelde, R., Okino, K. & Murai, Y. (2008). Crustal structure of the ultra-slow
1116 spreading Knipovich Ridge, North Atlantic, along a presumed amagmatic portion of oceanic
1117 crustal formation. *Marine Geophysical Researches*, *29*(2), 109-134.
- 1118 Kardell, D.A., Christeson, G.L., Estep, J.D., Reece, R.S. & Carlson, R.L. (2019). Long-lasting
1119 evolution of layer 2A in the Western South Atlantic: Evidence for low-temperature hydrothermal
1120 circulation in old oceanic crust. *Journal of Geophysical Research: Solid Earth*, *124*(3), 2252-
1121 2273.
- 1122 Kelley, D.S., Karson, J.A., Früh-Green, G.L., Yoerger, D.R., Shank, T.M., Butterfield, D.A., et
1123 al. (2005). A serpentinite-hosted ecosystem: The Lost City Hydrothermal Field, *Science*,
1124 *307*(5714), 1428– 1434. <https://doi.org/10.1126/science.1102556>
- 1125 Klingelhöfer, F., Géli, L., Matias, L., Steinsland, N., & Mohr, J. (2000). Crustal structure of a
1126 super-slow spreading centre: A seismic refraction study of Mohns Ridge, 72°N. *Geophysical*
1127 *Journal International*, *141*(2), 509–526. <https://doi.org/10.1046/j.1365-246X.2000.00098.x>
- 1128 Korenaga, J., Holbrook, W.S., Kent, G.M., Kelemen, P.B., Detrick, R.S., Larsen, H.C., et al.
1129 (2000). Crustal structure of the southeast Greenland margin from joint refraction and reflection
1130 seismic tomography. *Journal of Geophysical Research*, *105*, 21591.
1131 <https://doi.org/10.1029/2000JB900188>
- 1132 Kreemer, C., Blewitt, G., & Klein C.E. (2014). A geodetic plate motion and Global Strain Rate
1133 Model. *Geochemistry, Geophysics, Geosystems*, 3849–3889.
1134 <https://doi.org/10.1002/2014GC005407>
- 1135 Lavier, L.L., Buck, W.R., & Poliakov, N.B. (1999). Self-consistent rolling-hinge model for the
1136 evolution of large-offset low-angle normal faults. *Geology*, *27*, 1127–1130, doi:10.1130/0091-
1137 7613(1999)027<1127:SCRHMF>2.3.CO;2.
- 1138 Leroy S., & Cannat, M. (2014). MD 199/SISMO-SMOOTH cruise, Marion Dufresne R/V.
1139 <https://doi.org/10.17600/14003300>
- 1140 Leroy, S., Cannat, M., Momoh, E., Singh, S., Watremez, L., Sauter, D., et al. (2015). Anatomy of
1141 ultra-slow spreading Southwest Indian Ridge: The 2014 SISMOSMOOTH cruise. Abstract
1142 V21A-3027 Paper presented at the 2015 AGU, San Francisco, CA, 14–18 Dec.
- 1143 Li, J., Jian, H., Chen, Y. J., Singh, S. C., Ruan, A., Qiu, X., et al. (2015). Seismic observation of
1144 an extremely magmatic accretion at the ultraslow spreading Southwest Indian Ridge.
1145 *Geophysical Research Letters*, *42*(8), 2656–2663. <https://doi.org/10.1002/2014GL062521>

- 1146 Lin, J., Purdy, G.M., Schouten, H. Sempere, J.C., & Zervas, C. (1990). Evidence from gravity
1147 data for focused magmatic accretion along the Mid-Atlantic Ridge. *Nature* 344, 627–632.
1148 <https://doi.org/10.1038/344627a0>
- 1149 Mével, C. (2003). Serpentinization of abyssal peridotites at mid-ocean. *Comptes Rendus*
1150 *Geoscience*, 335(10–11), 825–852. <https://doi.org/10.1016/j.crte.2003.08.006>
- 1151 Miller, D.J. & Christensen, N.I. (1997). Seismic velocities of lower crustal and upper mantle
1152 rocks from the slow-spreading Mid-Atlantic Ridge, south of the Kane Transform Zone (MARK).
1153 *In Proceedings-Ocean Drilling Program Scientific Results*, 437-456. National Science
1154 Foundation.
- 1155 Minshull, T.A., Muller, M.R., Robinson, C.J., White, R.S., & Bickle, M.J. (1998). Is the oceanic
1156 Moho a serpentinization front? *Geological Society, London, Special Publications*, 148(1), 71–80.
1157 <https://doi.org/10.1144/GSL.SP.1998.148.01.05>
- 1158 Minshull, T.A., Muller, M.R., & White, R.S. (2006). Crustal structure of the Southwest Indian
1159 Ridge at 66°E: Seismic constraints. *Geophysical Journal International*, 166(1), 135–147.
1160 <https://doi.org/10.1111/j.1365-246X.2006.03001.x>
- 1161 Momoh, E., Cannat, M., Watremez, L., Leroy, S., & Singh, S. C. (2017). Quasi-3-D Seismic
1162 Reflection Imaging and Wide-Angle Velocity Structure of Nearly Amagmatic Oceanic
1163 Lithosphere at the Ultraslow-Spreading Southwest Indian Ridge. *Journal of Geophysical*
1164 *Research: Solid Earth*, 122(12), 9511–9533. <https://doi.org/10.1002/2017JB014754>
- 1165 Momoh, E., Cannat, M., & Leroy, S. (2020). Internal Structure of the Oceanic Lithosphere at a
1166 Melt-Starved Ultraslow-Spreading Mid-Ocean Ridge: Insights From 2-D Seismic Data.
1167 *Geochemistry, Geophysics, Geosystems*, 21(2). <https://doi.org/10.1029/2019GC008540>
- 1168 Moser T.J. (1991). Shortest path calculation of seismic rays. *Geophysics*, 56, 9–159.
1169 <https://doi.org/10.1190/1.1442958>
- 1170 Moser T.J., Van Eck T., & Nolet G. (1992). Hypocenter determination in strongly heterogeneous
1171 earth models using the shortest path method. *Journal of Geophysical Research: Solid Earth*, 97,
1172 6563–6572. <https://doi.org/10.1190/1.1442958>.
- 1173 Muller, M.R., Robinson, C.J., Minshull, T.A., White, R.S., & Bickle, M.J. (1997). Thin crust
1174 beneath Ocean Drilling Program Borehole 735B at the Southwest Indian Ridge? *Earth and*
1175 *Planetary Science Letters*, 148(1–2), 93–107. [http://dx.doi.org/10.1016/S0012-821X\(97\)00030-7](http://dx.doi.org/10.1016/S0012-821X(97)00030-7)
- 1176 Muller, M.R., Minshull, T.A. & White, R.S. (1999). Segmentation and melt supply at the
1177 Southwest Indian Ridge. *Geology*, 27(10), 867-870.
- 1178 Muller, M.R., Minshull, T.A., & White, R.S. (2000). Crustal structure of the Southwest Indian
1179 Ridge at the Atlantis II Fracture Zone. *Journal of Geophysical Research*, 105(B11), 25809 –
1180 25828.
- 1181 Müller, R.D., Sdrolias, M., Gaina, C., & Roest, W.R. (2008). Age, spreading rates, and spreading
1182 asymmetry of the world’s ocean crust. *Geochemistry, Geophysics, Geosystems*, 9(4), 1–19.
1183 <https://doi.org/10.1029/2007GC001743>
- 1184 Nedimović, M.R., Carbotte, S.M., Harding, A.J., Detrick, R.S., Canales, J.P., Diebold, J.B., et al.
1185 (2005). Frozen magma lenses below the oceanic crust. *Nature*, 436(7054), 1149-1152.

- 1186 Nedimović, M.R., Carbotte, S.M., Diebold, J.B., Harding, A.J., Canales, J.P., & Kent, G.M.
1187 (2008). Upper crustal evolution across the Juan de Fuca ridge flanks. *Geochemistry, Geophysics,*
1188 *Geosystems*, 9(9). <https://doi.org/10.1029/2008GC002085>
- 1189 Newman, K.R., Nedimović, M.R., Canales, J.P. & Carbotte, S.M. (2011). Evolution of seismic
1190 layer 2B across the Juan de Fuca Ridge from hydrophone streamer 2-D travelttime tomography.
1191 *Geochemistry, Geophysics, Geosystems*, 12(5).
- 1192 Niu, X., Ruan, A., Li, J., Minshull, T.A., Sauter, D., Wu, Z., et al. (2015), Along-axis variation in
1193 crustal thickness at the ultraslow spreading Southwest Indian Ridge (50°E) from a wide-angle
1194 seismic experiment, *Geochemistry, Geophysics, Geosystems*, 16, 468–485,
1195 doi:10.1002/2014GC005645
- 1196 Papazachos C., & Nolet G. (1997). P and S deep velocity structure of the Hellenic area obtained
1197 by robust nonlinear inversion of travel times. *Journal of Geophysical Research: Solid Earth*,
1198 102(B4), 8349–8367. doi: <https://doi.org/10.1029/96JB03730>.
- 1199 Parnell-Turner, R., Sohn, R.A., Peirce, C., Reston, T.J., MacLeod, C.J., Searle, R.C., & Simão,
1200 N.M. (2017). Oceanic detachment faults generate compression in extension. *Geology*, 45, 923–
1201 926. <https://doi.org/10.1130/G39232.1>
- 1202 Peterson, J.J., Fox, P.J., & Schreiber, E. (1974). Newfoundland ophiolites and the geology of the
1203 oceanic layer. *Nature*, 247(5438), 194-196.
- 1204 Raitt, R.W. (1963). The crustal rocks. *The Sea*, vol. 3, 85–102. Edited by M. N. Hill. Wiley
1205 Interscience, New York.
- 1206 Reston, T., & McDermott, K.G. (2011). Successive detachment faults and mantle unroofing at
1207 magma-poor rifted margins. *Geology*, 39(11), 1071-1074.
- 1208 Reston, T. (2018). Flipping detachments: The kinematics of ultraslow spreading ridges. *Earth*
1209 *and Planetary Science Letters*, 503, 144–157. <https://doi.org/10.1016/j.epsl.2018.09.032>
- 1210 Rouméjon, S., Cannat, M., Agrinier, P., Godard, M., & Andreani, M. (2014). Serpentinization
1211 and fluid pathways in tectonically exhumed peridotites from the southwest Indian ridge (62-
1212 65°E). *Journal of Petrology*, 56(4), 703–734. <https://doi.org/10.1093/petrology/egv014>
- 1213 Sauter, D., & Cannat, M. (2010). The Ultraslow Spreading Southwest Indian Ridge. *Diversity of*
1214 *Hydrothermal Systems on Slow Spreading Ocean Ridges*, (November), 153–173.
1215 <https://doi.org/10.1029/2008GM000843>
- 1216 Sauter, D., Cannat, M., & Mendel, V. (2008). Magnetization of 0-26.5 Ma seafloor at the
1217 ultraslow spreading Southwest Indian Ridge, 61°-67°E. *Geochemistry, Geophysics, Geosystems*,
1218 9(4), 1–23. <https://doi.org/10.1029/2007GC001764>
- 1219 Sauter, D., Cannat, M., Rouméjon, S., Andreani, M., Birot, D., Bronner, A., et al. (2013).
1220 Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million
1221 years. *Nature Geoscience*, 6(4), 314–320. <https://doi.org/10.1038/ngeo1771>
- 1222 Schlindwein, V. & Schmid, F. (2016). Mid-ocean-ridge seismicity reveals extreme types of
1223 ocean lithosphere. *Nature*, 535(7611), 276–279. <https://doi.org/10.1038/nature18277>

- 1224 Schrenk, M.O., Kelley, D.S., Bolton, S.A., & Baross, J.A. (2004). Low archaeal diversity linked
1225 to seafloor geochemical processes at the Lost City Hydrothermal Field, Mid-Atlantic Ridge.
1226 *Environmental Microbiology*, 6(10), 1086-1095.
- 1227 Seher, T., Crawford, W.C., Singh, S.C., Cannat, M., Combier, V., & Dusunur, D. (2010). Crustal
1228 velocity structure of the Lucky Strike segment of the Mid-Atlantic Ridge at 37°N from seismic
1229 refraction measurements. *Journal of Geophysical Research: Solid Earth*, 115(B3).
- 1230 Seyler, M., Cannat, M., & Mével, C. (2003). Evidence for major-element heterogeneity in the
1231 mantle source of abyssal peridotites from the Southwest Indian Ridge (52° to 68°E).
1232 *Geochemistry, Geophysics, Geosystems*, 4(2). <https://doi.org/10.1029/2002GC000305>
- 1233 Smith, D.K., Cann, J.R., & Escartín, J. (2006). Widespread active detachment faulting and core
1234 complex formation near 13°N on the Mid-Atlantic Ridge. *Nature*, 442(7101), 440-443.
- 1235 Talwani, M., Le Pichon, X., & Ewing, M. (1965). Crustal structure of the mid-ocean ridges: 2.
1236 Computed model from gravity and seismic refraction data. *Journal of Geophysical Research*,
1237 70(2), 341-352.
- 1238 Talwani, M., Windisch, C.C., & Langseth Jr, M.G. (1971). Reykjanes ridge crest: A detailed
1239 geophysical study. *Journal of Geophysical Research*, 76(2), 473-517.
- 1240 Tarantola, A. (1987). Inversion of travel times and seismic waveforms. *Seismic tomography*,
1241 135-157.
- 1242 Toomey, D.R., & Foulger, G.R. (1989). Tomographic inversion of local earthquake data from
1243 the Hengill-Grensdalur central volcano complex, Iceland. *Journal of Geophysical Research:*
1244 *Solid Earth*, 94(B12), 17497-17510.
- 1245 Tucholke, B.E., & Lin, J. (1994). A geological model for the structure of ridge segments in slow
1246 spreading ocean crust. *Journal of Geophysical Research: Solid Earth*, 99(B6), 11937-11958.
- 1247 Tucholke, B.E., Lin, J., & Kleinrock, M.C. (1998). Megamullions and mullion structure defining
1248 oceanic metamorphic core complexes on the Mid-Atlantic Ridge. *Journal of Geophysical*
1249 *Research: Solid Earth*, 103(B5), pp.9857-9866.
- 1250 Van Avendonk, H.J.A., Harding, A.J., Orcutt, J.A., & McClain, J.S. (1998). A two-dimensional
1251 tomographic study of the Clipperton transform fault. *Journal of Geophysical Research: Solid*
1252 *Earth*, 103, 17885–17899. doi: <https://doi.org/10.1029/98JB00904>
- 1253 Van Avendonk, H.J.A., Hayman, N.W., Harding, J.L., Grevemeyer, I., Peirce, C., & Dannowski,
1254 A. (2017). Seismic structure and segmentation of the axial valley of the Mid-Cayman Spreading
1255 Center. *Geochemistry, Geophysics, Geosystems*, 1–13. <https://doi.org/10.1002/2017GC006873>
- 1256 VanderBeek, B.P., Toomey, D.R., Hooft, E.E.E., & Wilcock, W.S.D. (2016). Segmentation of
1257 mid-ocean ridges attributed to oblique mantle divergence. *Nature Geosciences*, 9, 636–642.
1258 <https://doi.org/10.1038/ngeo2745>
- 1259 Vera, E.E., & Diebold, J.B. (1994). Seismic imaging of oceanic layer 2A between 9°30'N and
1260 10°N on the East Pacific Rise from two-ship wide-aperture profiles. *Journal of Geophysical*
1261 *Research*, 99(B2), 3031–3041. <https://doi.org/10.1029/93JB02107>

- 1262 Watremez, L., Lau, H.K.W., Nedimović, M.R., & Louden, K.E. (2015). Traveltime tomography
1263 of a dense wide-angle profile across Orphan Basin. *Geophysics*, *80*(3), B69–B82.
1264 <https://doi.org/10.1190/geo2014-0377.1>
- 1265 Weekly, R.T., Wilcock, W.S.D., Toomey, D.R., Hooft, E.E.E., & Kim, E. (2014). Upper crustal
1266 seismic structure of the Endeavour segment, Juan de Fuca Ridge from traveltime tomography:
1267 Implications for oceanic crustal accretion. *Geochemistry, Geophysics, Geosystems*, *15*(4), 1296–
1268 1315. <https://doi.org/10.1002/2013GC005159>
- 1269 Wessel, P., & Smith, W.H.F. (1998). New, improved version of Generic Mapping Tools
1270 released. *Eos, Transactions American Geophysical Union* (*79*), 579-579.
1271 <https://doi.org/10.1029/98EO00426>.
- 1272 Wilcock, W.S.D., Solomon, S.C., Purdy, G.M. & Toomey, D.R. (1992). The seismic attenuation
1273 structure of a fast-spreading mid-ocean ridge. *Science*, *258*(5087), 1470-1474.
- 1274 White, R.S., Mckenzie, D., & O'Nions, R.K. (1992). Oceanic crustal thickness from seismic
1275 measurements and rare earth element inversions. *Journal of Geophysical Research*, *97*(B13),
1276 19683-19715.
- 1277 Xu, M., Zhao, X., & Canales, J. P. (2020). Structural variability within the Kane oceanic core
1278 complex from full waveform inversion and reverse time migration of streamer data. *Geophysical*
1279 *Research Letters*, *47*, e2020GL087405 <https://doi.org/10.1029/2020GL087405>
- 1280 Zhang, J., & Töksöz, M.N. (1998). Nonlinear refraction traveltime tomography. *Geophysics*, *63*,
1281 1726–1737, doi: <https://doi.org/10.1190/1.1444468>.
- 1282 Zhao, M., Qiu, X., Li, J., Sauter, D., Ruan, A., Chen, J., et al. (2013). Three-dimensional seismic
1283 structure of the Dragon Flag oceanic core complex at the ultraslow spreading Southwest Indian
1284 Ridge (49°39'E). *Geochemistry, Geophysics, Geosystems*, *14*(10), 4544–4563.
1285 <https://doi.org/10.1002/ggge.20264>
- 1286 Zhou, H., & Dick, H.J.B. (2013). Thin crust as evidence for depleted mantle supporting the
1287 Marion Rise. *Nature*, *494*(7436), 195-200.