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# Microseismicity and lithosphere thickness at a nearly-amagmatic oceanic detachment fault system

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1 **Microseismicity and lithosphere thickness at a flip-flop detachment fault**  
2 **system of a nearly-amagmatic mid-ocean ridge**

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6

7 **Oceanic detachment faults play a central role in accommodating the plate**  
8 **divergence at slow-ultraslow spreading mid-ocean ridges. Successive flip-flop**  
9 **detachment faults in a nearly-amagmatic region of the ultraslow spreading Southwest**  
10 **Indian Ridge (SWIR) at 64°30'E accommodate ~100% of plate divergence, with mostly**  
11 **ultramafic smooth seafloor. Here we present new microseismicity data, recorded by**  
12 **ocean bottom seismometers, showing that the axial brittle lithosphere is on the order of**  
13 **15 km thick under the nearly-amagmatic smooth seafloor, which is no thicker than**  
14 **under nearby volcanic seafloor or at more magmatic SWIR detachment systems. Our**  
15 **data reveal that microearthquakes with normal focal mechanisms are collocated with**  
16 **seismically-imaged damage zones of the active detachment fault and of antithetic**  
17 **hanging-wall faults, suggesting that both faults accommodate almost all of plate**  
18 **divergence. The level of the hanging-wall seismicity is significantly higher than that**  
19 **documented at more magmatic detachments of slow-ultraslow ridges, which may be a**  
20 **unique feature of nearly-amagmatic flip-flop detachment systems.**

21

22 The flip-flop detachment fault system discovered at a nearly-amagmatic region of the  
23 ultraslow spreading Southwest Indian Ridge (SWIR; full spreading rate of 14 mm/yr) near  
24 64°30'E represents a previously unknown seafloor spreading mode<sup>1-3</sup> (Fig. 1a). In this mode,  
25 detachment faults accommodate nearly 100% of plate divergence, continuously cutting into  
26 the footwalls of their predecessors, with flipping polarities every 0.6-1.5 Ma<sup>1,2</sup> (Fig. 1). The  
27 resulting seafloor morphology is the so-called smooth seafloor<sup>4</sup>, with extensive exposure of  
28 mantle-derived peridotites, only patches of hummocky basalts<sup>2</sup>, and low-temperature  
29 carbonate-brucite hydrothermal chimneys<sup>5</sup>. This newly-discovered seafloor spreading mode  
30 differs from the “classic” detachment-volcanic and volcanic-volcanic modes at slow  
31 spreading ridges and at more magmatically-robust portions of ultraslow spreading ridges,  
32 where at least one plate is dominated by abyssal-hill volcanic seafloor<sup>4,6-9</sup> and the detachment  
33 fault is characterized by dome-shaped corrugated surface<sup>10-12</sup>.

34 Seismicity provides a means to study magmatic, tectonic, and hydrothermal processes  
35 within the lithosphere of mid-ocean ridges<sup>13-19</sup> (MORs) and is an indirect proxy for the  
36 thermal regime by constraining the depth to the base of the brittle lithosphere<sup>20,21</sup>. Here, we  
37 present a catalog of 307 microearthquakes recorded during two short (8 and 19 days for the  
38 SMSMO and RVSMO catalogs, respectively) ocean bottom seismometer (OBS) deployments  
39 (Figs. 1 and 2a; Methods). These microearthquakes and 8 focal mechanisms (Methods) reveal  
40 a unique distribution of geodynamic stress and accommodation at the youngest active  
41 detachment system (DF1) of the SWIR 64°30'E.

## 42 **Results and discussion**

### 43 **Microseismicity at the SWIR 64°30'E**

44 The two short OBS deployments offer snapshots in time of the seismic activity at the  
45 youngest active detachment system. The average seismicity rate is 11.4 events per day (8.4

46 and 12.7 events per day in the SMSMO and RVSMO catalogs, respectively), including a 34-  
47 event seismic swarm in the RVSMO catalog, from Dec 22-23, 2016 (Supplementary Fig. 5).  
48 Most microearthquakes occurred in the axial valley (Fig. 2a) between the emergence of DF1  
49 (E1) and the breakaway of DF2 (B2). The highest number of events is recorded near the P2-  
50 P2' cross-axis profile (Figs. 2a and 2c). Earthquake hypocenters have depths between 0 and  
51 15 km below the seafloor (bsf), and events in the shorter SMSMO catalog were mostly at less  
52 than 10 km bsf (Fig. 2b). Local magnitudes ( $M_L$ ) range from -0.5 to 3.2, with a magnitude of  
53 completeness of 1.1 and a b-value of 0.9 based on the Gutenberg-Richter relation<sup>22</sup> (Methods  
54 and Supplementary Fig. 6). Focal mechanisms (Methods) correspond to normal faulting, as  
55 expected in an extensional context, except for one strike-slip faulting event (Fig. 2a).

56 Many microearthquake hypocenters plotted in the cross-axis profiles P1-P1' and P2-P2'  
57 (Figs. 2d and 2e) are aligned with the trace of the subseafloor detachment fault plane as  
58 inferred from a series of subparallel seismic reflectors with a dip of 50-60°<sup>23,24</sup>. In all three  
59 cross-axis profiles, and particularly P3-P3', several events are scattered in the detachment  
60 hanging wall. Focal mechanisms of these hanging-wall earthquakes display a prevalence of  
61 normal faults with an average dip of 50° at 2-7 km bsf (Figs. 2e and 2f). These dips are  
62 consistent with the geometry of nearby north-dipping seismic reflectors<sup>23</sup> (Fig. 2f) and with  
63 small-offset fault scarps at the seafloor<sup>2</sup>, suggesting that these small faults are conjugate with  
64 the detachment fault.

65 Along the ridge axis (P0-P0'), we also observed a larger number of earthquakes at the  
66 transition between volcanic and smooth seafloor (near the P2-P2' profile; Figs. 2c and 2e).  
67 Combining this observation with the previous observation of subhorizontal seismic reflectors  
68 interpreted as intrusive magmatic sills beneath this transition<sup>24</sup>, we propose that seismicity  
69 may be elevated here because the crystallized basalts or gabbros (beneath the volcanic  
70 seafloor) are more prone to seismogenic rupture than the ultramafic basement (beneath the

71 smooth seafloor) in which stress may be accommodated by creeps due to serpentinization.  
72 Our observations may thus provide a framework to examine earthquake generation at  
73 detachment systems, interacting with sparse magmatism.

#### 74 **Maximum depth of earthquakes and the axial thermal regime**

75 The thickness of the axial brittle lithosphere, which is commonly interpreted by the  
76 maximum depth of earthquakes<sup>20,25,26</sup>, is predicted to increase as spreading rate decreases<sup>20</sup>  
77 and/or as melt supply decreases<sup>27</sup>. The 64°30'E region of the ultraslow spreading SWIR,  
78 being nearly amagmatic, may be regarded as a calibration for the brittle lithosphere thickness  
79 of the MOR system. Although our two OBS deployments only recorded a few hundred  
80 microearthquakes, the maximum depth of earthquake hypocenters is on the order of 15 km,  
81 and this depth is mostly uniform along the ridge axis, across the transition from volcanic to  
82 nearly-avolcanic smooth seafloor (Fig. 2c). The thickness of the brittle lithosphere is mainly  
83 controlled by the thermal regime with its base roughly corresponding to the ~650°C  
84 isotherm<sup>21,28,29</sup> (i.e., at least 15 km deep at the SWIR 64°30'E). This temperature condition is  
85 consistent with the minimum depth of 18 km for the 800-1000°C isotherm at the SWIR  
86 64°30'E, determined from petrological constraints for the high-stress ductile deformation of  
87 sheared peridotites<sup>30,31</sup>.

88 A greater maximum depth of microearthquakes (~20 km) was found at the adjacent  
89 magma-poor SWIR 65°10'E<sup>32</sup>, but these earthquakes were located using a significantly  
90 different velocity model constrained from the magmatically-robust segment #8 volcano<sup>33</sup>  
91 (Supplementary Fig. 2 ). We also obtain a maximum earthquake depth of ~20 km if we apply  
92 their velocity model to our events (Methods and Supplementary Fig. 8), although this model  
93 is absolutely unsuitable to the nearly-amagmatic setting of the SWIR 64°30'E.

94 Intriguingly, the maximum earthquake depth at the Dragon Horn area (SWIR 49°36'E),

95 which has the same spreading rate but is more magmatic than the SWIR 64°30'E, is also on  
96 the order of 15 km<sup>18,34</sup>. There thus appears to be a disconnection between the maximum  
97 earthquake depth and melt supply at ultraslow spreading ridges, putting into question a direct  
98 relationship between the thickness of the axial brittle lithosphere and the amount of melt  
99 supply to the ridge axis. A recent numerical thermal model provides a possible explanation  
100 by considering melt emplacement depth<sup>35</sup>: at a given spreading rate and melt supply, the  
101 thermal regime can be colder if melt is emplaced in the shallow hydrothermally-active  
102 region. This shallow melt body will be cooled very rapidly, leading to an axial thermal  
103 regime beneath the hydrothermal domain that is identical to no melt supply<sup>35</sup>.

#### 104 **Microseismicity at detachment systems**

105 The seismicity pattern of the active flip-flop detachment fault at the SWIR 64°30'E is  
106 characterized by earthquakes aligned with the trace of the detachment fault plane and by  
107 coinciding with antithetic normal faults in the detachment hanging wall (Fig. 3b). The  
108 detachment-faulting events are similar to those observed at the more magmatic corrugated  
109 detachment faults, such as at 26°10'N<sup>15</sup> (TAG), 13°20'N<sup>16,17</sup>, and 14°50'N (Logatchev) of the  
110 Mid-Atlantic Ridge<sup>15-17,19</sup> (MAR) and at the SWIR Dragon Horn<sup>18,34</sup>. However, these  
111 detachment faults have very few hanging-wall earthquakes (Fig. 3). We propose that the  
112 hanging-wall seismicity may be a signature of the nearly-amagmatic flip-flop detachment  
113 system, where the plate spreading is accommodated by both detachment and hanging-wall  
114 faulting with very few magma intrusions. Such hanging-wall faults may be newly generated  
115 as the plate stretches and/or the relic of damage zones of the previous footwall. In contrast to  
116 the corrugated mode of detachment faults, magma intrusions are responsible for a  
117 considerable part of the plate spreading in the hanging wall, which largely reduces the  
118 hanging-wall faulting and seismicity.

119 In conclusion, our study of two short OBS deployments at the nearly-amagmatic 64°30'E  
120 section of the SWIR reveals an active flip-flop detachment fault and its hanging-wall  
121 seismicity observed at no other detachment system. We also suggest that the upper limit of  
122 lithospheric thickness at oceanic spreading centers may be on the order of 15 km.

## 123 **Methods**

### 124 **Microearthquake experiments**

125 The first experiment, using 14 OBSs in a cross configuration, recorded 8 days of  
126 microearthquakes in between airgun shots during the SISMOSMOOTH active seismic survey  
127 in October 2014 (R/V *Marion Dufresne*; SMSMO catalog; Fig. 1). The second experiment,  
128 using 6 OBSs in a hexagon configuration, continuously recorded 19 days of  
129 microearthquakes during the ROVSMOOTH cruise in December 2016 (R/V *Pourquoi Pas?*;  
130 RVSMO catalog; Fig. 1). Each OBS recorded three orthogonal ground motions plus pressure  
131 signals, with all channels recording at 250 Hz during the SISMOSMOOTH cruise and at 500  
132 Hz during the ROVSMOOTH cruise.

### 133 **Earthquake detection**

134 The internal clocks of the OBSs were synchronized on deployment and recovery, and a linear  
135 drift correction was applied. Earthquake events were network detected by the CONDET  
136 program in the SEISAN software<sup>36</sup> using the STA/LTA trigger algorithm, and an automatic  
137 picking procedure<sup>37</sup> was used to pick P and S wave arrival onsets. These events were  
138 registered in the SEISAN database, and P- and S-wave arrival onsets were manually refined  
139 (Supplementary Fig. 1).

### 140 **1-D velocity model**

141 The 1-D P-wave velocity model was calculated using the VELEST program<sup>38</sup>. The initial  
142 velocity model was extracted from a seismic refraction experiment across DF1 from the

143 SISMOSMOOTH cruise<sup>23</sup>. This model generally agrees with a broader velocity model at the  
144 same area<sup>39</sup> (Supplementary Fig. 2). Only events with  $OBS \geq 6$  and  $GAP \leq 180^\circ$  were used in  
145 the VELEST program. The best-fitting P-wave velocity model was iteratively searched  
146 (Supplementary Fig. 2). The final root-mean-square (RMS) is 107 ms. The S-wave velocity  
147 ( $V_s$ ) model is calculated using a best-fitting  $V_p/V_s$  ratio of 1.7, based on the Wadati diagram  
148 that plots the travel time of P-wave versus travel time differences of P- and S- waves (S-P  
149 time; Supplementary Fig. 3).

### 150 **Earthquake location and relocation**

151 The initial earthquake locations were searched by the NonLinLoc software with the Oct-tree  
152 algorithm<sup>40</sup> and the SWIR 64°30'E velocity model (Supplementary Fig. 2). The maximum  
153 likelihood hypocenter is used to locate each earthquake event, and a three-dimension error  
154 ellipsoid (68% confidence) is generated from the posterior density function (PDF) scatter  
155 samples<sup>40</sup>. 507 events of SMSMO (122) and RVSMO (385) catalogs were located with four  
156 or more stations, and 388 events of SMSMO (88) and RVSMO (300) catalogs are well  
157 located with horizontal and depth errors of  $<5$  km and RMS residual of  $<100$  ms  
158 (Supplementary Figs. 8a-1 to 8d-1). Station corrections, given by the average travel time  
159 residuals at each OBS calculated by the NonLinLoc software in an iterative way, were  
160 applied for the P and S phases (Supplementary Fig. 4): the mean absolute station correction is  
161  $60 \pm 40$  ms in both catalogs. P- and S-waves travel time residuals follow the Gaussian  
162 distribution with an average RMS misfit of 34 ms (Supplementary Fig. 9). Bootstrap analysis  
163 of location errors was applied for four chosen groups of NonLinLoc located events to show  
164 the stability of the hypocenter estimates: 1) two swarm events in the RVSMO catalog, 2) two  
165 deep events in the RVSMO catalog (beneath smooth and volcanic seafloor), 3) one hanging-  
166 wall event in the SMSMO catalog, and 4) two detachment-fault events in both SMSMO and  
167 RVSMO catalogs (Supplementary Fig. 10).



168 We also applied the SWIR 65-66°E velocity model<sup>32</sup> (Supplementary Fig. 2), constrained  
169 from a more magmatically-robust area than our study area<sup>23,33</sup>, to locate earthquakes recorded  
170 in our study area using the NonLinLoc software (Supplementary Figs. 8a-2 to 8d-2).  
171 Earthquakes with more distant epicenters to the OBS network tend to have deeper  
172 hypocenters to form an inverted V shape of along-axis hypocenter depth distribution  
173 (Supplementary Figs. 8b-2), which is similar to what was proposed at the SWIR 65-66°E<sup>32</sup>.  
174 NonLinLoc hypocenters with six or more stations, horizontal and depth errors of <5 km, and  
175 RMS residual of <100 ms, were relocated using the Double-Difference Hypocenter  
176 (HypoDD) algorithm<sup>41</sup>. The relocation uses both catalog and cross-correlation  
177 (Supplementary Figs. 11a-3 to 11d-3) and runs using the python module HypoDDpy<sup>42</sup>. A  
178 time window of 300 ms was applied based on pickings of P and S arrival onsets, and cross-  
179 correlated waveforms with a correlation coefficient lower than 0.6 were rejected.  
180 Supplementary Fig. 12 shows the differences between the NonLinLoc locations and the  
181 HypoDD relocations for 30 randomly selected events. 307 well-constrained absolute  
182 hypocenters were relocated with mean relative location errors of 500 m E-W, 400 m N-S, and  
183 500 m in depth.

184 We also tested catalog only (Supplementary Figs. 11a-1 to 11d-1) and cross-correlation only  
185 (Supplementary Figs. 11a-2 to 11d-2) in the HypoDD algorithm, which show more located  
186 earthquakes than both catalog and cross-correlation (Supplementary Figs. 11a-3 to 11d-3).  
187 Hypocenter location patterns in three algorithms are relatively stable.

### 188 **Earthquake magnitude calculation**

189 The definition of local magnitudes ( $M_L$ ) is given by<sup>43</sup>:

$$190 \quad M_L = \log(A) + n \log(r) + K r + C, \quad (1)$$

191 where A (in nm) is the maximum amplitude of horizontal components picked in the Wood-

192 Anderson seismogram<sup>44</sup>,  $r$  (in km) is the hypocentral distance,  $C$  is a correction for each  
193 OBS, and  $n$  and  $K$  are constants to be calculated and related to geometrical spreading and  
194 attenuation of seismic waves, respectively. The local magnitudes, parameters  $n$  and  $K$ , and  
195 station correction can be solved by a least-squares criterion that produces an optimal  
196 solution<sup>45,46</sup>. For the SMSMO and RVSMO catalogs together, we obtain  $n = -2.923$ ,  $K =$   
197  $5.85 \times 10^{-3}$ , and  $C = (-3)-(-2)$ . Magnitude completeness ( $M_c$ ) is determined as 1.1 using the b-  
198 value stability approach<sup>47</sup>, resulting in a b-value of 0.9.

### 199 **First-motion focal mechanism**

200 To calculate best-fitting focal mechanisms, we use two first-motion-based algorithms,  
201 HASH<sup>48</sup> and FOCMEC<sup>49</sup>. Multiple criteria were applied: apparent first-motion polarities of  
202 P-wave onsets  $\geq 8$ , azimuthal gaps  $\leq 250^\circ$ , the weighted fraction of misfit polarities  $< 10\%$ ,  
203 RMS of fault plane uncertainty from HASH  $\leq 35^\circ$  (95% confidence), and similar reasonable  
204 solutions generated by both approaches. Eight acceptable focal mechanisms were found in  
205 the SMSMO catalog (Fig. 2). The azimuthal gaps of accepted focal mechanisms are all  $> 90^\circ$ ,  
206 so that their quality grades based on the HASH criteria are all in category E (A is the best  
207 constrained). We did not obtain focal mechanisms in the RVSMO deployment due to the  
208 lesser number of OBSs.

### 209 **Data availability**

210 OBS locations, two earthquake catalogs, swarm events, and focal mechanisms in this study  
211 are provided in the Supplementary Information. Any remaining raw datasets of this study and  
212 additional information of the SISMOSMOOTH<sup>50</sup> and ROVSMOOTH<sup>51</sup> cruises are available  
213 at <https://doi.org/10.17600/14003300> and <https://doi.org/10.17600/16002000>.

## 214 Code availability

215 The software and codes used in this study included: SEISAN software<sup>36</sup>  
216 (<http://www.seisan.info/>), VELEST program<sup>38</sup> (<https://seg.ethz.ch/software/velest.html>),  
217 NonLinLoc software<sup>40</sup> (<http://alomax.free.fr/nlloc/>), Double-Difference Hypocenter  
218 (HypoDD) algorithm<sup>41</sup> (Version 2.0; <https://www.ldeo.columbia.edu/~felixw/hypoDD.html>)  
219 and its python module HypoDDpy<sup>42</sup> (<https://doi.org/10.5281/zenodo.18907>), HASH<sup>48</sup> and  
220 FOCMEC<sup>49</sup> programs internally in the SEISAN software, and GMT<sup>52</sup> (Version 6;  
221 <https://www.generic-mapping-tools.org/>).

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352

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### 360 **Author Contributions Statement**

361 J.C. processed the microseismicity data and wrote the manuscript. W.C. supervised data  
362 processing, interpretation, and writing. M.C. developed the project, participated in the  
363 SISMOSMOOTH and ROVSMOOTH cruises, led the data collection, and supervised  
364 interpretation and writing.

365 **Competing Interests Statement**

366 The authors declare no competing interests.

367

368 **Fig. 1 | OBS locations and tectonic interpretation of the flip-flop detachment fault**  
369 **system at the eastern SWIR.** (a) Tectonic map with locations of the OBS networks:  
370 SMSMO (14 OBSs) and RVSMO (6 OBSs). The base map is created based on shipborne  
371 bathymetry data<sup>4</sup>. Geological and tectonic information (see legend for symbols) includes  
372 breakaways (B1-B6) and emergences (E1-E6) of successive detachment faults, corrugated  
373 surface, the boundary between volcanic and smooth seafloor, and linear sketches of scarps  
374 and volcanic ridges<sup>1</sup>. Yellow star is the low-temperature Old City hydrothermal field with  
375 carbonate-brucite chimneys<sup>5</sup>. The white dashed square marks the bounds of Fig. 2a. (b)  
376 Tectonic interpretation of the successive flip-flop detachment fault system along the PP'  
377 cross-section<sup>1</sup>. Black and gray dashed lines are the 7.5 km/s velocity contours<sup>23,39</sup>. Locations  
378 of OBSs are projected to the PP' cross-section. bsl: below sea level.

379

380 **Fig. 2 | Distribution of earthquakes and focal mechanisms.** (a) Bathymetric map of the  
381 SWIR 64°30'E area showing 307 events of the SMSMO (blue circles) and RVSMO (orange  
382 circles) catalogs, the RVSMO seismic swarm (green circles), and 8 determined focal  
383 mechanisms. Cross in the legend shows the average absolute horizontal location uncertainty  
384 of 3.2 km ( $1\sigma$ ). Geological information (see legend for symbols) includes breakaways,  
385 emergences, and the boundary between volcanic and smooth seafloor<sup>1</sup>. Best-fitting focal  
386 mechanisms have clear upward (black dots) and downward (white dots) first motions of P-  
387 wave onsets (Methods). Depth profiles (P0-P0' to P3-P3') are marked as labelled white lines  
388 in Fig 2a, with white dashed squares showing the corresponding boundaries for projected  
389 earthquakes in Figs. 2c-2f. (b) Histograms of earthquake depths below seafloor for the  
390 SMSMO (blue) and RVSMO (orange) catalogs, including the seismic swarm (green). (c)  
391 Along-axis depth profile P0-P0' projecting earthquakes within  $\pm 8$  km off the profile ( $VE=1$   
392 and the same below). Vertical bar shows the average absolute vertical uncertainty of 2.8 km  
393 ( $1\sigma$ ). The classification of volcanic (pink) and smooth (green) seafloor is indicated<sup>4</sup>. Gray  
394 dashed line is the 7.5 km/s velocity contour<sup>39</sup>. Labelled gray dashed lines show depths below  
395 the seafloor (the same below). (d) and (e) Across-axis depth profiles P1-P1' and P2-P2'

396 projecting earthquakes within  $\pm 3$  km off the profiles. Black dashed lines indicate the fault  
397 plane adapted from Fig. 2f. (f) Across-axis depth profile P3-P3' projecting earthquakes within  
398  $\pm 5$  km off the profile. Dotted lines represent seismic reflectors, interpreted as DF1 damage  
399 zone<sup>23</sup>, with the main detachment fault plane tentatively drawn in the center (subseafloor  
400 solid black line). Black<sup>23</sup> and gray<sup>39</sup> dashed lines are the 7.5 km/s velocity contours. Focal  
401 mechanisms are projected to profiles P2-P2' and P3-P3'.

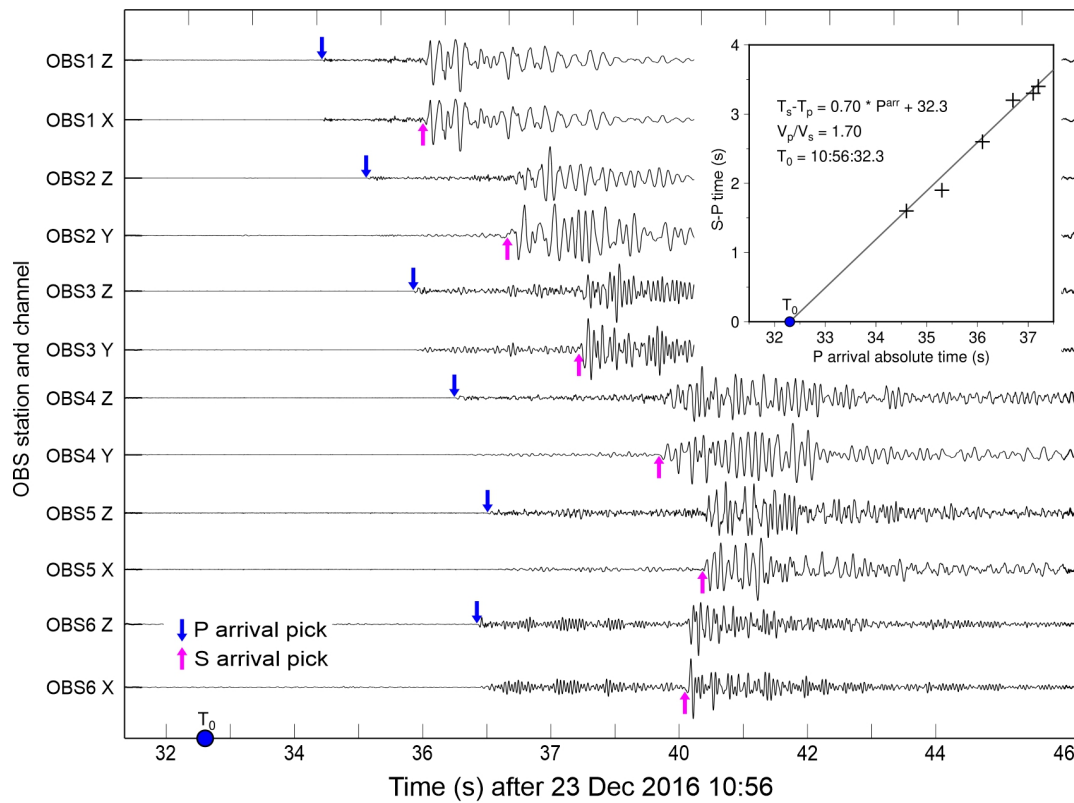
402

403 **Fig. 3 | Modes of detachment faults and their patterns of seismicity.** (a) 2D conceptual  
404 sketches of amagmatic flip-flop and magmatic corrugated modes of detachment faults. The  
405 flip-flop mode may have more hanging-wall faults to accommodate part of the plate  
406 spreading, while this part of plate spreading at the corrugated mode is accommodated by  
407 magma intrusions. (b-d) Microseismicity at the SWIR 64°30'E (this study), and the MAR  
408 26°10'N<sup>15</sup> and 13°20'N<sup>16,17</sup> (VE=1). Labelled dashed black lines show velocity contours of  
409 7.5 km/s (SWIR 64°30'E<sup>39</sup> and MAR 13°20'N<sup>53</sup>) and 7 km/s (MAR 26°10'N<sup>54</sup>). Yellow star is  
410 the low-temperature Old City hydrothermal vent. Red stars are high-temperature  
411 hydrothermal vents. NVR: neovolcanic ridge. B: breakaway. E: emergence.

412

413

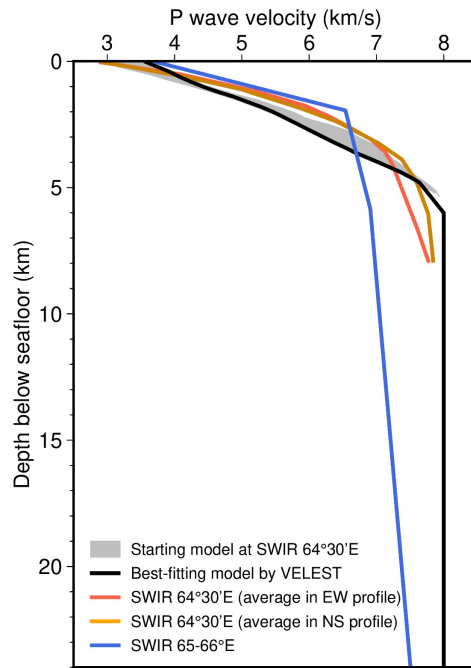




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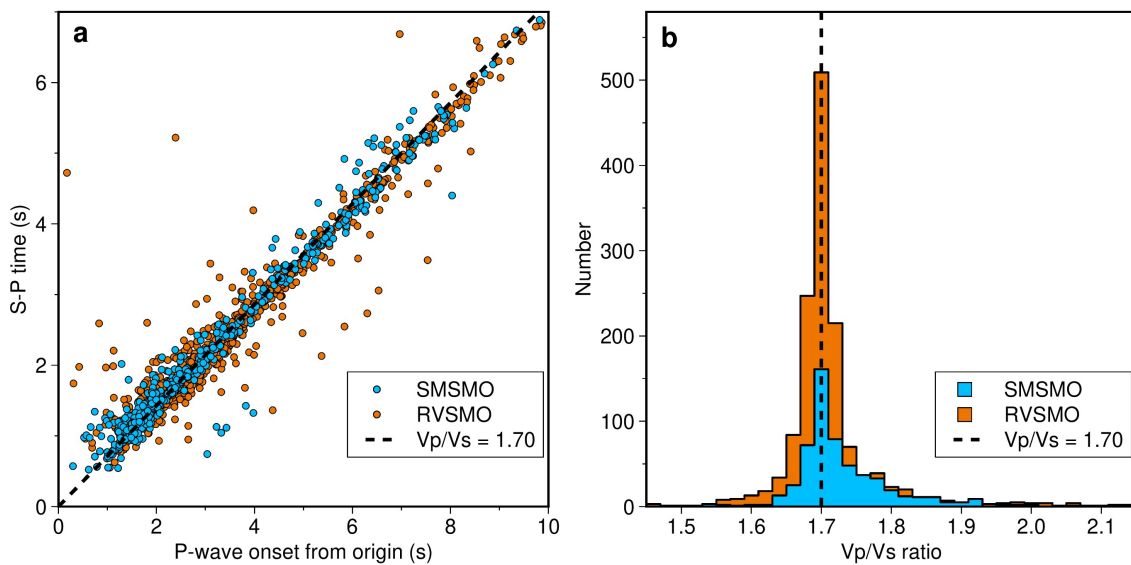
415 **Supplementary Fig. 1 | Typical event waveforms.** The event occurred at  
 416 64.394°E/27.883°S 11.7 km below seafloor with a local magnitude of 2.3, at 10:56, 23 Dec  
 417 2016 in RVSMO catalog. The inset shows the P-wave arrival absolute time versus arrival  
 418 time differences of P- and S-waves (S-P time), yielding the origin time (T<sub>0</sub>) of 10:56:32.3  
 419 and a V<sub>p</sub>/V<sub>s</sub> ratio of 1.7.

420



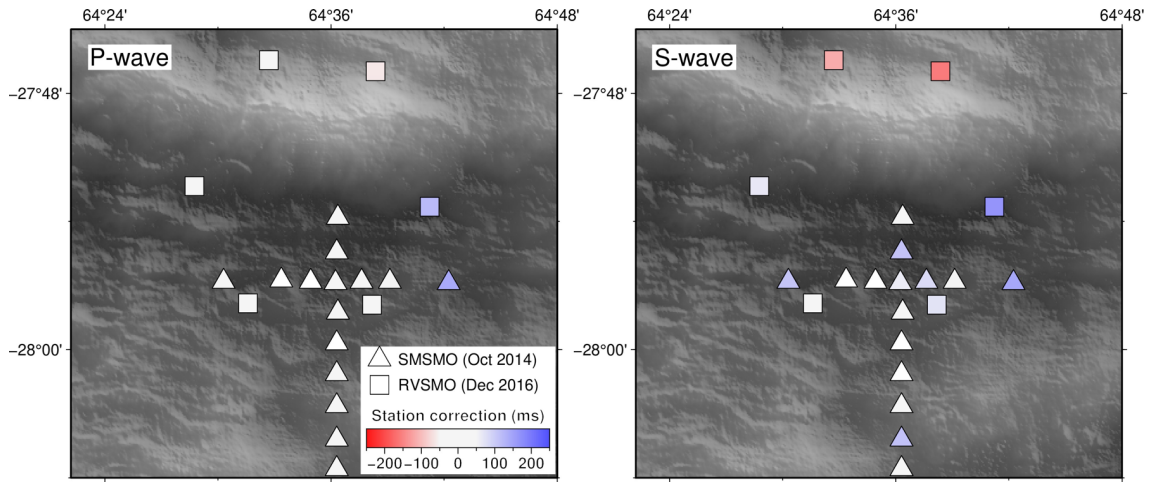
421

422 **Supplementary Fig. 2 | 1-D P wave velocity model.** Starting model (gray area) at the SWIR  
 423 64°30'E is extracted from a seismic refraction experiment<sup>23</sup>. The best-fitting model (black  
 424 line) is iteratively searched by the VELEST program<sup>38</sup>. Red and orange lines are average  
 425 velocity models in EW and NS profiles at the SWIR 64°30'E<sup>39</sup>. Blue line is the velocity  
 426 model at the SWIR 65-66°E<sup>32</sup>.



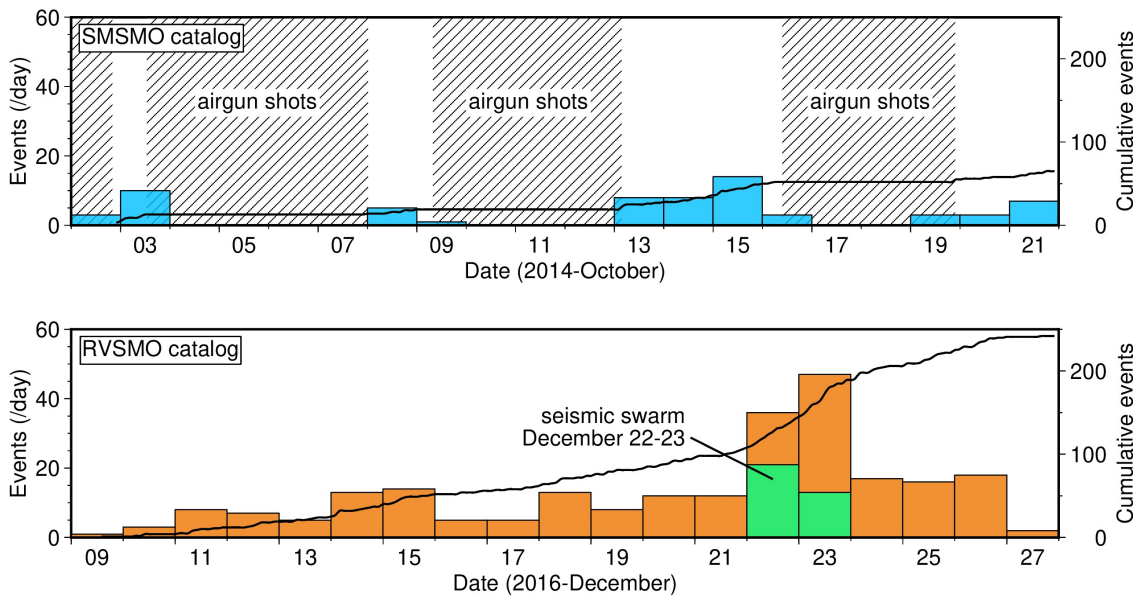
427

428 **Supplementary Fig. 3 | Wadati diagram.** (a) P-wave onset from origin versus S-P time  
 429 (Wadati diagram) for both SMSMO (orange) and RVSMO (blue) catalogs. (b) Histogram of  
 430  $V_p/V_s$  ratio.  $V_p/V_s$  ratio is calculated from the slopes of the Wadati diagram. The best-fitting  
 431  $V_p/V_s$  ratio is 1.7.



432

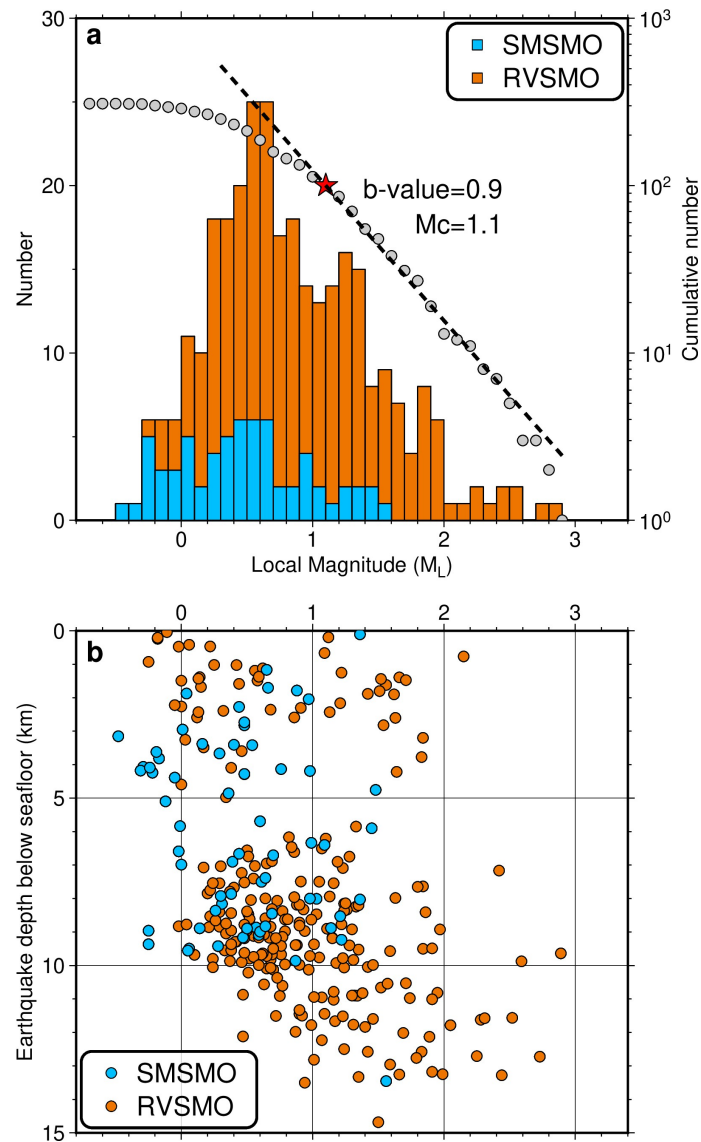
433 **Supplementary Fig. 4 | Station corrections of P- and S-wave returned by NonLinLoc.**



434

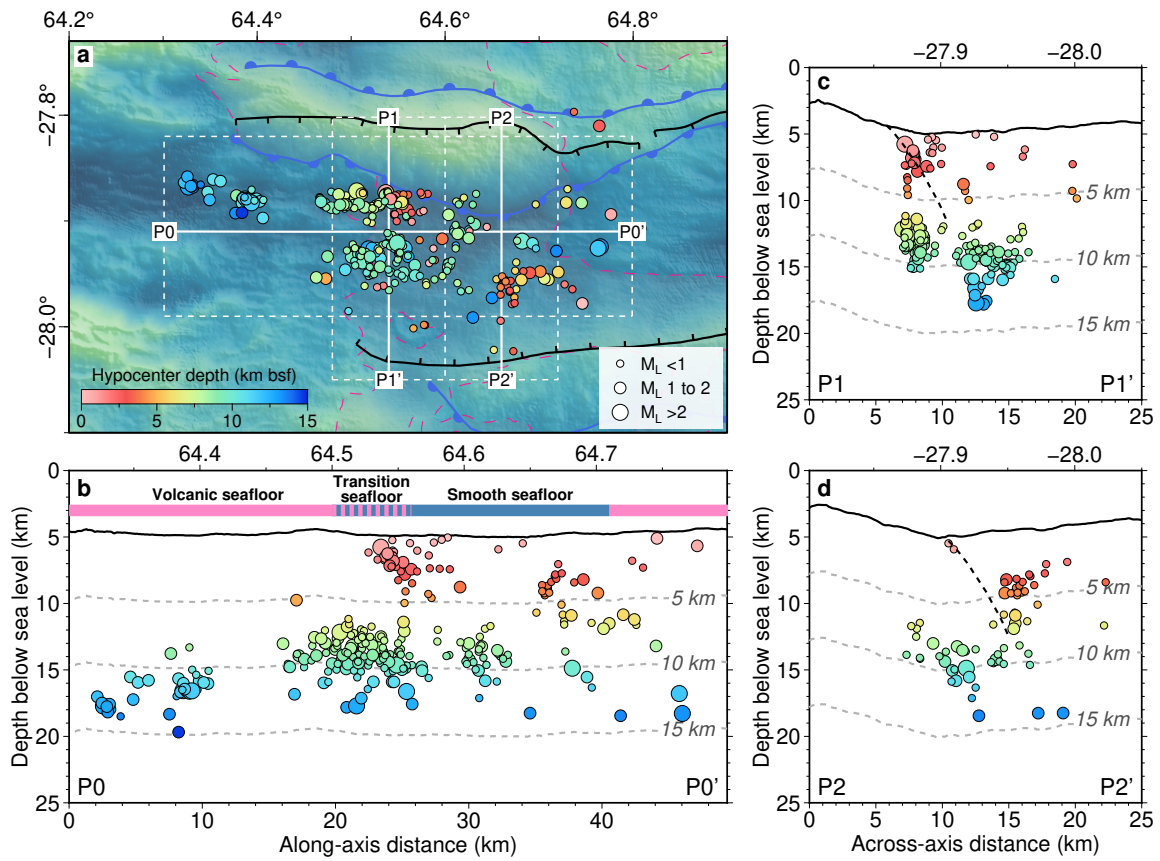
435 **Supplementary Fig. 5 | Histogram and cumulative histogram of located earthquakes for**  
 436 **the SMSMO and RVSMO catalogs.**

437



438

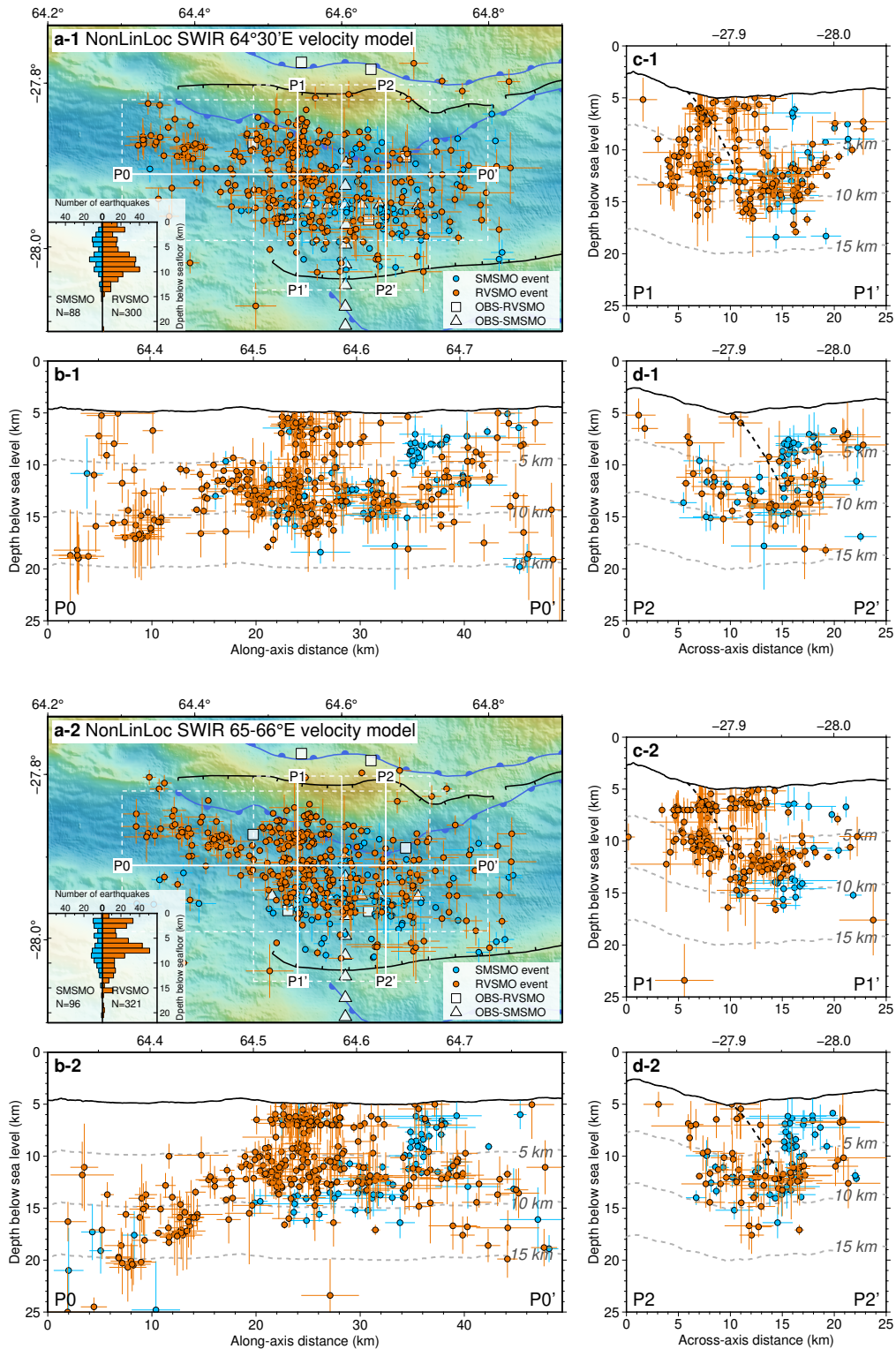
439 **Supplementary Fig. 6 | Distribution of local magnitude ( $M_L$ ).** (a) Histograms of local  
 440 magnitude for the SMSMO (blue) and RVSMO (orange) catalogs (left Y-axis). The  
 441 cumulative number of earthquakes for both catalogs (gray circles) as a function of local  
 442 magnitude (right Y-axis). Magnitude completeness ( $M_c$ ) is determined as 1.1 (red star) using  
 443 the b-value stability approach<sup>47</sup>, resulting in a b-value of 0.9 (slope of the dashed line). (b)  
 444 Local magnitude as a function of earthquake depth for the SMSMO (blue) and RVSMO  
 445 (orange) catalogs.



446

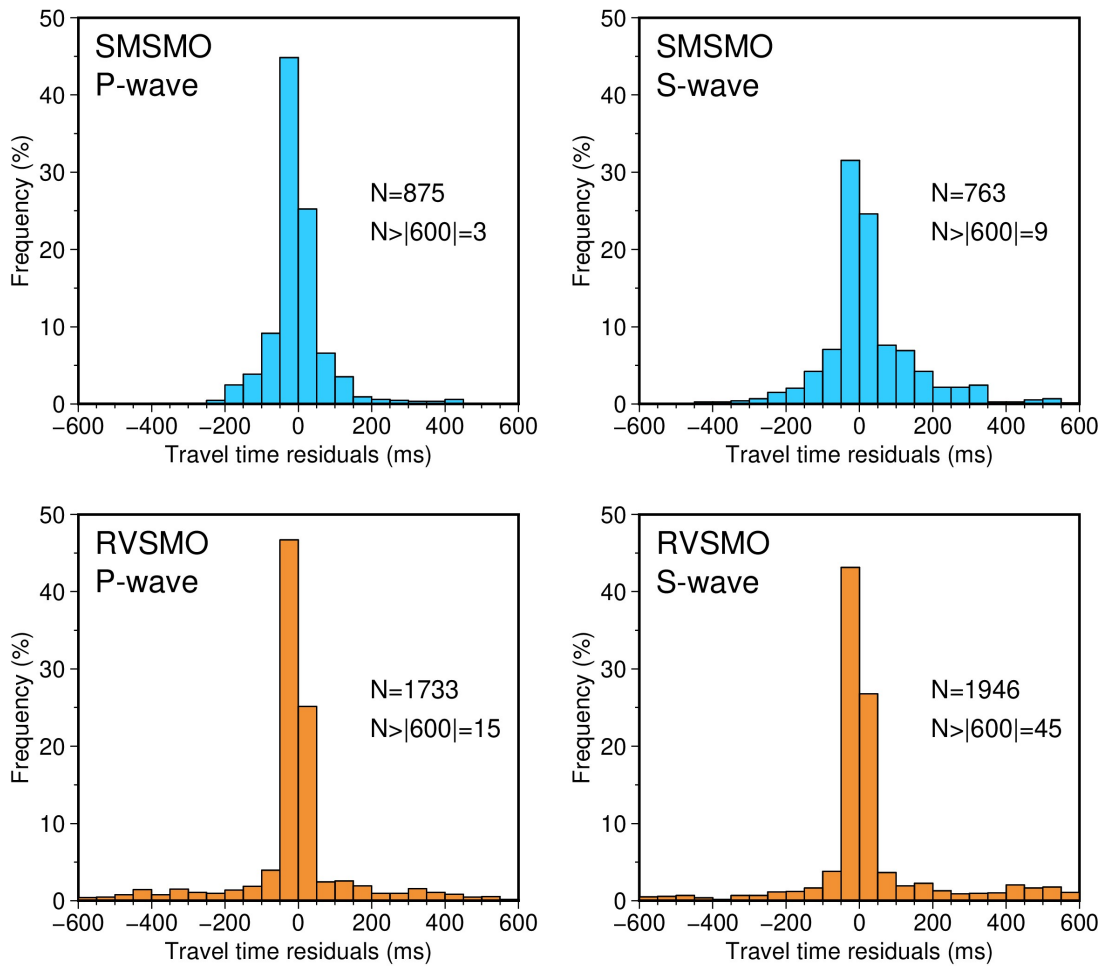
447 **Supplementary Fig. 7 | Earthquake relocations, color coded based on hypocenter depths**  
 448 **and circle size based on local magnitude ( $M_L$ ).**

449

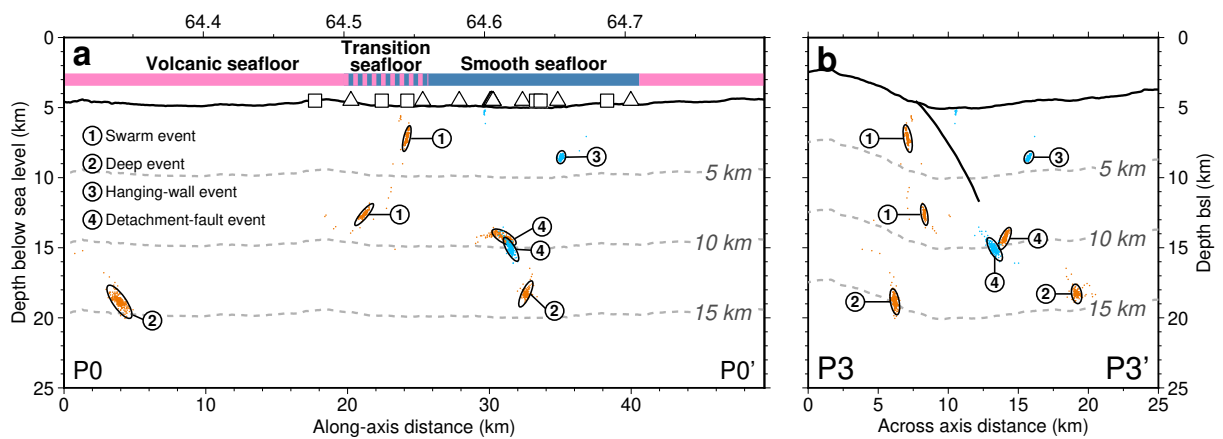


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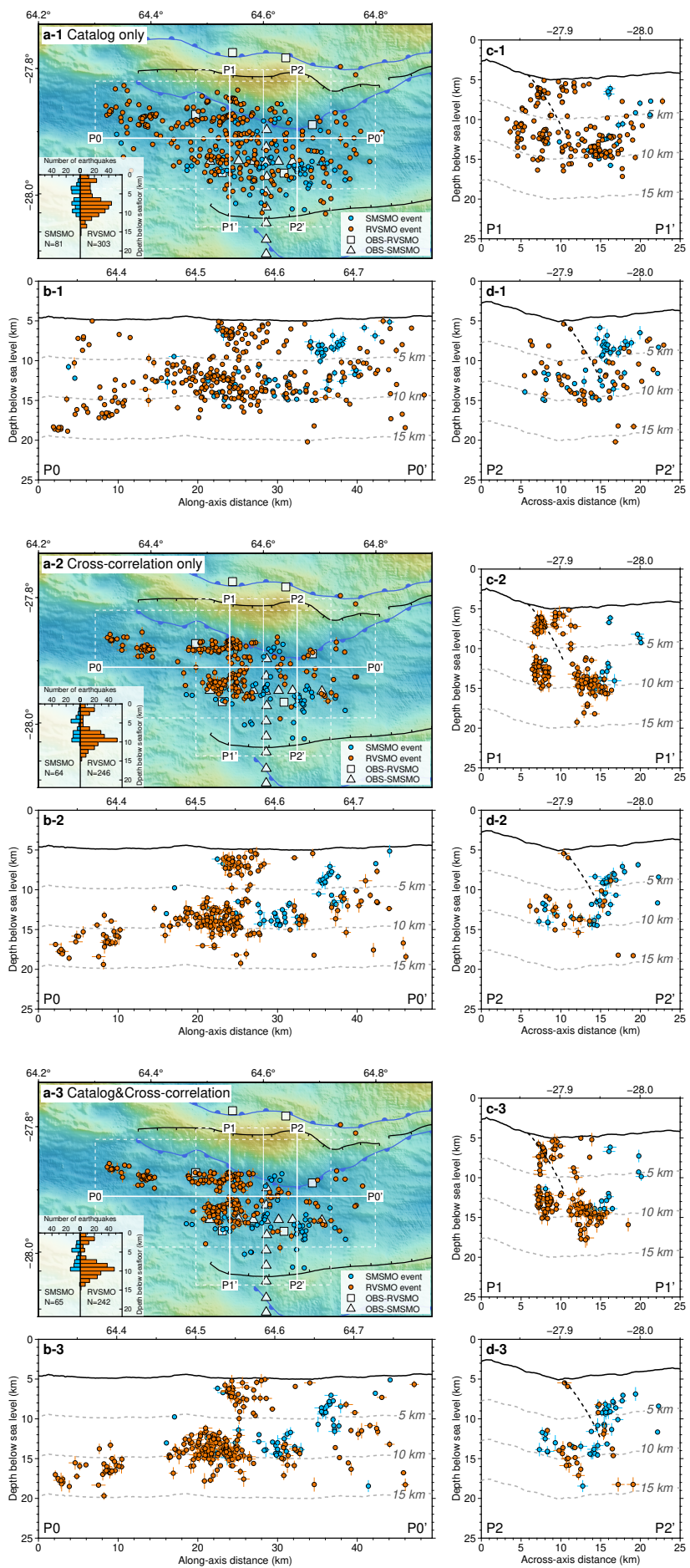
451 **Supplementary Fig. 8 | Earthquake locations.** See legend for symbols. Earthquake  
 452 locations using the NonLinLoc with the SWIR 64°30'E velocity model (**a-1** to **d-1**).  
 453 Earthquake locations using the NonLinLoc with the SWIR 65-66°E velocity model (**a-2** to **d-**  
 454 **2**), compared with the NonLinLoc results with the SWIR 64°30'E velocity model (pale gray).  
 455 Velocity models see Supplementary Fig. 2. Error bars represent absolute location errors.



457 **Supplementary Fig. 9 | Frequency distribution of P- and S-wave travel time residuals**  
 458 **for the SMSMO (blue) and RVSMO (orange) catalogs.**



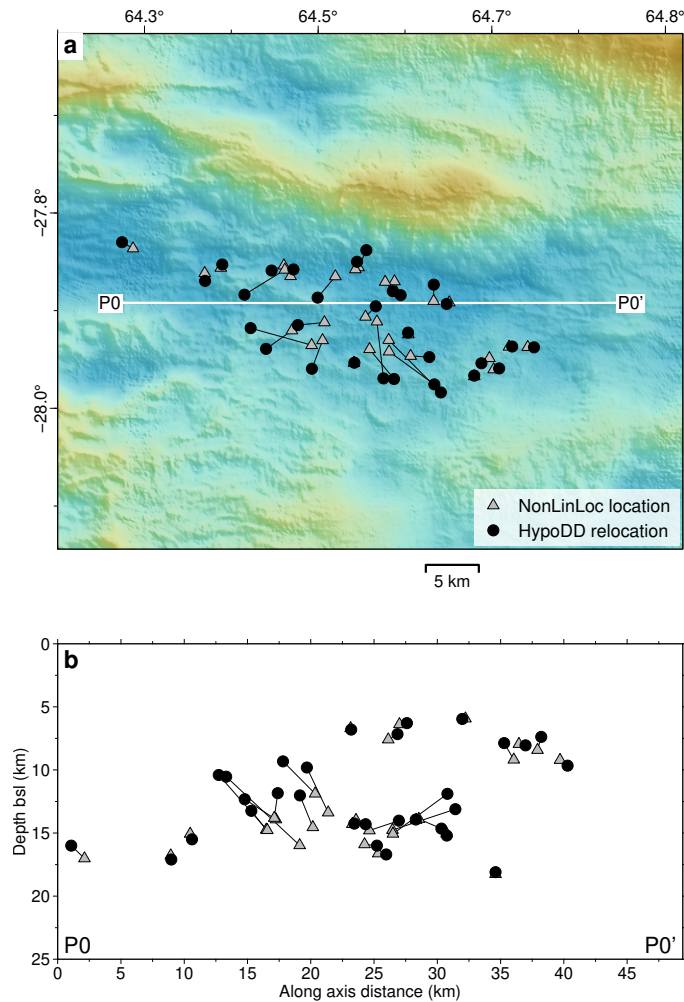
460 **Supplementary Fig. 10 | Bootstrap analysis of location errors for four chosen groups of**  
 461 **NonLinLoc located events.** Blue and orange dots represent events in the SMSMO and  
 462 RVSMO catalogs, respectively. Perturbations were randomly applied 300 times to P and S  
 463 arrivals, which were constrained by travel time residuals shown in Supplementary Fig. 9.





465 **Supplementary Fig. 11 | Earthquake relocations.** See legend for symbols. Tests of  
466 earthquake relocation using the HypoDD with catalog only (**a-1** to **d-1**), cross-correlation  
467 only (**a-2** to **d-2**), and catalog&cross-correlation (**a-3** to **d-3**; same results as Fig. 2). Error  
468 bars represent relative location errors.

469



470

471 **Supplementary Fig. 12 | Differences of NonLinLoc locations and HypoDD relocations**  
472 **for 30 randomly selected events.** Each event is connected by a black line between the  
473 results of the NonLinLoc location and the HypoDD relocation (catalog&cross-correlation).  
474 (a) Map view. (b) events projected on the along-axis P0-P0' profile.

475

476 **Inventory of Supporting Information**

- 477       Supplementary Figs. 1-12.
- 478       FocalMechanism.txt
- 479       OBS\_station.txt
- 480       RVSMO\_catalog.txt
- 481       SMSMO\_catalog.txt
- 482       Swarm\_Dec22\_23\_2016.txt
- 483