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## Tracking subducted ridges through intermediate-depth seismicity in the Vanuatu subduction zone

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### **Abstract:**

The distribution of intermediate-depth seismicity beneath the Vanuatu archipelago includes several seismic clusters/alignments and gaps, including a remarkable 200 × 150 km gap beneath central Vanuatu. We show that a zone of enhanced seismicity beneath this gap corresponds to the most likely trace of the subducted D'Entrecasteaux Ridge (DER) and that another region of aligned seismicity to the south may correspond to another significant, now disappeared ridge. We suggest that regions of aligned intermediate-depth seismicity beneath Vanuatu are traces of subducted oceanic features on the downgoing plate, probably caused by enhanced hydration beneath them prior to subduction. The seismic gap above the DER trace, previously interpreted as a tear in the slab, may instead be a region of reduced hydration due to thick/unfractured input crust, low bending of this crust before subduction and/or greater slab residence time at shallower subducted depths, the latter two being directly related to DER collision. We propose that an uneven distribution of intermediate-depth seismicity at subduction zones may provide a window to the history and effects of subducted oceanic features.

1 Tracking subducted ridges through intermediate-depth seismicity in the Vanuatu  
2 subduction zone

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14 **ABSTRACT**

15         The distribution of intermediate-depth seismicity beneath the Vanuatu archipelago includes  
16 several seismic clusters/alignments and gaps, including a remarkable  $200 \times 150$  km gap beneath  
17 central Vanuatu. We show that a zone of enhanced seismicity beneath this gap corresponds to the  
18 most likely trace of the subducted D'Entrecasteaux Ridge (DER) and that another region of aligned  
19 seismicity to the south may correspond to another significant, now disappeared ridge. We suggest that  
20 regions of aligned intermediate-depth seismicity beneath Vanuatu are traces of subducted oceanic  
21 features on the downgoing plate, probably caused by enhanced hydration beneath them prior to  
22 subduction. The seismic gap above the DER trace, previously interpreted as a tear in the slab, may  
23 instead be a region of reduced hydration due to thick/unfractured input crust, low bending of this crust  
24 before subduction and/or greater slab residence time at shallower subducted depths, the latter two  
25 being directly related to DER collision. We propose that an uneven distribution of intermediate-depth  
26 seismicity at subduction zones may provide a window to the history and effects of subducted oceanic  
27 features.

28

29 **INTRODUCTION**

30         The ~500 km long Vanuatu archipelago overlies one of world's most seismically active  
31 subduction zones, with an average of one magnitude 7+ earthquake recorded per year since 1972  
32 (National Earthquake Information Center). The present-day convergence rate between the Vanuatu  
33 islands and the subducting Australian plate varies from 120 mm/yr in the south to 160 mm/yr in the  
34 north, but slows to 35 mm/yr in the center (Fig. 1) (Calmant et al., 2003; Bergeot et al., 2009). This  
35 slowing, and the existence of uplift sequences affecting part of the forearc islands (up to 6 mm/yr over  
36 the past 150 Ka) (Taylor et al., 2005), can be linked to the subduction of a large and irregular  
37 bathymetric feature: the D'Entrecasteaux Ridge (DER). The DER, which extends back along the  
38 Australian Plate to New Caledonia, appears to have entered into subduction 2-3 Ma at the Epi  
39 reentrant, ~160 km to the south (Fig. 1); (Greene et al., 1994; Meffre and Crawford, 2001).

40 Intermediate depth seismicity (50-300 km depth) in the Vanuatu region is mostly  
41 constrained by the global seismic network. Shallow seismicity (< 50 km depth) is constrained by a  
42 temporary network that focused on the central forearc in 2008-9 (Baillard et al., 2015). Intermediate-  
43 depth seismicity in the Vanuatu region falls on or near a Wadati-Benioff zone corresponding to the  
44 subducting slab and is highly variable along-strike, with several clusters or alignments of intense  
45 seismicity as well as several regions almost completely lacking seismicity (Fig. 2A). Most authors  
46 associate variations in intermediate-depth seismicity with how much water is subducted and the depth  
47 and temperatures at which dehydration embrittlement occurs (e.g., Hacker et al., 2003; Yamasaki and  
48 Seno, 2003; Omori et al., 2004; Milsch and Scholz, 2005) and the maximum depth of this seismicity  
49 is generally greater in colder subducting slabs than in warmer ones (Kirby et al., 1996; Omori et al.,  
50 2004; Abers et al., 2013). Most of these observations and models are derived from differences  
51 between subduction zones, but variations are also observed within some subduction zones (e.g.,  
52 Eberhart-Phillips et al. (2013) for New Zealand and Shillington et al. (2015) for Alaska), where they  
53 are generally explained as local differences in hydration prior to subduction associated with  
54 differences in plate fabric orientation with respect to the trench axis.

55 In this study we show that a region of enhanced seismicity in Central Vanuatu (Area C in Fig. 2A)  
56 corresponds to the most likely trace of the subducted DER. We suggest that the enhanced seismicity  
57 results from dehydration processes of the oceanic crust and upper mantle beneath the DER and that  
58 the aseismic region above it could be caused by lower hydration of surrounding slab. Other  
59 alignments of intermediate-depth seismicity beneath Vanuatu could also correspond to subducted  
60 bathymetric features, including one just north of the DER trace (Area N in Fig. 2A) and another 400  
61 km to the south (Area S in Fig. 2A), in front of a possible subduction front reentrant (Figs. 1 and 2B).  
62 The traces of these features could provide a means for determining the past geometry and effects of  
63 subduction and collisions at the Vanuatu and other subduction zones.

64

65 **SEISMICITY VARIATIONS AROUND THE DER**

66           Regions of enhanced intermediate-depth seismicity are often associated with local  
67 dehydration of minerals within the subducting slab as it descends (Eberhart-Phillips et al., 2013;  
68 Shillington et al., 2015; Paulatto et al., 2017). The northern portion of the DER, composed of Eocene  
69 magmas, can be described as a fossil transform fault or subduction zone that links up with the fossil  
70 New-Caledonia subduction zone, which was mainly active during the Eocene. The southern portion of  
71 the DER, including the Bougainville seamount (Fig. 4), can be considered as a Eocene volcanic arc  
72 (Maillet et al., 1983; Collot et al., 1994; Schellart et al., 2006; Mortimer et al., 2014). The history and  
73 nature of the DER indicate a highly fractured system, with deep faults allowing enhanced hydration to  
74 oceanic mantle depths as has been observed at other subduction zones (e.g., Lefeldt & Grevemeyer,  
75 2008; Lefeldt et al., 2009; Ivandic et al., 2010; Fujie et al., 2013; Shillington et al., 2015). The  
76 relatively high thermal parameter of the Australian plate at intermediate depth ( $> 2400$ : Text T1 and  
77 Baillard et al., 2015) allows hydrous minerals to be carried deep in the mantle before dehydration.

78           We estimated the position of the subducted DER under the Vanuatu arc by fitting a curve on  
79 the descending slab between the current point of collision and the point of collision 2-3 Ma projected  
80 along the slab (Fig. S1 and Text T2). The position and the termination of this projected ridge  
81 correspond to a region of enhanced intermediate-depth seismicity beneath the slab's biggest seismic  
82 gap (Figs. 2A, 3 and S2). The trace of this enhanced seismicity extends from 100 to 200 km depth,  
83 indicating upper oceanic mantle deserpentinization: oceanic crust eclogitization is generally limited to  
84  $< 150$  km depth (e.g., Hacker et al., 2003b; Maruyama and Okamoto, 2007) and the apex of this  
85 process is estimated at 75 km depth in Vanuatu (Baillard et al., 2015), whereas the apex of oceanic  
86 mantle deserpentinization is estimated at 170–220 km for Vanuatu (Syracuse et al., 2010). Most  
87 intermediate-depth Vanuatu earthquakes have N-S (Trench-parallel) strike directions, suggesting that  
88 they are driven by slab pull forces (Christova et al., 2004), but some events along the DER trace have  
89 E-W orientations (Fig. S3), consistent with the orientation of the DER horsts and grabens (Maillet et  
90 al., 1983).

91           A 200 km wide “gap” in intermediate-depth seismicity from 50-200 km depth lies just above  
92 and south of the aforementioned seismicity alignment (Area C in Fig. 2). The gap was previously

93 interpreted to be the signature of the subducted DER itself (Marthelot et al., 1985) or a tear in the  
94 subducting slab (Prévot et al., 1991; Chatelain et al., 1992) but, based on more recent understanding  
95 of the controls on intermediate-depth seismicity, we propose that it is a low hydration region. This  
96 low hydration could be pre-existing or driven by the DER collision. The pre-existing North Loyalty  
97 Basin is composed of a ~15 km thick, relatively unfractured oceanic crust (Pontoise et al., 1980;  
98 Maillet et al., 1983), which may be relatively un-hydrated. The DER collision tends to flatten the  
99 entry of the adjacent plate into subduction and slow the convergence rate, reducing the bending force  
100 on that plate before subduction and increasing the time that the plate would spend at shallow depths.  
101 This reduced bending at shallow depths could limit the penetration of faults and therefore the  
102 hydration of the oceanic lower crust and upper mantle, while the long time at shallow subduction  
103 depths would allow more time for eclogitization reactions in the crust to run their course before the  
104 slab descends to intermediate-earthquake depths. If these last two “active” processes are indeed  
105 important in reducing slab hydration, then the shift of the gap to the south with increasing depth  
106 suggests that the slowed convergence currently observed around south Santo island is a long-term  
107 feature which has migrated north with the DER collision zone.

108

#### 109 **OTHER LINEATIONS OF INTERMEDIATE-DEPTH SEISMICITY**

110 Other lineations of intermediate-depth seismicity beneath Vanuatu may also be linked to  
111 subducted oceanic features (Fig. 2A). One such feature starts just north of the DER lineation at  
112 approximately 100 km depth and extends northward to ~200 km depth (Area N in Fig. 2A). It is, like  
113 the DER trace, oblique to the convergence direction. This feature could be linked to a subducted  
114 portion of the West Torres Plateau (Fig. 1), which is currently colliding offshore north Santo island,  
115 causing the uplift of the Torres islands (Taylor et al., 1985). Similar to the DER trace, there is a  
116 secondary cluster of events with E-W strike, suggesting the possible reactivation of pre-existing faults  
117 (Fig. S3). Intermediate-depth seismicity also appears to be slightly reduced above this lineation.

118 Another strong lineation of intermediate-depth earthquakes is observed near Tanna and Erromango  
119 islands (Area S in Fig. 2A). This feature does not correlate with any current seamounts or ridges on  
120 the subducting plate, but a morphologic feature on the trench just southwest of Tanna (Figs. 1 and 2B)  
121 could be a reentrant caused by an ancient collision front.

## 122 **DISCUSSION**

123 Lineations in intermediate-depth seismicity may reveal the subduction history at other subduction  
124 zones where strongly hydrated oceanic features enter into subduction. For example, Nakajima and  
125 Hasegawa (2006) observed a lineation of seismicity that could be linked to a subducted fracture zone.  
126 Other examples include a lineation of intermediate-depth earthquakes beneath Ecuador, which  
127 appears to correlate with the subducted prolongation of the Grijalva Fracture Zone (Fig. S4) and  
128 similar correlations beneath Peru with the Nazca fracture zone and beneath Tonga-Kermadec with the  
129 Louisville Ridge (Figs. S5-6).

130 Variations in intermediate-depth seismicity have been also observed to correlate with variations in  
131 surface volcanic rheology (Eberhart-Phillips et al., 2013). Vanuatu intermediate-depth earthquake  
132 lineations appear to correlate with along-arc variations in isotopic ratios (Fig. S7), high Ba/La and  
133 Pb/Nd ratios are observed directly above subducted features, indicating possible enrichment by slab  
134 derived fluids (Peate et al., 1997) released predominantly in the vicinity of the subducted features.  
135 Finer-scale isotope measurements are needed to validate this hypothesis.

136 Where intermediate depth earthquakes do not correlate with present-day topographic features on the  
137 subducting plate, they may help to identify subducted features with no remaining seafloor trace. Both  
138 the enhanced seismicity and any seismic gaps around them could be studied to determine if there was  
139 significant blocking or slowing of convergence when the feature subducted. Deducing the past history  
140 of oceanic features could help both kinematic constructions of local plate history and our  
141 understanding of the role of subducted oceanic features on arc magmatism.

## 142 **CONCLUSION**



143 Lineations and gaps in intermediate-depth seismicity beneath the Vanuatu arc appear to be associated  
144 with deeply fractured subducted features. The clearest correlation is observed with the  
145 D'Entrecasteaux ridge, whose most likely continuation beneath the Vanuatu arc corresponds to a  
146 region of enhanced intermediate-depth seismicity within the subducted slab (Fig. 4). A large region  
147 of reduced intermediate-depth seismicity above this zone may result from reduced oceanic/mantle  
148 hydration there, either as an effect of pre-existing thick oceanic crust of the North Loyalty Basin or  
149 because of processes related to reduced bending behind the DER collision zone: 1) reduced deep  
150 hydration of pre-subducted slab through reduced bending and fault penetration and 2) increased  
151 dehydration of subducted oceanic crust at shallow depths because of a longer residence there.

152 Other lineations that may be associated with subducted features include 1) an oblique zone just north  
153 of the DER extension, which may correspond to the West Torres Plateau going back to a time when it  
154 was closer to the location of the Torres forearc islands; 2) a dip-parallel zone beneath Tanna and  
155 Erromango islands, which may be associated with a completely subducted hydrated ridge.

156 Such lineations may provide a picture of past shallow subduction zone features, which could be used  
157 to model and/or explain past changes in seismicity and plate motions.

158

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269

270

271 **FIGURE CAPTIONS**

272 Figure 1. The Vanuatu archipelago. Main islands with active volcanoes are filled in red. White arrows  
273 indicate the interseismic convergence rates along the subduction front (Calmant et al., 2003; Bergeot  
274 et al., 2009). Contour with triangles shows subduction front and solid black contour is the 3500 m  
275 depth contour on the island arc side of the subduction front. White rounded boxes surround the Epi  
276 and Tanna reentrants. The tilted black box shows the bounds used for the along-arc view in Fig 2. AP:  
277 Australian Plate; NFB: North Fiji Basin; DER: D'Entrecasteaux Ridge; NLoB: North Loyalty Basin.

278 Figure 2. Along-arc view of Vanuatu seismicity and reentrants. Positions of active volcanoes are  
279 indicated by red triangles, other major islands by black bars. A) Earthquakes since 1972 (circles) as a  
280 function of depth. "Seismic gap" is outlined by polygons with dashed borders and seismicity  
281 clusters/alignments are outlined by rounded boxes. B) Distance between the subduction front and the  
282 3500 m depth contour shown in Fig.1. The Tanna and Epi reentrants are labeled.

283 Figure 3. Seismicity from global and 2008-9 local networks and the projected subducted DER. Red  
284 line is the constant curvature model of the DER shown in Fig. S1. Dashed lines are the limits for  
285 different long-term convergence rates and DER shapes.

286 Figure 4. Conceptual figure showing how the distribution of intermediate-depth earthquakes (red  
287 stars) relates to subducted topographic features. The dense fracture systems associated with these  
288 features favor hydration of oceanic crust and upper mantle prior to subduction. Hydrous minerals are  
289 then progressively dehydrated with increasing depth, triggering intermediate-depth earthquakes.  
290 Dehydration progresses from the oceanic crust at lower depths (eclogitization) to the oceanic upper  
291 mantle at greater depths (deserpentinization). The region of white rounded shapes indicates the  
292 seismogenic zone. SB: Sabine Bank; BS: Bougainville Seamount; Gbr: Gabbro; Bsh: Blue Schist;  
293 Prd: Peridotite; Srp: Serpentine



Figure 40° 160° 180°  
0°

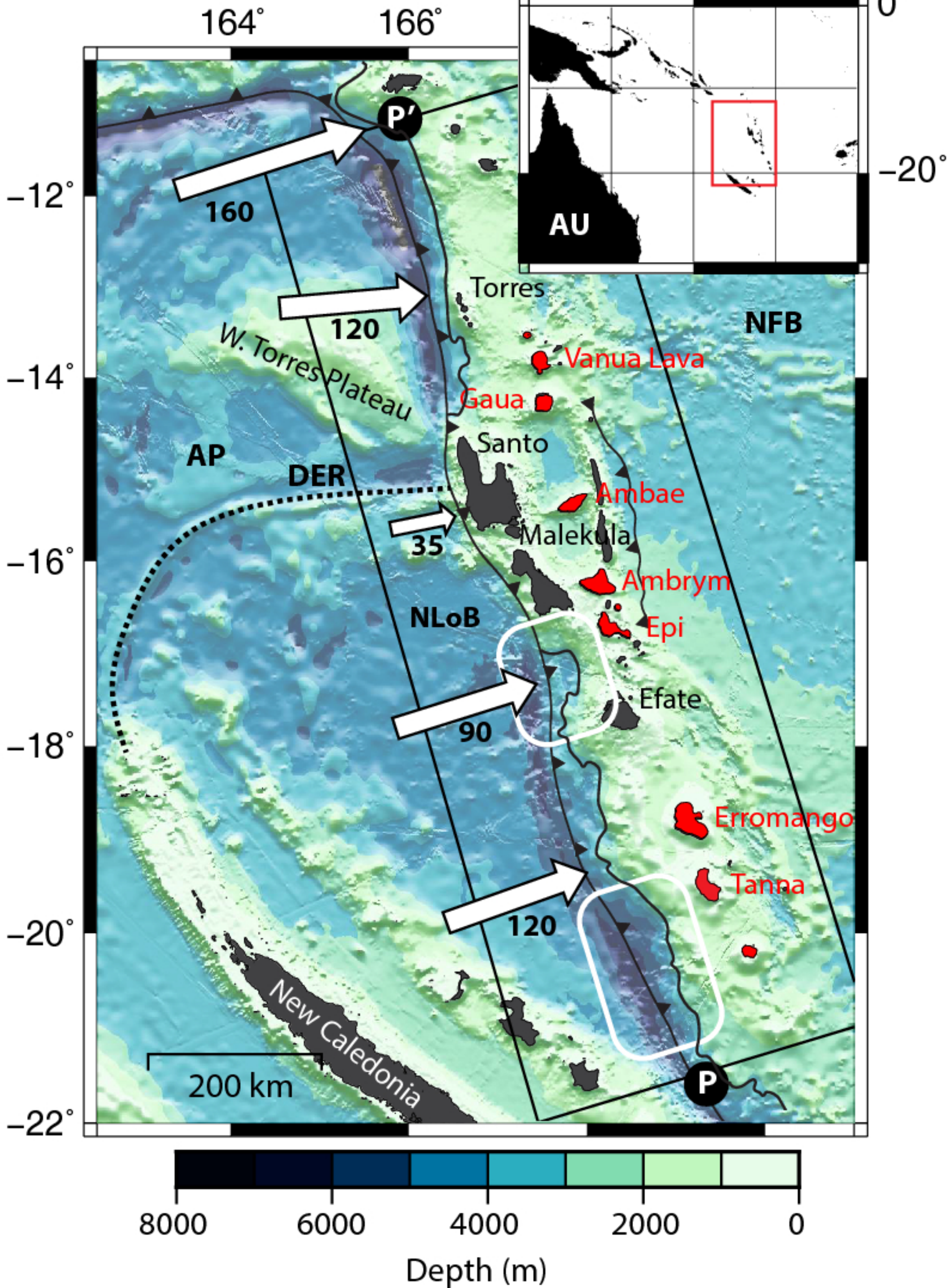




Figure 2

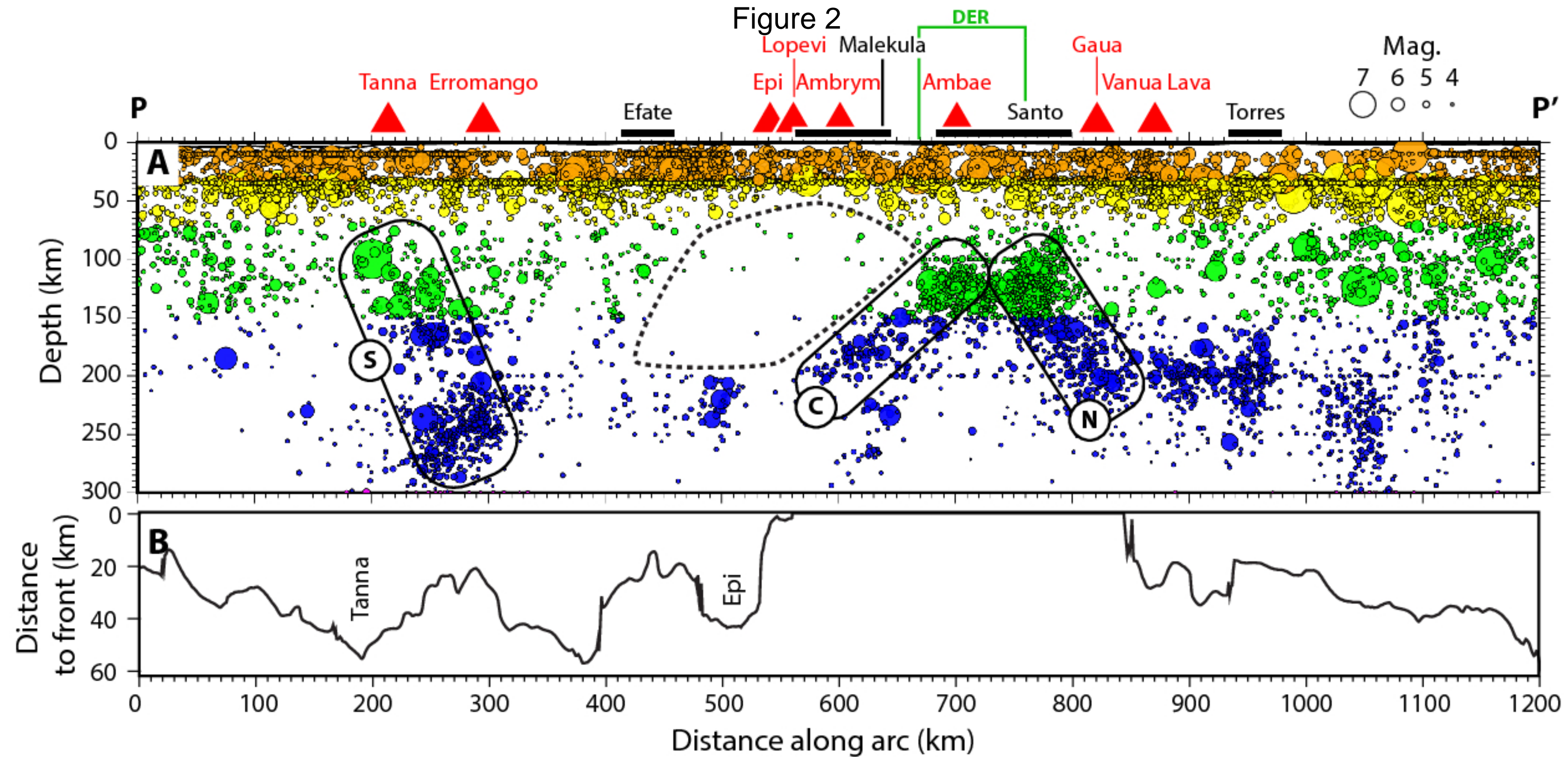




Figure 3

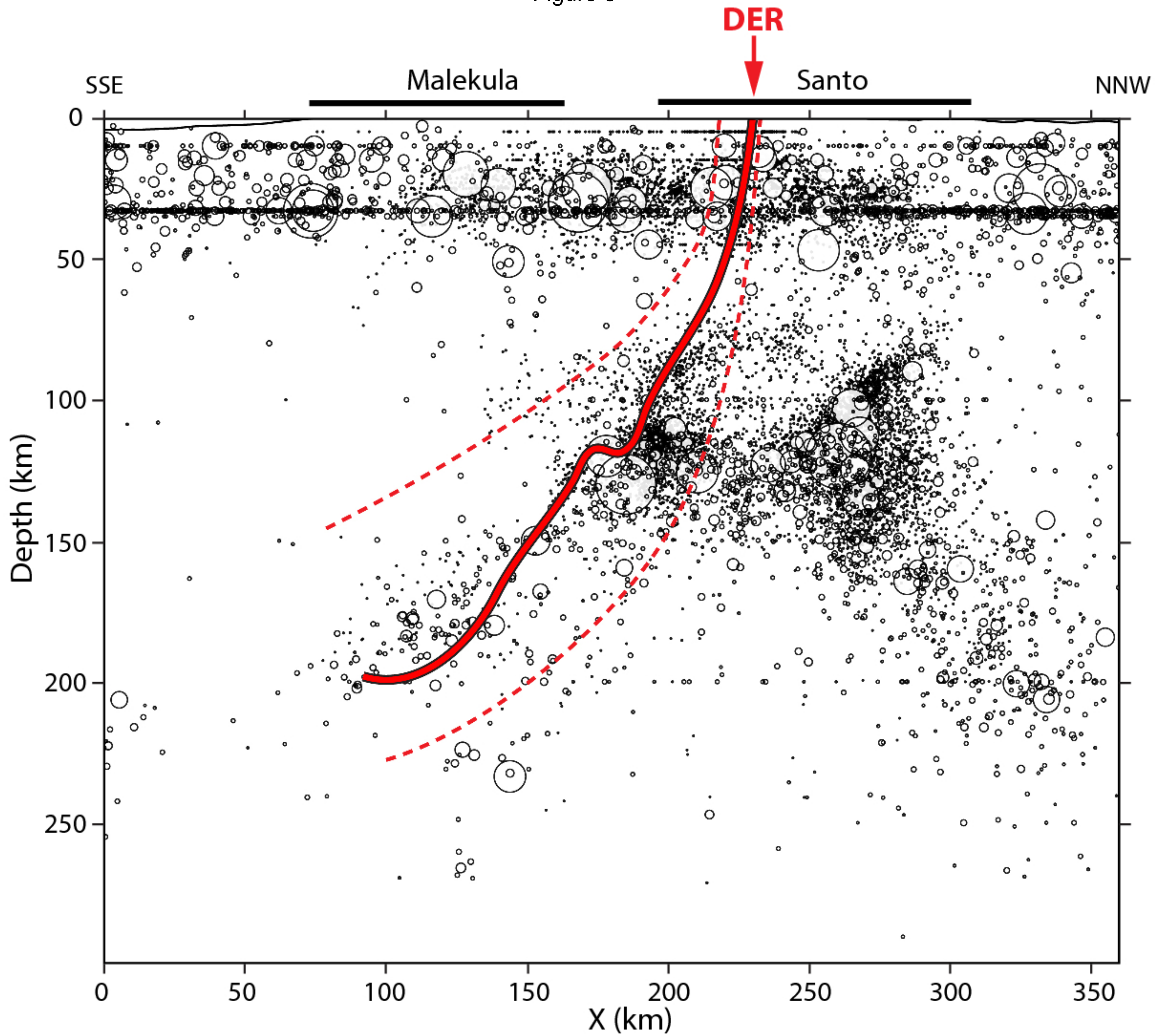




Figure 4

