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Subducted seafloor relief stops rupture in South American great earthquakes: implications for rupture behaviour in the 2010 Maule, Chile earthquake

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1 *Subducted seafloor relief stops rupture in South*
2 *American great earthquakes: Implications for rupture*
3 *behaviour in the 2010 Maule, Chile earthquake.*

4 *Robert Sparkes, Frederik Tilmann, Niels Hovius and John*
5 *Hillier*

6
7 **ABSTRACT**

8 Great subduction earthquakes cause destructive surface deformation and ground
9 shaking over hundreds of kilometres. Their rupture length is limited by the
10 characteristic strength of the subduction plate interface, and by lateral variations in
11 its mechanical properties. It has been proposed that subduction of topographic
12 features such as ridges and seamounts can affect these properties and stop rupture
13 propagation, but the required relief and physical mechanisms of topographic rupture
14 limitation are not well understood. Here we show that the rupture limits of thirteen
15 historic great earthquakes along the South America-Nazca plate margin are strongly
16 correlated with subducted topography with relief >1000m, including the Juan
17 Fernandez Ridge. The northern limit of rupture in the M_w 8.8 Maule, Chile earthquake
18 of 27 February 2010 is located where this ridge subducts. Analysis of intermediate-
19 magnitude earthquakes shows that in most places the subduction of high seafloor
20 relief creates weak, aseismic zones at the plate interface, which prevent rupture
21 propagation, but that the Juan Fernandez Ridge is associated with a locally strong
22 plate interface. The maximum rupture length, and thus magnitude, of great
23 subduction earthquakes is therefore determined by the size and lateral spacing of
24 topographic features where they are present on the subducting plate.

25 ***Introduction***

26 The amount of displacement in an earthquake is commonly proportional to its rupture
27 length (Wells and Coppersmith, 1994). This determines the area that can be affected by
28 strong ground motion and surface deformation and, where relevant, the amplitude and
29 length scale of associated tsunamis. In most earthquakes, rupture termination is likely
30 to be determined by the energy available for rupture tip propagation along a plane with
31 relatively uniform properties, but for larger potential rupture planes, there is an
32 increased likelihood that mechanical properties vary along the plane. Mechanical
33 heterogeneities could impede rupture tip propagation, or, alternatively, serve as
34 rupture nucleation points. If indeed they exist, these effects may be expected to be
35 most prominent for the largest earthquakes, and they could give rise to segmentation
36 of very long seismogenic fault zones.

37 Globally, great megathrust earthquakes ($M_w \geq 8.0$) accommodate the majority of
38 shortening along subduction margins. They repeatedly rupture the same margin
39 segments (Beck *et al.*, 1998, Comte *et al.*, 1986), with lengths exceeding the ~100 km
40 width of the seismogenic zone. There are indications that rupture termination in great
41 subduction earthquakes could be forced by along-strike variation of properties of the
42 plate interface (Kelleher and McCann, 1976, Sladen, 2009, Bilek, 2010, in press,
43 Loveless *et al.*, 2010, in press). For example, coincidence of some rupture areas of great
44 subduction earthquakes with large negative forearc gravity anomalies along subduction
45 margins has been attributed to localized strong plate interface friction (Song and
46 Simons, 2003, Llenos and McGuire, 2007), and rupture areas have been found to
47 coincide with forearc basins, possibly the surface expression of subduction erosion
48 (Wells *et al.*, 2003, Ranero and von Huene, 2000). However, such forearc features can
49 depend on as well as influence the frictional properties along the plate interface,
50 making it difficult to establish the direction of causality.

51 Incoming seafloor structures have long been suspected to have an influence on plate
52 interface structure (Cloos, 1992, Scholz and Small, 1997, Bilek *et al.*, 2003). Notably,
53 rupture in the 1946 earthquake along the Nankai trough was deflected around a
54 subducting seamount (Kodaira *et al.*, 2002). This may have been caused by an increase
55 of normal stress, and hence seismic coupling, on the subducted topography (Scholz and
56 Small, 1997), or by the formation of a weak, aseismic area where strain cannot build up
57 (Bilek *et al.*, 2003). Regardless of the mechanism, in the case of subducted seafloor
58 topography the direction of causality is unambiguous. If a correlation between the
59 location of subducted seafloor topography and the extent of earthquake ruptures can
60 be demonstrated then it is clear that the former has influenced the latter by affecting
61 the frictional properties of the plate interface. Although many previous studies have
62 noted the apparent coincidence of incoming seamount chains and earthquake
63 segmentation, the statistical significance of these observations has hitherto not been
64 tested, nor is it clear how large a seamount chain has to be before it can (co-)determine
65 rupture segmentation.

66 Acknowledging the fact that several other factors may affect rupture propagation along
67 a subduction plate interface, we have sought to isolate and determine the strength and
68 nature of the role of subducted topography in rupture termination in great
69 earthquakes, and the critical size of subducted topography. We have done this by
70 exploring the randomness or otherwise of the collocation of extrapolated seafloor
71 relief, great earthquake rupture limits and patches of subdued background seismicity
72 along the Pacific margin of South America between 12°S and 47°S. On this margin, the
73 Nazca Plate moves eastward at ~65 mm/yr relative to, and is subducted under South
74 America (Angermann *et al.*, 1999). Large sections of the Nazca Plate have smooth
75 seafloor with topographic relief <200 m, but elsewhere seamount chains with varying
76 relief of up to 3.5 km are carried into the subduction trench, enabling a quantitative

77 exploration of the effect of subducting topography on seismicity. Since 1868, 15 great
78 earthquakes have occurred along the Nazca margin (See Fig. 1 and Table 1), including
79 the largest recorded earthquake, $M_w 9.5$ in 1960. These earthquakes had rupture
80 lengths from 150 to 1,050 km. On 27 February 2010, a ~600 km section of the Nazca
81 margin ruptured in the $M_w 8.8$ Maule earthquake. Here, we demonstrate that the
82 sustained subduction of seafloor features with relief in excess of ~1.0 km has
83 systematically stopped rupture in these historic great earthquakes on the Nazca margin.
84 We argue that in most cases rupture termination is due to the creation of weak,
85 aseismic zones in the plate interface. In addition, we explore the possible causes of
86 rupture termination in the 2010 Maule earthquake. It has not been our intention to
87 carry out a global survey of subduction margins, but although the critical height of
88 subducted topography may vary between settings, its role in stopping earthquake
89 rupture is likely to be similar along the Nazca margin and elsewhere.

90 ***Constraints on Rupture Zones and Subducting Topography***

91 Subduction zone earthquakes with $M_w < 8.0$ tend to rupture distances less than 100 km
92 and their rupture zones have aspect ratios close to one. As 100km is comparable to the
93 width of the seismogenic zone, the endpoints of these major but not great earthquakes
94 cannot tell us whether there are features along strike that may have stopped their
95 rupture. Whilst some $M_w 7-7.9$ earthquakes have ruptured larger distances, in the
96 interest of consistency we have restricted our study to $M_w > 8.0$, as these great events
97 should all have ruptured the plate interface over more than 100 km in the trench-
98 parallel direction, making it possible to identify parts of the plate interface that may
99 have acted as a barrier or nucleation point for earthquake rupture. Earthquakes with
100 $M_w < 8.0$ will be considered in the discussion section.

101 The anecdotal record of very large earthquakes along the Nazca margin stretches back
102 to at least 1575 (Cisternas *et al.*, 2005), but events before 1868 are insufficiently
103 documented to determine the extent of their rupture zones in any detail. Since that
104 year, 15 earthquakes with estimated moment magnitude $M_w \geq 8.0$ have occurred on the
105 margin. For events prior to 1973, rupture zones have been determined from damage
106 intensity and co-seismic subsidence (Kelleher, 1972, Spence *et al.*, 1999, Cisternas *et al.*,
107 2005), and we have used published estimates (see Table 1), with the exception of the
108 1908 $M_w 8.0$ earthquake offshore Peru, which is insufficiently documented to be
109 included in this study. After 1973, rupture zones can be constrained from aftershock
110 locations (Wells and Coppersmith, 1994, USGS NEIC catalog). We have done this for all
111 recent great earthquakes, including the 2010 Maule event. Uncertainty in the mapping
112 of rupture zones is due to the gradual decrease of slip toward the rupture tip, and the
113 imperfect correlation between the rupture zone and the distribution of aftershocks,
114 seismic intensities and co-seismic subsidence. The resulting uncertainty is less than 50
115 km (Kelleher, 1972), and rupture limits determined from aftershock observations match
116 other published rupture area estimates (Comte *et al.*, 1986, Delouis *et al.*, 1997,
117 Sobesiak, 2000, Tavera *et al.*, 2002) to within 40 km. Our findings are therefore not
118 sensitive to the exact method of defining rupture zones, and this uncertainty cannot be
119 easily reduced for historical earthquakes.

120 Seafloor topography was constrained from the TOPEX global seafloor bathymetry
121 dataset (Smith and Sandwell, 1997), which is created from satellite altimetry. This
122 dataset was chosen for its consistent derivation of the depth both along the margin and
123 in the open ocean, and for its inclusion of seamounts unmeasured by sonic soundings,
124 but the accuracy of seamount heights may be ± 100 m or more (Marks and Smith,
125 2007). We have calculated seafloor relief by taking the difference between the depth at
126 a point and the mean depth of the seafloor within a radius of 3° , which is generally

127 ~4000 m. The Nazca Plate has prominent topographic features with positive relief >400
128 m, including the Nazca Ridge (Spence *et al.*, 1999), which has relief of up to 3500 m,
129 and several seamount chains with approximately linear trends for >500 km extending
130 to the subduction zone. Assuming some continuity of seamount chain formation
131 through time, it is likely that associated topography has already subducted and
132 interfered with the plate interface. However, independent evidence of subducted relief
133 (Kodaira *et al.*, 2002) only exists in isolated locations such as the subducted Papudo
134 seamount along the extension of the Juan Fernandez Ridge (von Huene *et al.*, 1997).
135 Where we have found three or more topographic features with relief above a threshold
136 value to align we have extrapolated their assumed linear trend into the subduction
137 zone, taking into account offsets on known fracture zones. Moreover, we have assumed
138 that in this case a topographic feature of a magnitude similar to that of the visible
139 seafloor topography has already entered the subduction zone. The validity of this
140 assumption can only be tested with targeted seismic surveys. The shallow dip of the
141 seismogenic plate interface, ~18° on average (Tichelaar and Ruff, 1991), makes a
142 correction for dip unnecessary near the plate boundary. Positive relief on the Nazca
143 seafloor was contoured at 200 m intervals upward of 400 m, and contours were
144 extrapolated into the subduction zone by projecting the widest parts of identified
145 topography. Likely locations of subducted relief are shown in Figures 1 and 2.

146 ***Collocation of subducted topography and earthquake rupture*** 147 ***endpoints***

148 Rupturing in historical great earthquakes repeatedly arrested at 32°S and 15°S, on the
149 subducted Juan Fernandez Ridge (JFR) and the Nazca Ridge respectively (Fig. 2). These
150 ridges comprise the largest positive relief on the Nazca Plate. Other rupture limits are
151 associated with subducted topography at 20°S, 25°S and 47°S. Specifically, 11 out of the

152 26 rupture limits in well documented great earthquakes were within 40 km of a zone
153 with inferred subducted relief >1000 m, although only ~22% of the studied margin is
154 within this distance. Whilst it has been possible for great earthquake ruptures to be
155 located entirely between zones with high subducted relief (e.g., the 1939 event at 35° -
156 37°S), rupture zones generally do not appear to have crossed subducted relief >1000 m,
157 with only one exception, the 1922 event which traversed an assumed obstruction at
158 28°S.

159 To test the statistical significance of our observations, we have compared the
160 distribution of historical rupture zones with simulated patterns of rupture zones along
161 the margin. Using a Monte Carlo approach, and observing that even in the absence of
162 any subducted relief rupture limits from neighbouring earthquakes tend to collocate,
163 forming subduction zone segments (Beck *et al.*, 1998), we have concatenated the
164 rupture lengths of the thirteen sufficiently constrained historical earthquakes (not
165 including the 2010 Maule earthquake), locating the first earthquake randomly along
166 the South American margin, and repeating 2000 times. Two scenarios, representing
167 end-member hypotheses for earthquake-topography interaction, were applied. In the
168 first, ‘unconstrained’ scenario, subducted topography has no effect on rupture
169 propagation. In this scenario, the next rupture in a sequence was started at the limit of
170 the preceding earthquake.

171 This process was repeated to link 13 rupture zones, with rupture zone limits lying in
172 nearby-pairs. The total length of this group exceeds the length of the margin along
173 which the actual earthquakes occurred, due to overlap of ruptures over the record
174 interval. Simulated rupture limits outside the geographic range of the historic
175 earthquakes (12°S – 47°S) were discarded, and equal coverage along the margin was
176 maintained. Note that proximity of rupture limits is a feature shared by most, but not

177 all actual earthquake rupture zones (see Figure 2). Pairs of neighbouring rupture ends
178 are a natural consequence of a segmented subduction zone in which earthquakes do
179 not generally have overlapping rupture zones, irrespective of the mechanism of the
180 segmentation.

181 In the second, ‘constrained’ scenario, rupture was stopped by subducted relief of a
182 given minimum size H_{min} . The next earthquake rupture zone was located immediately
183 beyond this relief. Relocated rupture limits were scattered at random within 50 km of
184 the restricting topographic feature to represent the uncertainty of the actual
185 observations. The alternative that earthquake rupture starts rather than stops on high
186 subducted topography is not explored in detail for reasons given in the discussion,
187 below.

188 If subduction of high standing seafloor topography has an effect on earthquake rupture
189 propagation, then this effect may act some distance from the subducted feature, and
190 the apparent width of a feature varies with H_{min} . To account for this, and for the
191 uncertainty in the rupture endpoint location, we have varied the search distance S_D
192 within which earthquake rupture endpoints are deemed to be associated with
193 subducted topography. For a given search distance S_D and H_{min} , the simulation routine
194 was repeated 2,000 times, generating a total of 26,000 earthquakes. The number of
195 rupture limits for a specified S_D was normalized for comparison with the 26 limits of
196 historic rupture zones. S_D was varied in steps of 5 km. H_{min} was varied in 200 m
197 increments.

198 Historical data plot between the average results simulated for the constrained and
199 unconstrained scenarios, and are close to the results of the constrained model at
200 moderate relief, 800 – 1200 m, and search distances of 35 – 45 km (Fig. 3 a,b). This

201 suggests that along the Nazca margin, features larger than 800 m commonly stop
202 earthquake rupture propagation, and agrees with anecdotal observations.

203 An alternative test procedure, using earthquakes with $M_w \geq 8.0$ sampled randomly from
204 the logarithmic Gutenberg-Richter relationship between earthquake magnitude and
205 frequency rather than the historical earthquake catalogue, and assigning rupture area
206 according to a common earthquake magnitude-length scaling law (Wells and
207 Coppersmith, 1994), has yielded comparable results (supplementary information). A
208 further alternative in which earthquakes were distributed individually rather than being
209 linked together also produced equivalent findings.

210 ***Statistical significance of collocation***

211 The collocation of historical rupture limits with subducted topography has not arisen by
212 chance, according to a statistical significance test based on the probability density
213 function of the distribution of simulated unconstrained earthquakes. In this test, we
214 have determined the probability P that the number of rupture limits located within a
215 given search distance S_D from subducted topography of a given size H for randomly
216 positioned, unconstrained earthquakes exceeds the number of historical rupture limits
217 that meet the same criteria.

218 Our underlying assumption is that the number of rupture limits falling randomly near
219 topographic features (N_{uc}) can be determined directly from the unconstrained
220 distribution of rupture zones. Within groups of 26 simulated earthquake limits (N_{total}),
221 those within a given distance of subducted topography were counted, and their
222 probability function $P(N_{uc} \geq N_{real})$ was determined. The probability of the
223 unconstrained simulation (N_{uc}) having at least as many rupture limits near significant
224 topography as the actual data (N_{real}) is given by:

$$225 \quad \mathbf{P}(\text{reproduced}) = \mathbf{P}(N_{uc} \geq N_{real}) = \sum_{n=N_{real}}^{n=N_{total}} \mathbf{P}(N_{uc} = n)$$

226 Figure 3c shows a diagonal region in $S_D - H_{min}$ space in which correlation is strongest
 227 between relief and rupture endpoints. This is because increasing S_D and H_{min}
 228 concurrently causes the same area of the margin to be considered. The minimum relief
 229 at which subducted features affect the location of rupture limits is equivalent to the
 230 lowest relief within this domain of significant correlation. At this relief the number of
 231 subducted topographic features included is maximal, and S_D smallest, without adverse
 232 effect on the correlation.

233 For $H > 1000$ m and $S_D = 40$ km, rupture limits and subducted topography are
 234 significantly correlated, with $P = 1.4$ % (Fig. 3c). Note that no features have a maximum
 235 positive relief between 800 m and 1200 m. This limits the precision with which we can
 236 define critical relief for rupture collocation. Relief > 1000 m admits the same number of
 237 subducted features as > 800 m, but the additional width of features caused by using the
 238 lower threshold does not increase the amount of collocation.

239 Subducted relief < 800 m does not appear to stop or start earthquake rupture
 240 propagation. The Nazca plate has much topography with relief of 400 - 800 m, but at S_D
 241 $= 40$ km, $P = 4.3$ % for $H > 800$ m, whereas P increases to 28 % for $H > 400$ m, indicating
 242 the absence of significant correlation at this relief threshold. Nevertheless, subduction
 243 of topography < 800 m may still affect the slip distribution in particular earthquakes
 244 (Kodaira *et al.*, 2002).

245 **Discussion**

246 Collocation of subducted topography and rupture limits could arise from rupture
 247 initiation or termination. Assuming that the epicenter location denotes the initiation of

248 rupture, it can be determined whether topography starts or stops great earthquakes.
249 Six out of thirteen studied earthquakes had epicenters within 40 km of topography with
250 $H > 1000$ m, whilst ~22 % of the margin lies within this distance (See Fig. 2). The chance
251 of this occurring at random is 22 %, according to an analysis of the synthetic
252 distribution of epicenters, equivalent to the analysis of endpoints summarized above.
253 This correlation is much weaker than the match between rupture endpoints and
254 topography. None of the six events have rupture zones which cross subducting
255 topography, but in all rupture has extended away from the topography. Hence, the
256 subduction of seafloor relief > 800 - 1000 m is likely to impede or stop earthquake
257 rupture, even if rupture nucleated on or near to that topography.

258 In the absence of significant subducting topography, earthquake rupture may be
259 stopped by other factors, either structural (e.g. forearc structure or geometry of the
260 slab) or because there is insufficient release of energy to propagate the rupture tip,
261 even in the absence of any structural changes. In fact, for all of the 14 earthquakes
262 considered here at least one of the endpoints was not close to subducted topography.

263 Effective and continued rupture arrest by subduction of high standing seafloor
264 topography may require topographic features to be spaced at less than the width of the
265 seismogenic zone. Along the Nazca margin, the width of this zone is ~100 km. Greater
266 separation between topographic features of sufficient size within an alignment could
267 leave gaps in the barrier to rupture propagation. This may be the case for the seamount
268 chain at 28°S where features with relief > 1000 m are up to 200 km apart. Its trend was
269 crossed by the 1922 great earthquake, the only such traverse on record.

270 According to our findings it is likely that there is a causal link between subducted
271 topography and great earthquake rupture limits. Along-margin rupture could be
272 stopped by subducted topography either because it forms a strongly coupled patch

273 within the seismogenic zone (Scholz and Small, 1997), too strong to break in the
274 rupture, or because it forms a weak, aseismic patch (Bilek *et al.*, 2003) which has no
275 stored strain to release. Assuming that the long-term rate of shortening is uniform
276 along the subduction margin, the local strength of the plate interface affected by
277 subduction of topography may be reflected in the seismic moment release between
278 great earthquakes, when these patches are expected to catch up with slip elsewhere
279 along the margin. Strong patches are likely to have a relatively high rate of seismic
280 moment release in small and intermediate size earthquakes in these intervals. Weak
281 patches cannot accumulate elastic strain and are expected to have subdued
282 background seismicity.

283 We have calculated the cumulative moment release between great earthquakes over
284 35 years since 1973, including all shallow, intermediate size earthquakes (depth<50 km,
285 M_w 5.0-7.9) within a 0.5° moving window, but excluding aftershocks within two months
286 of a great earthquake, as well as the largest intermediate event in each zone, which
287 results in a more robust estimate (Frohlich, 2007) (Fig. 2). Five of six locations along the
288 margin with subducted topography >1000 m have low background moment release.
289 Instead, substantial background moment release tends to be concentrated at great
290 earthquake rupture limits away from subducted topography, showing that segment
291 boundaries do have residual strain and that subducting topography changes the way in
292 which this is released. The anti-correlation of tall subducted topography and maxima of
293 intermediate seismicity indicates that this topography usually acts to weaken the plate
294 interface, promoting aseismic deformation and hence impeding earthquake rupture
295 along the margin. Weak interplate coupling associated with subducted topography has
296 been observed for the Nazca Ridge (Perfettini *et al.*, 2010) and in Japan (Mochizuki *et*
297 *al.*, 2008).

298 ***2010 Mw 8.8 Maule, Chile Earthquake***

299 Along the Nazca margin there is one exception to the collocation of subducted, high
300 seafloor topography and minimum background seismicity. At 32°S, potentially very tall
301 (>2 km) subducted topography of the JFR coincides with a peak in background
302 seismicity (Fig. 2). This location is of special interest because it is where northward
303 rupture propagation in the 2010 Maule earthquake arrested. The hypocenter of this
304 earthquake was located offshore at 35.8°S, 72.7°W, at an estimated depth of ~38 km,
305 with a thrust mechanism, striking at 18°N, parallel to the margin and dipping 18° to the
306 east (USGS NEIC Catalog). Aftershock locations indicate that the earthquake ruptured
307 the Nazca margin over a length of ~600 km (Fig. 1), occupying a known seismic gap
308 (Ruegg *et al.*, 2002). Along the South American margin, its rupture length was exceeded
309 in historical times only in the 1960 M_w 9.5 earthquake. Rupture extended northward to
310 33.1°S, overlapping the 1906 and 1985 rupture zones and stopping within 22 km of the
311 subducted JFR. Although this is consistent with our finding that subducted topography
312 >1,000 m is likely to stop rupture propagation, we believe that it is the presence of a
313 strong patch in the plate interface, borne out by high intermediate seismicity at this
314 location, rather than the weakening effect of subduction of seafloor topography that
315 has arrested northward rupture propagation in 2010. Uniquely, this is also the location
316 of a subducted fracture zone, a change in the gradient of the subducted slab (Barazangi
317 and Isacks, 1976), and a transition from a sediment filled to starved trench with an
318 associated change from subduction accretion to subduction erosion (Bangs and Cande,
319 1997). High background moment release at 32°S, and the elevated plate interface
320 strength it implies are likely to be the compound effect of all these factors, indicating
321 that the weakening effect of subduction of high seafloor topography can be drowned
322 out by strengthening due to other asperities.

323 Rupture in the Maule earthquake propagated southward to 38.6°S, unimpeded by
324 significant subducted topography. At its southern limit, the 2010 rupture area overlaps
325 the northern edge of the 1960 rupture area, indicating that the earlier earthquake may
326 not have released all stress in this area. The southern rupture limit coincides with a
327 large peak in background seismicity, a pattern found in at least eight historic great
328 earthquakes on the Nazca margin (Fig. 2).

329 ***Conclusions***

330 Along the South American Nazca margin rupturing in great earthquakes is likely to be
331 impeded by subducted topography with positive relief >1000 m, engaged in the
332 seismogenic part of the plate interface. In general, this appears to be due to mechanical
333 weakening of the plate interface, thus preventing the buildup of stresses required for
334 the propagation of very large earthquakes. This effect may require the actual presence
335 of a topographic feature within the seismogenic zone, and could dissipate after the
336 feature has been transported through this zone. On the subducted Juan Fernandez
337 Ridge it may be overprinted by other factors that have strengthened the plate interface
338 sufficiently to arrest rupturing in the 2010 Maule earthquake. Along margin sections
339 with subducted relief <800 m, rupturing in historical great earthquakes has been
340 unimpeded. The length of such sections may impose an upper bound on the possible
341 earthquake size, limiting hazard in some places. If this is true, then the largest
342 earthquakes between the intersections of the Nazca and Juan Fernandez ridges and the
343 South America plate margin will have rupture lengths no larger than 550 km
344 (equivalent $M_w 9.1$). In contrast, rupture could be unimpeded between the JFR and the
345 Chile Rise, over a length of 1,450 km, enabling an earthquake rupture 33% longer than
346 in the 1960 $M_w 9.5$ event on this segment of the Nazca margin.

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464 **Figure 1: Historic great subduction earthquakes along Pacific margin of South America. Where**
465 **epicenters plot outside identified rupture zones, this is likely due to inaccuracies in locating earthquakes**
466 **before the global installation of seismometers. Areas with more than 1000 m relief are marked on**
467 **shaded seafloor topography. Black dots and lines show the inferred location of subducted topographic**
468 **highs, grey regions show the area within 50 km of these highs. Inset: Detailed view of the area of the 27**
469 **February 2010 Maule earthquake. Red dots show aftershocks between February 27 and March 8, with**
470 **size scaled by magnitude.**

471
472

473 **Figure 2: Latitudinal distribution of seismicity and subducted relief along Nazca margin. Earthquake**
474 **rupture zones and epicenters are shown as black bars and white stars, respectively; thin black line is**
475 **seismic moment release in $M_w < 8.0$ earthquakes at depths less than 50 km since 1973 (0.5° moving**
476 **windows). Also shown are areas with inferred subducted seafloor relief, binned at 200 m vertical**
477 **intervals. Grey bars mark areas with likely subducted relief > 1000 m, transposed to the upper axes for**
478 **comparison. An exception to separation of relief and moment release is the JFR at 32°S .**
479

480 Figure 3: Relation between (inferred) subducted seafloor relief and rupture limits in actual and
481 simulated earthquake distributions. Circles show limits of 13 actual earthquake ruptures. Triangles and
482 squares show results for simulations in which rupture limits are/are not constrained by subducted
483 seafloor features, respectively. Synthetic results are based on 2000 runs with 13 earthquakes each. A)
484 Number of earthquake limits within search distance from (inferred) subducted seafloor relief >1000 m.
485 B) Number of earthquake ruptures within 40 km of (inferred) subducted seafloor relief of varying size.
486 Error bars denote the inter-quartile range of the synthetic results. Note how the plot of observed
487 earthquake rupture limits approaches that of topographically constrained, synthetic ruptures. C)
488 Probability of the observed correlation of earthquake rupture limits and subducted seafloor relief being
489 reproduced by chance by an unconstrained synthetic distribution. Strongest topography – rupture limit
490 correlation (marked in white) occurs between 1000 - 1600m relief and 40 - 80km search distance. The
491 diagonal nature of the domain with low P is due to a trade-off between relief and area searched;
492 increasing relief narrows admitted topographic features, reducing the area searched for a given S_D .

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Figure 1
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Figure 3
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Table 1
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Date	Source	Alternate rupture zone estimation	Location	Magnitude	Length (km)
13/08/1868	Spence 1999		Southern Peru	8.8	400
10/05/1877	Spence 1999		Northern Chile	8.8	400
8/17/1906	Kelleher 1972		Central Chile	8.6	250
11/11/1922	Kelleher 1972		Central Chile	8.4	390
1/25/1939	Kelleher 1972		Southern Chile	8.2	190
8/24/1942	Kelleher 1972		Central Peru	8.6	150
4/6/1943	Kelleher 1972		Central Chile	8.3	210
5/22/1960	Cisternas 2005		Southern Chile	9.5	1050
10/3/1974	Aftershocks		Central Peru	8	280
3/3/1985	Aftershocks	Comte 1986	Central Chile	8	250
8/1/1995	Aftershocks	Delouis 1997, Sobesiak 2000	Northern Chile	8	240
6/23/2001	Aftershocks	Tavera 2001	Southern Peru	8.4	360
8/15/2007	Aftershocks		Central Peru	8	160

Supplementary Information:

Gutenberg-Richter distribution

As well as generating earthquake distributions using the rupture lengths from measured earthquakes, rupture lengths were assigned at random according to the logarithmic Gutenberg-Richter magnitude relationship. Earthquake magnitudes were converted into lengths using scaling factors based on the earthquake moment. Lengths varied from 100 km at magnitude 8.0 up to an artificially limited maximum rupture length of 1000 km at Mw 9.5 and above due to the lack of naturally-occurring earthquakes existing above this length.

After determining the rupture length, the synthetic earthquake rupture procedure continued as before, placing earthquakes in groups of 13 and rupturing these in sequence along the subduction margin. Earthquake end points were allowed to rupture unrestricted, or to be restricted by projected subducting topographic features.

The results are similar to those obtained using the measured earthquake rupture zone lengths. At low relief, there is no correlation between rupture endpoints and topography, the observed number of rupture endpoints near to topography is reproducible by random positioning of synthetic endpoints. At moderate topographic heights (1000 – 1200 m) there is good correlation between rupture zone endpoints and a zone up to ~50km away from the topography.