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1 **Morphotectonic and morphometric analysis of the Nazca plate and the adjacent offshore**
2 **Peruvian continental slope – implications for submarine landscape evolution**

3

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22 **submarine slumping, curvature analysis, morphometric dating, submarine landscape evolution,**
23 **hazard potential**

24

25 **Abstract**

26

27 We use new swath bathymetry data acquired during the *RV Sonne* cruise GEOPECO and
28 complement them with swath data from adjacent regions to analyse the morphotectonics of the
29 Peruvian convergent margin. The Nazca plate is not covered with sediments and therefore has a
30 rough surface along the entire Peruvian trench. The styles of roughness differ significantly along the
31 margin with linear morphological features trending in various directions, most of them oblique to the
32 trench and roughness magnitudes of a few to several hundred meters. The lower slope is locally very
33 rough and at the verge of failure throughout the entire Peruvian margin, as a result of subduction
34 erosion causing the lower slope to over-steepen. Using curvature attributes to quantitatively examine
35 the morphology in the Yaquina and Mendaña areas revealed that the latter shows a larger local
36 roughness both seaward and landward of the trench. However, the amplitude of morphological
37 roughness is larger in the Yaquina area. We identified a 125 km² large slump on the Lima middle
38 slope. Morphometric dating suggests an age of 74500 years within 35 to 40% error. Estimated
39 incision rates on the upper slope are between 0.1 and 0.3 mm per year suggesting that landscape
40 evolution on the Peruvian submarine continental slope is similarly slow than that in the Atacama
41 desert.

42

43 **1. Introduction**

44

45 Quantifying variability in continental slope gradient or slump scar gradient as well as a description of
46 local and regional variability of seafloor morphology has only become possible since the late 1970's
47 when scientific swath mapping campaigns began, and has more frequently been undertaken since the
48 early 1990's, when a new generation of much more efficient swath mapping systems became available
49 (Bourillet et al., 1996). Unlike onshore morphometry, which has been widely applied employing

50 gridded digital elevation data, marine morphometry is considered to be still in its infancy (e.g. Ramsay
51 et al., 2006). However, although not frequently, high-resolution multibeam swath bathymetry has been
52 used for detailed and quantitative morphotectonic and morphometric analyses (e.g. Huchon and
53 Bourgois, 1990; Duperret et al., 1995; Pratson and Haxby, 1996; von Huene et al., 1999, Kukowski et
54 al., 2001, Sak et al., 2004, Mitchell, 2005) and also revealed its high potential in aiding to assess the
55 hazard potential of a margin (e.g. McAdoo et al., 2004). Morphometric dating of slumps using a
56 diffusion transport model has been suggested to be also applicable in submarine environments (e.g.
57 Mitchell, 1996).

58
59 According to the mode of material transfer, convergent margins are divided into accretive and erosive
60 ones and both show a very different morphology. The continental slopes of accretive margins like
61 Cascadia or Makran on a regional scale have a very gently inclined slope of less than 2° and are
62 mainly characterized by along-strike elongated topographic ridges forming the surface expression of
63 an accretionary wedge. The large length (up to more than 100 km) of these ridges and the relative
64 morphological smoothness of their flanks, while being relatively steep, suggest that these ridges are
65 quite stable (e.g. Pratson and Haxby, 1996; Kukowski et al., 2001). The continental slopes of those
66 margins undergoing subduction erosion and where therefore a pronounced accretionary wedge is
67 missing, are regionally steeper, and show a more irregular topography suggested to result from
68 distributed surficial mass wasting caused by over-steepening as a result of transferring material from
69 the tip of the slope to the subduction channel (e.g. Ranero and von Huene, 2000; von Huene and
70 Ranero, 2003). Compared to accretive margins, erosive margins like the Peruvian tend to be more
71 prone to the occurrence of major slumps, which have been made responsible for having caused
72 tsunamis with run-up heights up to 50 meters (e.g. von Huene et al., 1989).

73
74 The Peruvian convergent margin is a prominent example of a long-term erosive margin (e.g. Karig,
75 1974, von Huene and Lallemand, 1990, Clift et al., 2003). Here the nearly sediment-free and very
76 rough (Kulm et al., 1973, Huchon and Bourgois, 1990) Nazca plate is obliquely subducted beneath
77 South America. The structure of the margin is well known from reflection seismic (Moore and Taylor,
78 1988, von Huene et al., 1996), and wide-angle seismic (Hampel et al., 2004, Krabbenhöft et al., 2004)
79 data and parts of the margin have been surveyed with swath mapping and side scan sonar (e.g.
80 Bourgois et al., 1988; Hussong et al., 1988; Huchon and Bourgois, 1990; Li and Clark, 1991; Hagen,
81 1993; Li, 1995; Bourgois et al., 2007).

82
83 In this study we use new swath bathymetry data obtained during the German *RV Sonne* GEOPECO
84 cruise (Bialas and Kukowski, 2000) to analyse the morphology and deformation styles of the Nazca
85 plate approaching the trench and the continental slope along the Peruvian margin (Fig.1). We add
86 SEAPERC swath data (Huchon and Bourgois, 1990) to our data-base to extend the multibeam
87 coverage along the margin. The analysis of the whole dataset includes a quantitative comparison
88 employing curvature attributes for two sub-regions. We also attempt to morphometrically date a newly
89 identified slump on the upper continental slope off Lima. By doing so, we are able to roughly estimate
90 the rates of landscape evolution at the Peruvian continental slope.

91 92 **2 Geodynamic setting and structure of the Peruvian margin**

93
94 Along the Peruvian margin (Fig.1), the close to sediment-free oceanic Nazca Plate is subducting in
95 largely easterly direction (N78°E) beneath the South American continent at a present convergence rate
96 of ~68 mm/a (Norabuena et al., 1998) resulting in about 20° obliquity of convergence in recent times.
97 The age of the subducting plate increases from about 28 Ma north of 10°S to about 40 Ma south of

98 16°S (Fig.1) with a considerable jump in age across the Mendaña Fracture Zone (MFZ) (Müller et al.,
99 1997). The trench is well pronounced and more than 6000 m deep along most of the Peruvian margin.
100 It shallows towards the Nazca Ridge (NR), a prominent, more than 1000 km long basement ridge the
101 crest of which is rising about 1.5 km above the surrounding seafloor. This ridge has swept southwards
102 along the margin since its first collision at about 11°S some 10 Myr ago to 15°S where it presently
103 subducts beneath the Peruvian margin (Hampel, 2002, Rosenbaum et al., 2005).

104

105 Close to the trench, the descending Nazca plate dips between 5.5° and 9° and the average dip of the
106 lower continental slope varies regionally between 7° and 9° (Krabbenhöft et al., 2004, Hampel et al.,
107 2004). Juxtaposed to the trench is a small low-velocity accretionary wedge of less than 20 km width
108 throughout the margin and landward of it follows high-velocity continental basement most probably of
109 Palaeozoic age (von Huene et al., 1996, Krabbenhöft et al., 2004). Along the upper slope with a thick
110 Quaternary sediment cover, several elongated forearc basins, e.g. the Talara, Yaquina, Lima and Pisco
111 Basins, indicate significant Cenozoic subsidence.

112

113 Major Quaternary slumping has been reported from several localities along the Peruvian margin. A
114 polyphase large-scale submarine slump between 5°S and 6°S dated at 13.8 ± 2.7 ka (von Huene et al.,
115 1989; Bourgois et al., 1993; Duperret et al., 1995) and a giant slump identified at about 20°S (Li and
116 Clark, 1991) are the most prominent evidence for slope instability and related hazard potential.

117

118 **3. Data acquisition, processing, and analysis**

119

120 During *RV Sonne* cruise GEOPECO (Bialas and Kukowski, 2000) extensive swath mapping was
121 undertaken in several areas between 8°S and 16°S employing the onboard Hydrosweep system (Grant
122 and Schreiber, 1991). Swath data were acquired to cover certain areas (Fig.1) as well as when doing
123 seismic profiling and transits.

124

125 The individual beams of a swath are often of different quality. Whereas beams close to the centre of a
126 swath hit the seafloor at a right angle and usually are of high quality, the beams at the edges of a swath
127 hit the seafloor at low angles which may lead to a lower quality. In order to obtain a high quality swath
128 map, it is necessary to place ship tracks sufficiently close to obtain some overlap between neighbouring
129 swaths. This was done in the Yaquina area and along the lower continental slope, and we therefore
130 obtained full coverage in these areas. Ship's speed was less than 10 knots while mapping, and 4 to 5
131 knots during seismic work. We added further individual swaths obtained e.g. during wide angle
132 seismic work (Hampel et al., 2004; Krabbenhöft et al., 2004) to our data set. Spatial resolution along a
133 swath is about 200 m in water depths as deep as the trench and 70 meters and higher in water
134 shallower than 2000 meters, respectively. Along track, the spacing of swaths was some 10s of meters
135 according to the ship's speed.

136

137 Each swath was edited using the freely available MB system software package (Caress and Chayes,
138 1995) for visual inspection of the data quality. The latter was generally high, due to the calm weather
139 during the entire cruise. Non-frequent erroneous outer beams were removed from the data set. After
140 editing, the raw data were converted to depth using a water sonic velocity profile obtained from a CTD
141 (conductivity-temperature-depth tool) at a trench-near position (Bialas and Kukowski, 2000). Vertical
142 accuracy of the depth-converted data is ± 2 meters. Geographical coordinates were assigned to each
143 beam using the ship's navigation. In a final step, data were re-formatted to 3 column ascii data to
144 generate various sub-grids for morphotectonic and morphometric analysis.

145

146 For this study, we also used swath bathymetry data obtained during *RV Jean Charcot* SEAPERC
147 cruise in 1986 (Bourgois et al., 1988), which we received as 3 column ascii data. We did not apply any
148 further processing to this data set, as it was used in several studies before (e.g. Bourgois et al., 1988;
149 Huchon and Bourgois, 1990; Duperret et al., 1995). Merging the GEOPECO and SEAPERC data
150 revealed a very good fit in the (small) overlapping regions confirming the good quality and reliability
151 of these data sets. In the Lima region, we digitized ODP bathymetry and added it to our data to enable
152 a more regional picture. The swath data were complemented with GINA (Lindquist et al., 2004) data
153 for some analyses to characterize the regional seafloor morphology across the edges of the areas
154 covered with swath bathymetry. However, all our interpretations have been exclusively derived from
155 the high-resolution swath data. Sub-grids and profiles were extracted from the whole data set for
156 detailed analysis and to display maps and perspective views.

157
158 A straight-forward strategy to quantitatively analyse a digital terrain model, such as a gridded swath
159 bathymetry data set is to compute the local dip for each cell, allowing to e.g. identify areas potentially
160 close to failure (e.g. McAdoo et al., 2004) or quantifying the morphological roughness (also called
161 ruggedness) of an area. However, many morphological features have a linear trend, which cannot be
162 identified from the dip alone. Here, curvature attributes computed from gridded curved surfaces, e.g.
163 gridded topographic data (Shary et al., 2004) or seismic horizons mapped from 3D reflection seismic
164 data sets (Roberts, 2001) are an efficient tool to support tectonic interpretation and detect features such
165 as faults or quantify local dip. Surface curvature attributes describe how much a surface deviates from
166 a plane and also may characterize the cause of this deviation (Roberts, 2001; Bergbauer & Pollard,
167 2003). Mathematically curvature is defined as the 2nd derivative of a curve. With this definition, a
168 dipping, but straight line has a zero curvature, while a non-straight line has a non-zero curvature. The
169 basic definition of curvature in two dimensions also holds for three dimensions, i.e. for a curved
170 surface. With this definition, for any given point on a curved plane an infinite number of curvatures
171 can be extracted, as the cut can be made in any direction. However, those curvatures defined by planes
172 orthogonal to the surface are most useful for structural analysis (Roberts, 2001). There will be one
173 curve with the largest curvature. Perpendicular to it is the curve with the smallest curvature. This
174 maximum and minimum curvatures then are used to derive further curvature attributes, but also can be
175 directly used e.g. to delimit faults and fractures. Curvature extracted in the direction of maximum dip
176 allows to measure the rate of change of dip. In this dip curvature (profile curvature in terrain analysis;
177 Shary et al., 2004) the direction of faults is preserved and therefore contains information
178 complementary to that derived from local dip.

179
180 To compute curvature attributes of gridded bathymetry surfaces we employed a least square quadratic
181 approximation fitting a local surface by using the neighbouring eight grid values which results in a set
182 of arithmetic expressions for the coefficients of the quadratic polynom describing the surface (Roberts,
183 2001). Grid cell size was carefully chosen in accordance with the spacing of the GEOPECO swath
184 bathymetry data, as a proper choice of grid cell size may be crucial for a sound interpretation
185 (Bergbauer & Pollard 2003). As curvature analysis is quite sensitive to filters applied, we used
186 unfiltered grids to avoid bias of the analysis. We extracted subsets of the bathymetry data to analyse
187 the nature of the Nazca plate approaching the trench and the lower slope in two areas, the Yaquina
188 area off Trujillo and the area of the MFZ.

189
190 A slump scar or a fault scar is steepest just after failure and re-adjusts through superficial erosion to
191 the average regional slope angle with time. For transport limited systems, like at continental slopes,
192 this process of degradation can be approximated with a diffusion process (Coleman and Watson,
193 1983; Mitchell, 1996) and therefore can be described by the diffusion equation

194 $\partial z / \partial t = dc (\partial^2 z / \partial x^2),$

195 where z is elevation, t is time, dc is the diffusion coefficient and x is the horizontal distance. The faster
196 a slump scar degrades to the regional slope, the larger is the diffusion coefficient. Analytical and
197 numerical solutions for the diffusion equation have been proposed yielding the product of the diffusion
198 coefficient and the age of the slump or faulting event (e.g. Nash, 1981; Coleman and Watson, 1983;
199 Mitchell, 1996). This means that the equation is underdetermined as long as both, the diffusion
200 coefficient and the age of a slump are not known. However, it enables to date a slump
201 morphometrically relative to a slump in the same setting, which has been dated using other techniques,
202 e.g. isotopic methods. The analytical solution of Coleman and Watson (1983) offers the possibility to
203 date a slump without knowing the slope of the escarpment just after failure. However, this method has
204 been debated, because it suggests that the degradation is dependent on the height of the scarp, and
205 because it does not account for sedimentation but it offers to date a slump without knowing the slope
206 gradient just after failure. Otherwise, plausible estimates need to be made for the slope gradient just
207 after faulting or slumping, e.g. assuming a vertical scarp or the angle of repose.

208

209 **4. Morphological characteristics of the Peruvian slope and facing Nazca plate**

210

211 In the following description and quantitative analysis of the swath bathymetry data we focus on two
212 key-areas (Yaquina and MFZ) seaward of the trench where full coverage allows to quantitatively
213 analyse the surface of the Nazca plate. Further, the new bathymetry data enable to visualize the
214 morphology of the lower slope continuously along about 400 km along the margin. In the Lima region,
215 full coverage was achieved on the middle and parts of the upper and lower slopes, respectively. Here,
216 we were able to identify a major slump and estimate its age using the above mentioned diffusion law
217 based morphometry and comparison with a well-known (Bourgois et al., 1993; Duperret et al., 1995)
218 slump further to the north in the Paita area.

219

220 **4.1 Morphology of the Nazca plate approaching the Peruvian margin**

221

222 Generally, the surface of the Nazca plate seaward of the Peru trench is close to sediment-free
223 (<http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html>). In the absence of sediment coverage,
224 original surface roughness, i.e. as generated at the spreading centre, will be maintained on old oceanic
225 crust (Bird and Pockalny, 1994). Therefore, at sediment-starved margins like the Peruvian one the
226 morphology of the oceanic crust at the trench still mimics the processes and directions of its
227 generation.

228 The main regional topographic feature of the Nazca plate close to the Peru trench is a ripple pattern
229 made of elongated highs and lows oriented at different angles to the trench with a spacing of a few
230 kilometres and a height difference of about 100 to a few hundreds of meters (Figs.2, 3). Seaward of
231 Trujillo trough and the northern Lima trench, this pattern is similar in shape and height magnitude to
232 that found on young (0 to 10 Ma) Nazca plate crust not far away from the East Pacific Rise
233 (Grevemeyer et al., 2002). Although the depth of the trench changes along the Peruvian margin, the
234 regional bend of the Nazca plate towards the trench is similar along the entire margin with the seafloor
235 50 km seaward of the trench being approximately 1.3 to 1.4 km shallower than the trench (Fig.3). The
236 only exception is Nazca ridge, where the Nazca plate is bending considerably steeper.

237

238 **4.1.1. Yaquina area**

239

240 Between 7.5° S, the latitude, at which Trujillo Trough intersects with the trench, and the northern edge
241 of the Mendaña Fracture zone the Nazca plate seafloor shows some unique features. Between 8° S and

242 8.65° S, five parallel, ridge-shaped features trending grossly parallel to the convergence direction
243 (N78E), enter the trench (Fig.4). At the seaward trench wall, some of them are cut by bending-related
244 normal faults. We interpret them as relicts of former transform faults, which are now healed. A half-
245 moon shaped re-entrant on the lower continental slope facing one of these “ridges” at 8.25° S is
246 similar to re-entrants formed in the wake of subducting seamounts (e.g. Dominguez et al., 1997)
247 indicating that this “ridge” has already been subducting some distance beneath the lower slope. South
248 of 8.65°S, several roughly north-south trending ridges of about 35 km length enter the trench. These
249 basalt ridges are oblique to any other feature, including the direction of convergence. The direction of
250 their long axes is at angles of 14° to 24° relative to the trench (Fig.2a). We interpret them to result
251 from off-axis magmatism and having remained in their original direction and shape when approaching
252 the trench. These ridges mark the largest local scale roughness of the Nazca plate with the height
253 difference between the top of the basalt ridges and the surrounding seafloor being as large as more
254 than 800 m at some locations (Fig.2, 3, 4).

255 256 4.1.2 Mendaña Fracture Zone

257
258 Morphologically, the MFZ is a sequence of elongated features trending perpendicular to the trench
259 (Fig.5). Its width is at least 80 km. In the north, the elongated features resemble ridges being parallel
260 to each other and south of 10.5° S, the morphology shows several stair case like steps which are
261 dipping to the SE. The width of both the ridges and the steps is about 10 to 15 km and their surfaces
262 are generally very rough. The difference in elevation between adjacent ridges and troughs on average
263 is several hundred meters and up to 600 m at maximum. The flanks to the troughs, which are mostly
264 characterized by rough surfaces, are steeply dipping. This pattern is well compatible with differential
265 vertical motion along numerous parallel sub-vertical faults indicating extension in N-S direction
266 (Fig.5). Bending related normal faults cannot be clearly identified, however, the irregular surface of
267 the ridges and troughs and the partially bad swath coverage may obscure such features. The ridges and
268 steps maintain their shapes when entering the trench and are cut off along a straight line (Fig.5). There
269 are no re-entrants or other morphological features indicating their subduction at the tip of the lower
270 continental slope. Either these features are too small to influence the lower slope morphology in a
271 characteristic manner or they have just arrived at the trench. Off Yaquina, only the most pronounced
272 ridge (3 in Fig.4) created a re-entrant. This ridge however is wider and higher than the other ridges off
273 Yaquina and those forming the MFZ. This would suggest that the MFZ is already subducting beneath
274 the Peruvian slope, but a feature too smooth to significantly affect the lower slope morphology.

275
276 To compare Nazca plate as well as the trench and its both sides quantitatively, we applied curvature
277 analysis to the Yaquina region (Fig.6) and the MFZ (Fig.7) and also present histograms showing the
278 distribution of local dip in the two areas, seaward and landward of the trench, respectively (Fig.8). The
279 ripple-topography on the Nazca plate facing the Yaquina slope is characterized by walls of about 10°
280 dip on average with portions of the flanks being as steep as 15° to 20° (Fig. 6b). Between the ripples,
281 the seafloor is close to flat and the “regional” roughness does not increase towards the trench. We
282 could not identify bending related normal faults in this part of the Nazca plate. The N-S-trending scarp
283 at 81.05° W (see black arrows in fig.6a) is as steep as at least 15° throughout its entire length. The
284 basalt ridges in the trench have steep flanks and relatively flat tops with NW-SE-trending structures,
285 similar to those just west of the N-S-scarp (Fig.4, 6a). The immediate proximity of negative and
286 positive values of dip curvature confirms the sudden change of morphology along the basalt ridges
287 (see black arrows in Fig.6c) and suggests to interpret the scarp at the tip of the western flank of the
288 westernmost ridge as a fault scarp.

289

290 A much larger portion of the MFZ surface has a steepness of more than 5° compared to the Yaquina
291 trench region (Fig.8). Between 80.4° W and 80.2°W, a roughly N-S oriented linear trend cuts through
292 the entire length of the area displayed (black arrows in Fig.7b, c). The direction of this trend is at high
293 angle to the ship's course and therefore cannot be an artefact. We suggest it to be the surface
294 expression of a fault, probably a strike-slip fault with a normal component. This structure is difficult to
295 identify from just the topographic map (Fig.5, 7a). Here, like for the trench-perpendicular normal
296 faults, the immediate proximity of positive and negative dip-curvature values (red arrows in Fig.7b, c)
297 confirms that these structures may be interpreted as faults.

298

299 4.1.3 Lima area

300

301 At 11.75° S, ripple-shaped structures on the Nazca plate are parallel to the trench (Fig.2b), whereas at
302 13.5°S they strike more southerly generating about 10° obliquity (Fig.2c) between the ripples and the
303 trench. A comparison with the area in-between (Gagnon et al., 2004) reveals that the trend of these
304 morphological features changes at 12.5° S. The spacing between neighbouring peaks is approximately
305 5 to 10 km. In profile view, at 13.5° S, the morphology of the seaward wall of the trench looks like
306 tilted steps with seaward slopes more shallowly dipping than landward slopes. The ripple-shaped
307 morphology with an elevation amplitude of a few hundred meters is a regional pattern seaward of the
308 Peruvian trench with the Yaquina region and the MFZ being pronounced exceptions. The ripples do
309 not have the same trend everywhere, which we interpret in accordance with Grevemeyer et al. (2002)
310 to be related to the different spreading directions when the Nazca plate crust was formed.

311

312 4.2 Trench and continental slope

313

314 Bathymetry profiles across the trench and continental slope at different latitudes (Fig.3) reveal a lower
315 slope with a similar large steepness of about 6° along the entire margin. Between 8°S and 11°S, the
316 lower slope is characterized by a rough and irregular morphology (Figs.4, 5) consisting of equi-
317 dimensional and elongated highs and lows, and also local ruggedness of the seafloor. This very much
318 resembles the morphology of the lower slope in the Paita area as described by Bourgois et al. (1988).
319 In agreement with these authors we interpret this morphology to results from local mass wasting. The
320 tip of the continental slope is not a straight line along the trench, but it locally advances and recedes in
321 an alternate way. This was named a meandering front by Huchon and Bourgois (1990), who describe
322 this type of deformation front in the Mendaña area. The new GEOPECO data reveal that this type of
323 deformation front continues at least as far north as 8°S.

324

325 Structural benches of some 10 to 30 km length are present on the continental slope throughout the
326 entire margin, however, their width and relative height are very variable (e.g. Schweller et al., 1981).
327 Several terraces and elongated ridges are regional marks in the morphology of the lower slope (Figs.4,
328 5). In the north, these features look more like narrow terraces, in the south more like peaked ridges.
329 Especially the ridges found along the lower slope facing the MFZ (Fig.5b) very much resemble
330 accretionary ridges found at margins like the Makran (Kukowski et al., 2001) or Cascadia (Pratson and
331 Haxby, 1996). Accordingly, we interpret them as accretionary ridges as well.

332

333

334 In the Yaquina area, the lower slope is characterized by two irregular bands of high steepness, which
335 locally can attain 30° indicating that large portions of the lower slope may be at the verge of failure.
336 The trench is not marked by a straight line, but as a sequence of advancing and retreating segments
337 (red arrows in Fig.6b). We interpret the advancing portions as originating from local slope failure.

338 This is very nicely seen in the display of dip-curvature (Fig.6c). Landward adjacent to the lower slope
339 is a narrow, but relatively flat mid-slope terrace. There, a patchy band made up of discontinuous very
340 narrow ridges (see blue arrows in Fig.6c) marks the surface expression of a fault, which we interpret to
341 be a continuation of a normal fault identified further to the south earlier (Bourgeois et al., 1988). Dip
342 curvature (Fig.6c) reveals the higher linearity and continuity of the slope benches compared to the
343 fault zone itself, which creates a patchy image, and the middle slope which exhibits irregular local-
344 scale topography.

345
346 The tip of the upper slope roughly coincides with 3000m water depth and is characterized by the
347 presence of numerous, grossly equally spaced mostly v-shaped gullies (Fig.9). This observation
348 reveals that here surface morphology could develop which has resulted from self-organisation
349 (Hampton et al., 1996). During the incision of these gullies, the upper Peruvian slope must have been
350 stable. The profiles across the upper slope show a significant ruggedness and irregularity of the
351 topography. However, the main gullies are still very prominent. Furthermore, the main gullies
352 straightly follow the dip of the slope and all of them are fed by numerous smaller feeder gullies
353 creating a dendritic pattern also observed at passive margins (Pratson and Haxby, 1996; Goff, 2001).
354 The gullies frequently are more than hundred meters deep, the main gullies even as deep as about 200
355 m. The average gradient of the upper slope is about 5°, which makes it close as steep as the lower
356 slope. In contrast to the latter it must be relatively stable since it is underlain by Palaeozoic
357 metamorphic continental basement. A possible reason for the higher stability of the upper slope is that
358 it consists of intact rock, which exhibits a high cohesion.

359
360
361 The lower slope in the MFZ area very much resembles the one of the Yaquina region, portions of it are
362 even steeper and the ridges are more discontinuous. The landward edge of the lower slope is marked
363 by a patchy, relatively flat area of considerable width, very different from what is observed in the
364 Yaquina region. Not only does the MFZ region exhibit a larger percentage of local dips of more than
365 5° and even 20° compared to the Yaquina off-trench region, but the same is observed at the continental
366 slopes (Fig.8). Especially the Mendaña continental slope is characterized by non-Gaussian distribution
367 of dip. The frequency distribution of local dip of both portions of the continental slope off Peru
368 analysed here is dissimilar to the one documented along the convergent accretive Oregon continental
369 slope (Pratson and Haxby, 1996). At the Peruvian margin, local slope gradients are significantly less
370 frequent and steep slope gradients are more frequent than at the Cascadia margin, with the regional
371 slope gradient being twice as high. This may imply that convergent margins undergoing subduction
372 erosion form their own class with regard to local slope. Also the regional slope of the Peruvian margin
373 seems to be significantly steeper than those of the other types of margins, confirming this suggestion.

374 375 **4.3 Surficial mass wasting and catastrophic mass transport**

376
377 Local surficial mass wasting is expressed in various ways along the central Andean submarine slope.
378 Local, but steady redistribution of material is characteristic for the lower slope in the Yaquina and
379 Mendaña regions (see 4.2), but also at the NR collision zone (Hampel et al., 2004). This implies that
380 the entire Peruvian margin may be characterised by this locally rugged lower slope. However, the
381 middle and upper slopes in these regions show different characteristics. The absence of gullies
382 suggests that the upper slope in the Mendaña region also is close to failure. In addition, at about
383 10.5°S, we identified a large slump mass at the tip of the upper slope (Fig. 5b).

384

385 The morphology of the Lima area in some aspects differs from the other parts of the Peruvian margin.
386 It has a wide mid-slope terrace and the surface of it is smoother than north of it. In the swilley south of
387 the Northern High (Pecher et al., 2001), a large meandering channel with tributary channel systems is
388 identified (Fig.10). In analogy to the term river drainage basin used for onshore runoff systems we call
389 it a turbidity current basin. The development of this channel system suggests a relatively long-term
390 stability of the mid-slope. From visual inspection, sub-basins do not mimic the basin itself, therefore
391 they are not self-similar (Dodds and Rothman, 2000).

392
393 Between 11.2°S and 11.4°S, a large slump mass covering an area of about 125 km² and having a
394 relatively steep seaward rim is identified from the swath data (Fig.10). Bathymetry profiles through
395 the escarpment and the slump mass (Fig.11) reveal a thickness of 200 m and volume of 40 km³ of the
396 slump mass. The toe of the slump escarpment is half-moon-shaped and the surface of the escarpment
397 comprises numerous gullies indicating that the slump must be old enough such that a drainage system
398 could evolve.

399
400 Both the slump off Paita and the Lima slump occurred on the middle slope between 3000 m and 4000
401 m water depth (Fig.11a,b), which may suggest that similar rocks occur beneath the slumps scarps.
402 Also, the escarpments of both slumps have approximately the same height (Fig.11c, d), which justifies
403 to normalize the analytical solution of Coleman and Watson (1983). Therefore, comparing both slump
404 scars morphometrically allows for a cautious estimation of the age of the Lima slump by using the
405 steepness of the escarpments and the far-field slopes, respectively (Fig.11b). The average slopes across
406 the escarpments and the far-field slopes are estimated graphically (Fig.11c, d). The average slope of
407 the Paita escarpment is as steep as 17° with a far-field slope in this portion of the Peruvian mid-slope
408 of about 5.7°. As its age is known, we estimated a diffusion coefficient of 0.0026 m²/yr for the Paita
409 slump, assuming the initial slump scarp was sub-vertical, as observed from the N-S profile across the
410 slump scarp. The slump scarp may have moved landward with the detachment fault as steep as 45° as
411 reported by Bourgois et al. (1988) on the middle and upper slope, producing a decrease of the relative
412 slope gradient of the scar, from its initial gradient (90°) to the actual one (17°). The average slope of
413 the Lima escarpment is 6.35° and the far-field slope 2.5°. Using the value of the diffusion coefficient
414 obtained for the Paita slump, we estimate the age of the Lima slump at 74520 years. For the age
415 estimate of the Paita slump, an error of 20% was estimated (Bourgois et al., 1993), which then is the
416 minimum error for the age of the Lima slump, as the estimation of its age is based on the estimation of
417 the age of the Paita slump The curved shape of the escarpments and the deviation of the profiles from
418 a straight line add an uncertainty of the estimation of the slope angles of about 1°, which would add an
419 error of 5 to 15 % depending on the actual slope. Since we describe large scarps with a height of
420 several hundred meters and given that bioturbation is usually limited to the uppermost about 50 cm of
421 sediment, we consider it to be of minor importance. This is supported by the observation that not far
422 from the upper edge of the Lima slump, competent rocks are outcropping (Pecher et al., 2001), which
423 do not seem to have been re-worked by bioturbation. Taking all this in account, the error in the
424 estimate of the age of the Lima slump may be as large as 35 to 40 %.

425
426 The gullies developed in the Lima slump escarpment reveal that it has been stable since slumping. To
427 assume that incision of the gullies started immediately after slumping enables to roughly estimate
428 incision rates. The gullies are at least as deep as 10 m with a maximum of about 25 m. This would
429 infer incision rates between 0.1 mm and 0.33 mm per year. Taking the potentially large error of the
430 age of the slump into account, incision rates may well vary between 0.07 and 0.5 mm per year.

431 432 **5. Discussion**

433

434 The new GEOPECO swath bathymetry data together with older complementary data enables to draw a
435 regional scale picture of the morphological features and their diversity of the Nazca plate and
436 continental margin off Peru. The close to sediment-free Nazca plate exhibits a remarkably high
437 roughness, though expressed in different styles along the Peruvian margin, mostly of higher roughness
438 than e.g. the Nazca plate off north Chile (von Huene and Ranero, 2003) and the Cocos plate off Costa
439 Rica north of Nicoya peninsula (Ranero and von Huene, 2000), respectively. Bending-related normal
440 faults, which are commonly observed on sediment-free oceanic plates close to subduction zone
441 trenches (e.g. Ranero and von Huene, 2000; Wright et al., 2000; Ranero et al., 2005), have been
442 identified in our swath data on the Nazca plate north of 9° S (Fig.4), in the Lima region between 11°
443 and 13.5° S (Fig.2), and in the collision zone of Nazca Ridge at about 15° S (Hampel et al., 2004).
444 Earlier studies in adjacent regions have revealed a consistent picture (Hussong et al., 1988). However,
445 bending-related normal faults are absent between 9° S and 11° S (Fig.4). Note, that for the MFZ, we do
446 not follow the interpretation of Huchon and Bourgois (1990), who reported bending-related normal
447 faults. However, as the SEAPERC data do not provide full coverage (See Fig.1), interpretation of
448 structures parallel to the ship tracks is problematic. These regions correspond with an unusual
449 morphology of high roughness and linear elements with different trends on the Nazca plate suggesting
450 that the direction of lower plate morphological features may suppress the formation of such faults,
451 whereas the amount of bending, or the average slope of the lower plate towards the trench (Fig.3) does
452 not seem to influence the occurrence and spacing of normal faults (Fig.2, 4). The ridges identified in
453 the Yaquina area trench consist of tholeiitic basalt of Miocene age (8.7 Ma, Kulm et al., 1974).
454 Miocene ages, although older, have also been found for basalts (16.5 Ma and 18.6 Ma) in the MFZ
455 (Bourasseau et al., 1993). This is considerable younger than the age of the Nazca plate close to the
456 trench (> 27 Ma, Fig.1) and infers that considerable mid-plate magmatism seems to have occurred in
457 the Miocene.

458

459 The trench is about 5 km wide along most of the Peruvian margin and has a flat surface, which is in
460 contrast e.g. to the north Chilean margin (von Huene and Ranero, 2003) that also is shaped by
461 subduction erosion. The toe of the continental slope is not straight but overprinted by ubiquitous local
462 slumps, which is similar to what is observed along the north Chilean margin (von Huene and Ranero,
463 2003), but different from most accretive margins (e.g. Kukowski et al., 2001, McAdoo et al., 2004).
464 The lower slope up to about 1500 m above the trench is of very similar steepness along the margin,
465 while escarpments on the middle slope become wider and more distinct from north to south (Fig.3).
466 We interpret the “ridges” or “benches” identified on the lower slope (Fig.3, 6, 7) as relicts of
467 accretionary ridges comparable to those at typical accretive margins. However, as sediment input also
468 during accretive phases most probably did not exceed some hundred meters thickness (von Huene et
469 al., 1996), they are quite narrow-spaced and not very pronounced. In this aspect, the Peruvian margin
470 is different from other erosive margins where there is no accretionary prism, but a margin wedge *sensu*
471 Ranero and von Huene, 2000, e.g. north Chile and Costa Rica.

472

473 The similarity of the morphology of the lower slope throughout the whole margin and the highly
474 variable morphology of the lower plate may infer that there is no direct link between them. A possible
475 reason is that the lower slope is at the verge of extensional failure (Davis et al., 1983), caused e.g. by
476 elevated fluid pressure or subduction erosion. High fluid pressure is quite likely close to the trench
477 (Kukowski & Pecher, 1999), reducing the effective strength along the décollement and therefore
478 facilitating extensional failure. The steepness of the lower slope may be caused by frontal subduction
479 erosion (Kukowski and Oncken, 2006), a process, by which material originating from gravitational
480 failure of the lower slope is incorporated in the subduction channel. A rough lower plate favours

481 subduction erosion. Therefore, if lower plate morphology were a factor driving slope instability this
482 would suggest that the roughness of the Nazca plate is sufficient to do so along the entire Peruvian
483 margin. This would imply that, as soon as lower plate roughness is sufficiently high, frontal
484 subduction erosion and gravitational failure of the lower slope occur independent of the specific style
485 of lower plate morphology. As most sediment-free lower plates exhibit a well pronounced surface
486 roughness, if true, this would imply that lower slopes at erosive margins may usually be at or close to
487 the limit of extensional failure.

488
489 The differences of both the Nazca plate morphology and the lower slope morphology in the Yaquina
490 and Mendaña areas, respectively, have been quantitatively revealed using curvature attributes. By
491 doing so, we have yield information that can not be extracted from traditional bathymetric maps nor
492 from single beam profiles. As the Nazca plate in the Mendaña region exhibits a higher percentage of
493 steeper areas compared to the Yaquina area, this would suggest e.g. a higher potential impact on
494 frontal subduction erosion. A largely N-S trending fault scar seaward of the trench cutting the MFZ
495 which was not identified from the topographic map, but only from the displayed curvature attributes
496 reveals the high potential of this method to process and interpret swath data.

497
498 Between 6° and 20° S, surface mass wasting mainly occurs at a local scale. The slump we identified on
499 the Lima (125 km²) slope covers an area considerably smaller than the Holocene slumps at 5° S and
500 20° S, which cover areas as large as 660 km² and 2200 km². However, the slumps identified off Peru
501 fall in size among the about 20 largest slumps in the entire north Atlantic, which occurred there in a
502 comparable late Pleistocene and Holocene period (Maslin et al., 2004). Slumps comparable in size to
503 that on the Lima slope were also reported in the southern Yaquina area (Bourgois et al., 1988).
504 Common to these slumps off Peru is that they originated along major (normal) faults on the middle
505 slope inferring a close relation with the extensional tectonics originating from over-steepening due to
506 subduction erosion. The Lima slump is located very close to the “Northern High”, a structural high,
507 beneath which methane flux rates are quite high such that a BSR could develop in a fast subsiding
508 environment (Pecher et al., 2001). If this slump had tectonic causes, the sudden absence of an 800 m
509 high sediment column would have significantly altered the stability conditions of gas hydrates.
510 However, on the other hand, the long-term stability of the Lima escarpment after slumping might infer
511 that hydrate triggered slumping not necessarily may result in regional scale catastrophic slope failure.

512
513
514 Although it needs several only loosely constrained assumptions and therefore contains a large error,
515 morphometric dating of submarine slumps offers an efficient tool to quantify the rates of submarine
516 landscape development. To our knowledge, the diffusion coefficient of 0.0026 m²/yr (with 35 to 40%
517 error) obtained from the Paita slump is the first reported from a convergent margin. Having the large
518 error in mind, this value is similar to a small diffusion coefficient of 0.007 m²/yr obtained for scarp
519 degradation in the Galapagos spreading centre (Mitchell, 1996). This slow degradation after slumping
520 at the Peruvian margin may explain why the Paita slump still looks very fresh and point to relatively
521 slow submarine landscape evolution at this margin.

522
523 Assuming that erodibility is largely the same along the Peruvian margin, the incision rates estimated
524 from the gullies in the Lima slump escarpment offer to estimate the age of the gullies at the Yaquina
525 upper slope, some of which are incised as deep as 200 m. If incision rates were between 0.1 and 0.3
526 mm per year, these gullies developed in 0.6 to 2 Myrs, inferring long-term stable conditions along this
527 portion of the upper submarine slope. Surface erosion in the hyper-arid Central Andes is slow and
528 several authors suggested that the Atacama desert is the oldest onshore landscape on earth (Dunai et

529 al., 2005; Gonzales et al., 2006). Schlunegger et al. (2006) report incision rate of 0.05 to 0.25 mm/yr at
530 18°S latitude. Also, Schildgen et al. (2007) report incision rates of 0.01 mm per yr during the
531 Cenozoic before 10 Ma, 0.26 mm/yr during late Miocene and 0.5 mm per yr during Pliocene for an
532 onshore canyon running towards the Peruvian coast at 16° S. These onshore rates are very similar to
533 those we obtained from our morphometric analysis for the submarine Peruvian slope. This would
534 imply that landscape evolution in the submarine and onshore Peruvian forearc is taking place at
535 comparable rates. Due to the arid climate prevailing in the Central Andes since the Oligocene (Dunai
536 et al., 2005), erosion in the onshore Central Andean forearc has been very slow throughout this time
537 period and the Peruvian continental slope received only very little terrestrial material. Therefore, the
538 slow rates of submarine landscape evolution may be a direct consequence of the slow rates of onshore
539 landscape evolution.

540

541 **6. Conclusions**

542

543 The new swath bathymetry data and complementary data presented in this paper allow to draw a
544 regional scale picture of the morphological diversity of the Nazca plate seaward of the Peru trench and
545 the Peruvian continental slope. We used morphometric analyses and curvature analyses more
546 extensively than done in previous studies. Such tools enable more quantitative information extracted
547 from swath bathymetry data in addition to displaying maps and their structural interpretation.

548

549 Several morphological features contribute to the large roughness of the surface of the Nazca plate: the
550 ripple morphology with an amplitude up to a few hundred meters as the most typical type of seafloor
551 morphology, palaeo-transform faults, basalt ridges with steep flanks and elevated as much as up to 800
552 m above the surrounding seafloor, and narrow ridges making up the MFZ in a horst-and-graben
553 sequence.

554

555 Bending-related normal faulting is widely present seaward of the Peru trench, but absent between 9
556 and 11 °S, which coincides with the very unusual morphology of the Nazca plate in the Yaquina
557 region.

558

559 The roughness of the Nazca plate decreases towards the south. The lower slope generally is very
560 unstable, whereas the upper slope is relatively stable with downslope transport taking place through
561 equi-spaced gullies. A comparison between the Yaquina and Mendaña regions reveal the large
562 roughness of the Nazca plate and the lower slope in both regions, but local steepness generally is
563 larger in the Mendaña region, whereas the magnitude of roughness is higher in the Yaquina region.

564

565 There is ample evidence for local failure due to over-steepened slopes. The local scale ruggedness and
566 failure of the lower slope is characteristic for the entire Peruvian margin and therefore most probably
567 linked to subduction erosion.

568

569 We identified a 125 km² large slump on the Lima middle slope. Comparison with a large slump off
570 Paita the age of which is known, allowed to morphometrically estimate the age of the Lima slump to
571 be 74.5 ka with an about 35 to 40% error. Scarp diffusion with a diffusion coefficient of 0.0026 m²/yr
572 and incision rates of 0.1 to 0.3 mm/yr are quite slow at the Peruvian margin, making rates of gully
573 incision and landscape evolution similar to those in the Atacama desert, which is regarded as the
574 slowest evolving onshore landscape.

575

576 The present study emphasises the usefulness of morphological and morphometric analyses in aiding
577 our understanding of hazard generation, especially for tsunamis and landslides. It also confirms that a
578 detailed knowledge of morphology which can only be achieved by swath mapping is essential to
579 understand the rates and styles of submarine landscape evolution.

580

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582

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589

590 **References**

591

592 Bergbauer, S., Pollard, D.D., 2003. How to calculate normal curvatures of sampled geological surfaces. *J. Struct.*
593 *Geol.* 25, 277 – 289.

594 Bialas, J., Kukowski, N. (eds.), 2000. Cruise Report SO 146 GEOPECO, GEOMAR Report 96, 490pp.

595 Bird, R.P., Pockalny, R.A., 1994. Late Cretaceous and Cenozoic seafloor and oceanic basement roughness:
596 Spreading rate, crustal age, and sediment thickness correlations. *Earth Planet. Sci. Lett.* 123, 239 – 254.

597 Bourasseau I., Juteau T., Karpoff, A.-M., Bourgois, J., Bellon., H., 1993. Exploration des structures volcaniques
598 de la ride d'accrétion de Mendaña au large du Pérou: résultats de la campagne Nautiperc du submersible *Nautilie*,
599 avril 1991. *C. R. Acad. Sci. Paris*, t.317, Série II, 1097 – 1103.

600 Bourgois, J., Pautot, G., Bandy, W., Boinet, T., Chotin, P., Huchon, P., Mercier de Lepinay, B., Monge, F.,
601 Monlau, J., Pelletier, B., Sosson, M., von Huene, R., 1988. Seabeam and seismic reflection imaging of the
602 tectonic regime of the Andean continental margin off Peru (4°S to 10°S). *Earth Planet. Sci. Lett.* 87, 111 – 126.

603 Bourgois, J., Lagabrielle, Y., De Wever, P., Suess, E., NAUTIPERC Team, 1993. Tectonic history of the
604 northern Peru convergent margin during the past 400 ka. *Geology* 21, 531 – 534.

605 Bourgois, J., Bigot-Cormier, F., Bourles, D., Braucher, R., Dauteuil, O., Witt, C., Michaud, F., 2007. Tectonic
606 record of strain buildup and abrupt co-seismic stress release across the northwestern Peru coastal plain, shelf,
607 and continental slope during the past 200 kyr. *J. Geophys. Res.* 112, B04104, doi:10.1029/2006JB004491.

608 Bourillet, J.F., Edy, C., Rambert, F., Satra, C., Loubrieu, B., 1996. Swath mapping system processing:
609 bathymetry and cartography. *Mar. Geophys. Res.* 18, 487 – 506.

610 Caress, D.W., Chayes, D.N., 1995. New software for processing sidescan data from sidescan-capable multibeam
611 sonars. In: *Proceedings of the IEEE Ocean 95 Conference* pp. 997 – 1000, Mar. Technol.Soc., Washington DC

612 Clift, P.D., Pecher, I.A., Kukowski, N., Hampel, A., 2003. Tectonic erosion of the Peruvian forearc, Lima Basin,
613 by steady-state subduction and Nazca Ridge collision. *Tectonics* 22/3, 1023, doi:10.1029/2002TC001386.

614 Coleman, S.M., Watson, K., 1983. Ages estimated from a diffusion equation model for scarp degradation.
615 *Science* 221, 263 – 265.

616 Davis, D., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *J.*
617 *Geophys. Res.* 88, 1153-1172.

618 Divins, D.L., NGDC Total Sediment Thickness of the World's Oceans & Marginal Seas, Retrieved date goes
619 here, <http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html>

620

621 Dodds, P.S., Rothman, D.H., 2000. Scaling, universality, and geomorphology. *Annu. Rev. Earth Planet. Sci.* 28,
622 571 – 610.

623 Dominguez, S., Lallemand, S.E., Malavieille, J., von Huene, R., 1998. Upper plate deformation associated with
624 seamount subduction. *Tectonophysics* 293, 207 – 224.

625 Dunai, T., Gonzales, G., Juez-Larré, J., 2005. Oligocene-Miocene age of aridity in the Atacama Desert revealed
626 by exposure dating of erosion-sensitive landforms. *Geology* 33, 321 – 324, doi:10.1130/G21184.1.

- 627 Duperret, A., Bourgois, J., Lagabrielle, Y., Suess, E., 1995. Slope instabilities at an active continental margin:
628 large-scale polyphase submarine slides along the northern Peruvian margin, between 5°S and 6°S *Mar. Geol.*
629 122, 303 – 328.
- 630 Gagnon, K., Chadwell, C.D., Norabuena, E., 2005. Measuring the onset of locking in the Peru-Chile trench with
631 GPS and acoustic measurements. *Nature* 437, 205 – 208.
- 632 Goff, J.A., 2001. Quantitative classification of canyon systems on continental slopes and a possible relationship
633 to slope curvature. *Geophys. Res. Letters* 28, 4359 – 4362.
- 634 Gonzales, G., Dunai, T., Carrizo, D., Allmendinger, R., 2006. Young displacement on the Atacama fault system,
635 northern Chile from field observations and cosmogenic ²¹Ne concentrations. *Tectonics* 25, TC3006,
636 doi:10.1029/2005TC001846.
- 637 Grant, J.A. and Schreiber, R., 1990. Modern swath sounding and sub-bottom profiling technology for research
638 applications: The Atlas Hydrosweep and Parasound systems. *Mar. Geophys. Res.* 12, 9 -19.
- 639 Grevemeyer, I., Schramm, B., Devey, C.W., Wilson, D.S., Jochum, B., Hauschild, J., Aric, K., Villinger, H.W.,
640 Weigel, W., 2002. A multibeam-sonar, magnetic and geochemical flowline survey at 14° 14'S on the southern
641 East Pacific Rise: insights into the fourth dimension of ridge crest segmentation. *Earth Planet. Sci. Lett.* 1999,
642 359 – 372.
- 643 Hagen, R.A., 1993. Fault patterns on the outer wall of the Peru-Chile trench. *Geo-Mar. Lett.* 13, 139 – 144.
- 644 Hampel, A., 2002. The migration history of the Nazca Ridge along the Peruvian active margin: a re-evaluation.
645 *Earth Planet. Sci. Lett.* 203, 665 – 679.
- 646 Hampel, A., Kukowski, N., Bialas, J., Hübscher, C., Heinbockel, R., 2004. Ridge subduction at an erosive
647 margin - the collision zone of the Nazca Ridge in southern Peru. *J. Geophys. Res.* 109, B02101,
648 doi:10.1029/2003JB002593.
- 649 Hampton, M.A., Lee, H.J., Locat, J., 1996. Submarine Landslides. *Rev. Geophys.* 31, 33 – 59.
- 650 Huchon, P., Bourgois, J., 1990. Subduction-induced fragmentation of the Nazca plate off Peru: Mendaña fracture
651 zone and Trujillo trough revisited. *J. Geophys. Res.* 95, 8419 – 8436.
- 652 Husson, D.M., Reed, T.B., Bartlett, W.A., 1988. SEAMARC II sonar imagery and bathymetry of the Nazca plate
653 and Peru forearc, ODP Leg 112. In: Suess E, von Huene R et al., Proc. ODP, Init Rept. 112, 125 – 130.
- 654 Karig, D.E., 1974. Tectonic erosion at trenches. *Earth Planet. Sci. Lett.* 21, 209 – 212
- 655 Krabbenhöft, A., Bialas, J., Kopp, H., Kukowski, N., Hübscher, C., 2004. Crustal structure of the Peruvian
656 continental margin from wide-angle seismic studies. *Geophys. J. Int.* 159, 749 – 964, doi:10.1111/j1365-
657 246X.2004.02425.x.
- 658 Kukowski, N., Schillhorn, T., Huhn, K., von Rad, U., Flueh, E.R., Husen, S., 2001. The Makran accretionary
659 wedge: morphotectonic analysis, erosive canyons, and implications for forearc mechanics. *Mar. Geol.* 173, 1-19.
- 660 Kukowski, N., Oncken, O., 2006. Subduction erosion – is this the “normal” mode of fore-arc material transfer
661 along the Chilean margin? In: Oncken O, Strecker M, Franz G, Ramos V (eds) *Andean Geodynamics, Frontiers*
662 *in Geosciences* 1, Springer, 217 – 236.
- 663 Kulm, L.D., Scheidegger, K.F., Prince, R.A., Dymond, J., Moore, T.C., 1973. Tholeiitic basalt ridge in the Peru
664 trench. *Geology* 1, 11 – 14.
- 665 Li, C., 1995. Forearc structures and tectonics in the southern Peru – Northern Chile continental margin. *Mar.*
666 *Geophys. Res.* 17, 97 – 113.
- 667 Li, C., Clark, A.L., 1991. SEAMARC II study of a giant submarine slump on the northern Chile continental
668 slope. *Mar. Geotechnology* 10, 257 – 268.
- 669 Lindquist, K.G., 2004. Global topography and bathymetry grid improves research efforts. *EOS Trans. AGU*, 85
670 (19): 186-187.
- 671
- 672 Maslin, M., Mikkelsen, N., Vilela, C., Haq, B., 1998. Sea-level- and gas hydrate controlled catastrophic
673 sediment failures of the Amazon Fan. *Geology* 1998, 1107 – 1110.
- 674 McAdoo, B.G., Capone, M.K., Minder, J., 2004. Seafloor geomorphology of convergent margins: Implications
675 for Cascadia seismic hazard. *Tectonics* 23, doi:10.1029/2003TC001570.
- 676 Mitchell, N.C., 2005. Interpreting long-profiles of canyons in the USA Atlantic continental slope. *Mar. Geol.*
677 214, 75 – 99.
- 678 Mitchell, N.C., 1996. Creep in pelagic sediments and potential for morphologic dating of marine fault scarps.
679 *Geophys. Res. Lett.* 23, 483 – 486.

- 680 Moore, G.F., Taylor, B., 1988. Structure of the Peru forearc from multichannel seismic-reflection data. In: Suess
681 E, von Huene R et al., Proc. ODP, Init Rept. 112, 71 – 76.
- 682 Müller, R.D., Roest, W.R., Royer, J.-Y., Gahagan, L.M., Sclater, J.G., 1997. Digital isochrones of the World's
683 ocean floor. *J. Geophys. Res.* 102/2, 3211 – 3214.
- 684 Nash, D.B., 1981. FAULT: a FORTRAN program for modeling the degradation of active normal fault scarps.
685 *Comp. Geosci.* 7, 249 – 266.
- 686 Norabuena, E., L. Leffler-Griffin, A. Mao, T. Dixon, S. Stein, I. S. Sacks, L. Ocola, and M. Ellis, Space geodetic
687 observations of Nazca-South America convergence across the Central Andes, 1998. *Science* 279, 358-362.
- 688 Pecher, I.A., Kukowski, N., Hübscher, C., Greinert, J., Bialas, J., 2001. The link between bottom simulating
689 reflections and methane flux into the hydrate stability zone – New evidence from Lima Basin, Peru Margin.
690 *Earth Planet. Sci. Lett.* 185, 343-354.
- 691 Pratson, L.F., Haxby, W.F., 1996. What is the slope of the U.S. continental slope ? *Geology* 24, 3 – 6.
- 692 Ramsay, L.A., Hovius, N., Lague, D., Liu, C.-S., 2006. Topographic characteristics of the submarine Taiwan
693 orogen. *J. Geophys. Res.* 111, F02009, doi:1029/2005JF000314.
- 694 Ranero, C.R., von Huene, R., 2000. Subduction erosion along the Middle America convergent margin. *Nature*
695 404: 748 – 752.
- 696 Ranero, C.R., Villaseñor, A., Morgan, J.P., Weinrebe, W., 2005. Relationships between bend-faulting at trenches
697 and intermediate-depth seismicity *Geochemistry, Geophysics, Geosystems* 12, doi:10.1029/2005GC000997.
- 698 Roberts, A., 2001. Curvature attributes and their application to 3D interpreted horizons. *First Break* 19/2, 85 –
699 100.
- 700 Rosenbaum, G., Giles, D., Saxon, M., Betts, P.G., Weinberg, R.F., Duboz, C., 2005. Subduction of the Nazca
701 Ridge and the Inca Plateau: Insights into the formation of ore deposits in Peru. *Earth Planet. Sci. Lett.* 239, 18 –
702 32.
- 703 Sak, P.B., Fisher, D.M., Gardner, T.W., 2004. Effects of subducting seafloor roughness on upper plate vertical
704 tectonism: Osa Peninsula, Costa Rica. *Tectonics* 23, TC1017, doi:10.1029/202TC001474.
- 705 Schildgen, T., Hodges, K.V., Whipple, K.X., Reiners, P.W., Pringle, M.S., 2007. Uplift of the western margin of
706 the Andean plateau revealed from canyon incision history, southern Peru. *Geology* 35, 523 – 526,
707 doi:10.1130/G23532A.1.
- 708 Schlunegger, F., Zeilinger, G., Kounov, A., Kober, F., Hüsser, B., 2006. Scale of relief growth in the forearc of
709 the Andes of northern Chile (Arica latitude, 18°S). *Terra Nova* 18, 217 – 223.
- 710 Schweller, W.J., Kulm, L.D., Prince, R.A., 1981. Tectonics, structure and sedimentary framework of the Peru-
711 Chile trench. In: *Nazca Plate: Crustal Formation and Andean Convergence*, Kulm, L.D. et al. (eds) *Mem. Geol.*
712 *Soc. Am.* 154, 323 – 349.
- 713 Shary, P.A., Sharaya, L.S., Mitusov, A.V., 2002. Fundamental quantitative methods of land surface analysis
714 *Geoderma*, 107, 1 – 32.
- 715 Somoza, R., 1998. Updated Nazca (Farallon)-South America relative motions during the last 40 Myr:
716 Implications for mountain building in the central Andean region. *J. South Am. Earth Sci.* 11, 211 – 215.
- 717 von Huene, R., Bourgois, J., Miller, J., Pautot, G., 1989. A large tsunamigenic landslide and debris flow along
718 the Peru trench. *J. Geophys. Res.* 94, 1703 – 1714.
- 719 von Huene, R., Lallemand, S.E., 1990. Tectonic erosion along the Japan and Peru convergent margins. *Geol.*
720 *Soc. Am. Bull.* 102, 704 – 720.
- 721 von Huene, R., Gutscher, M.-A., Pecher, I.A., 1996. Development of the accretionary prism along Peru and
722 material flux after subduction of Nazca Ridge. *Tectonics* 15, 19 – 33.
- 723 von Huene, R., Weinrebe, W., Heeren, F., 1999. Subduction erosion along the north Chile margin. *J*
724 *Geodynamics* 27, 345 – 358.
- 725 von Huene, R., Ranero, C.R., 2003. Subduction erosion and basal friction along the sediment-starved convergent
726 margin off Antofagasta. *J. Geophys. Res.* 108 (B2), 2079, doi:10.1029/2001JB001569.
- 727 Wessel, P., Smith, W.H.F., 1998. New, improved version of the Generic Mapping Tools released. *EOS Trans.*
728 *AGU* 79 (47), 579.
- 729 Wright, D.J., Bloomer, S.H., McLeod, C.J., Taylor, B., Goodlife, A.M., 2000. Bathymetry of the Tonga trench
730 and forearc: a map series. *Mar. Geophys. Res.* 21, 489 – 511.
- 731

732 **Figure captions**

733

734 Fig.1: Map displaying swath bathymetry recorded during the GEOPECO cruise and complemented with
735 coverage from the SEAPERC cruise (Bourgois, 1990) with black boxes indicating SEAPERC data. Red lines are
736 topographic profiles extracted from the swath data parallel to SO146 wide angle seismic profiles and shown in
737 Fig.3. Blue lines refer to the age of the ocean floor (Mill. years, Müller et al., 1997). Lower left insets show the
738 variation of convergence rate and obliquity at 12°S with time (Somoza, 1998). Red arrow indicates present
739 direction and rate of convergence (Norabuena et al., 1998). Orange boxes refer to subsequent figures.

740

741 Fig.2: Morphology of the Nazca plate and trench region in corridors at **A** 9°S (off Yaquina basin, yellow dotted
742 lines indicate crests of basalt ridges, white line indicates orientation of the trench), **B** 12°S (off northern Lima
743 basin), and **C** 13.5° S (off southern Lima basin) matching the position of wide angle seismic profiles
744 (Krabbenhöft et al., 2004). Outside the areas covered with swath data, bathymetry as obtained from the GINA
745 data set (Lindquist et al., 2004) is displayed for regional information. For location, see Fig.1.

746

747 Fig.3: Bathymetry profiles along SO146 wide angle seismic profiles. Insets show the lower slope. For location
748 see red lines in Fig.1.

749

750 Fig.4: Yaquina area. **A** Bathymetric map of the Nazca plate, the trench and continental slope. Numbers indicate
751 palaeo-transform faults. **B** Perspective image, view from S, illumination from NE. For location, see Fig.1.

752

753

754 Fig.5: Mendaña region **A** Bathymetric map of the Mendana fracture zone, trench, and lower slope (merged
755 SEAPERC (Bourgois et al., 1990) and GEOPECO data) **B** Perspective image, view from WWN, illumination
756 from NE. For location, see Fig.1.

757

758 Fig.6 **A** Bathymetry seaward and landward of the trench in the Yaquina area **B** Local dip **C** Dip curvature. For
759 location, see Fig.1.

760

761 Fig.7 **A** Bathymetry seaward and landward of the trench in the Mendana area **B** Local dip **C** Dip curvature. For
762 location, see Fig.1.

763

764 Fig.8: Histograms showing the frequency distribution of local slopes (same areas and data sets as in Figures 6
765 and 7. **upper** Yaquina area, left: Nazca plate seaward of the trench; right: continental slope landward of the
766 trench **lower** Mendaña area, left: Nazca plate seaward of the trench; right: continental slope landward of the
767 trench.

768

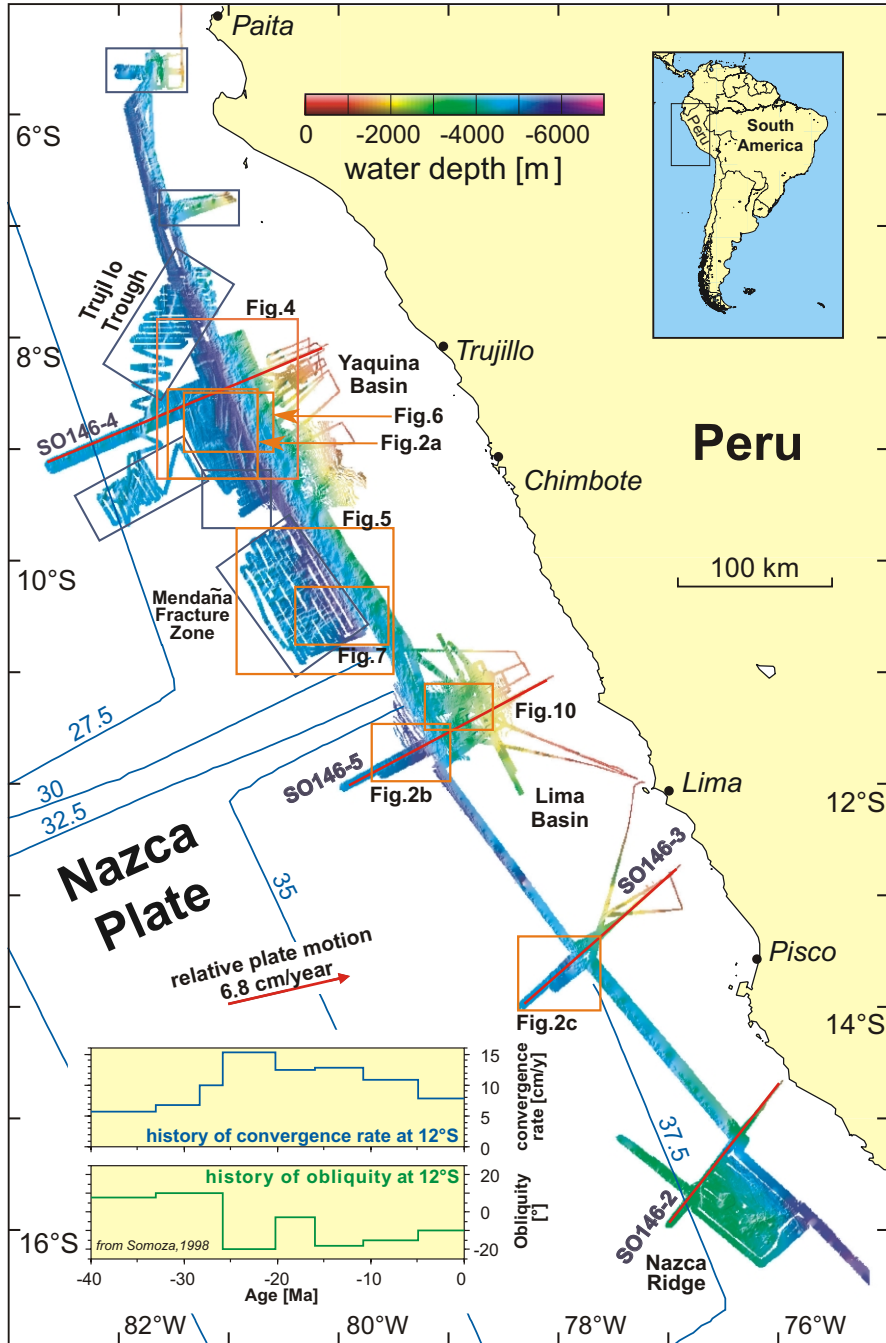
769 Fig.9: **A** large scale map of gullies at upper slope. For location, see Fig.4. **B** topographic profiles along the slope.
770 For location, see **A**.

771

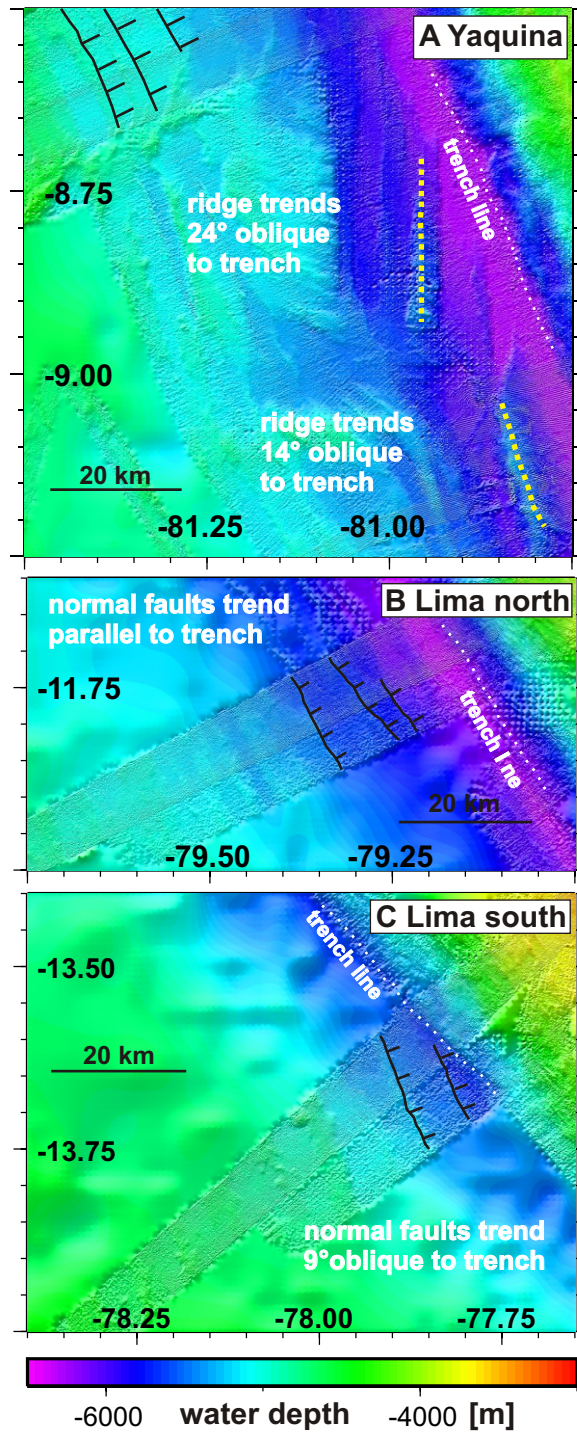
772 Fig.10: Lima Region: Bathymetric map of the mid and upper slope revealing a channel system originating from
773 distributed drainage, a half-moon shaped tip of a slump scar and the slump mass. White box indicates area
774 shown in Fig.11b.

775

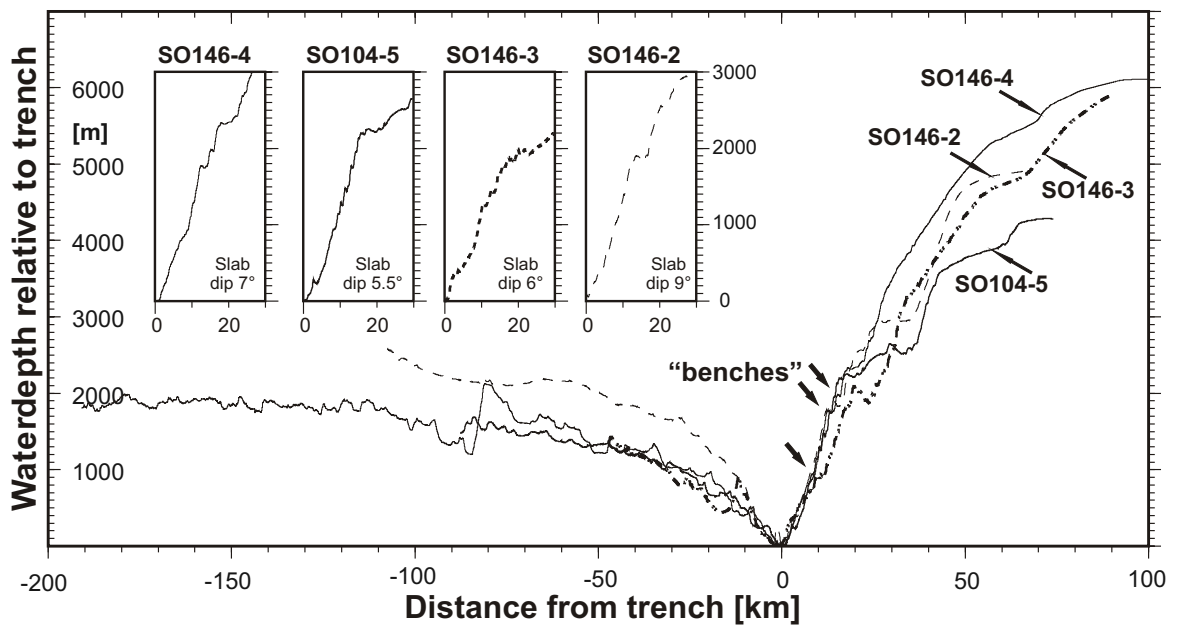
776 Fig.11: Morphometric dating of slumps: **A** Bathymetry of the Paita slump, **B** bathymetry of the Lima slump. In
777 both pictures, positions of profiles across the slump and along the slump scar are indicated **C** Profiles across the
778 Paita slump **D** Profiles across the Lima slump. Western and southern ends of the profiles were assigned to "0" on
779 the ordinate. For location of the Lima map, see Fig.10.



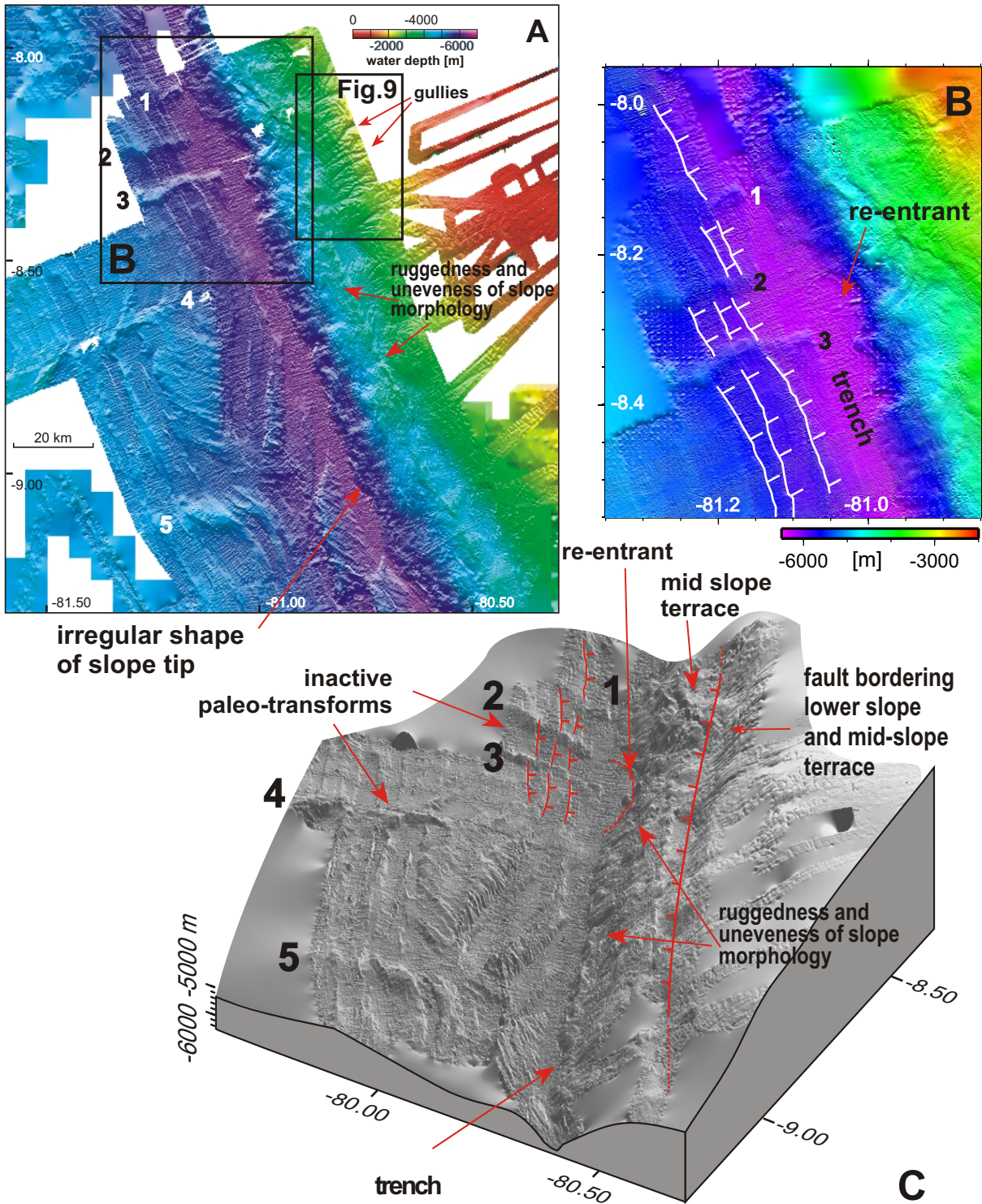
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.1



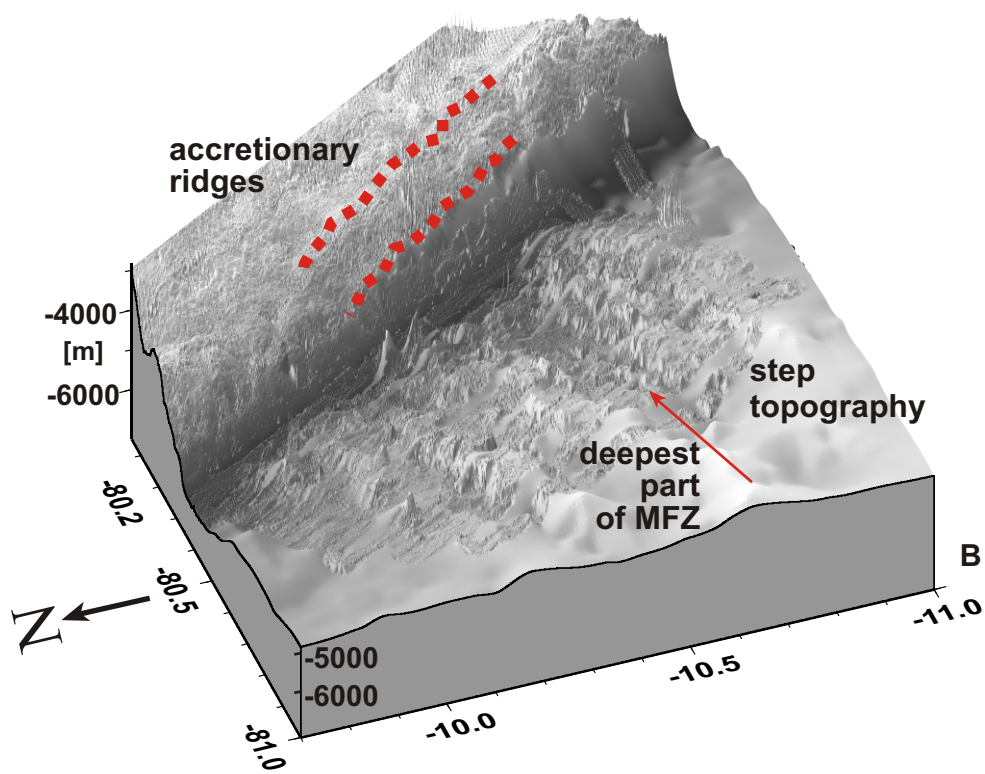
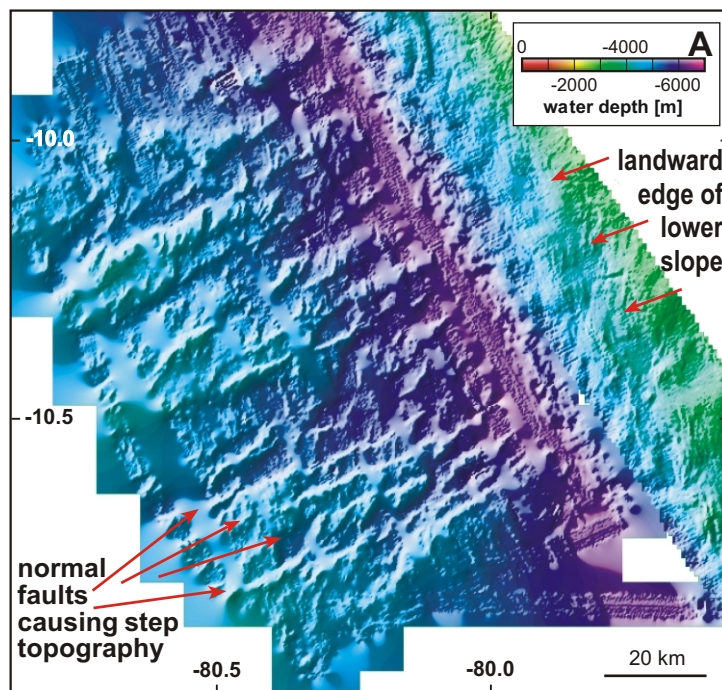
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.2



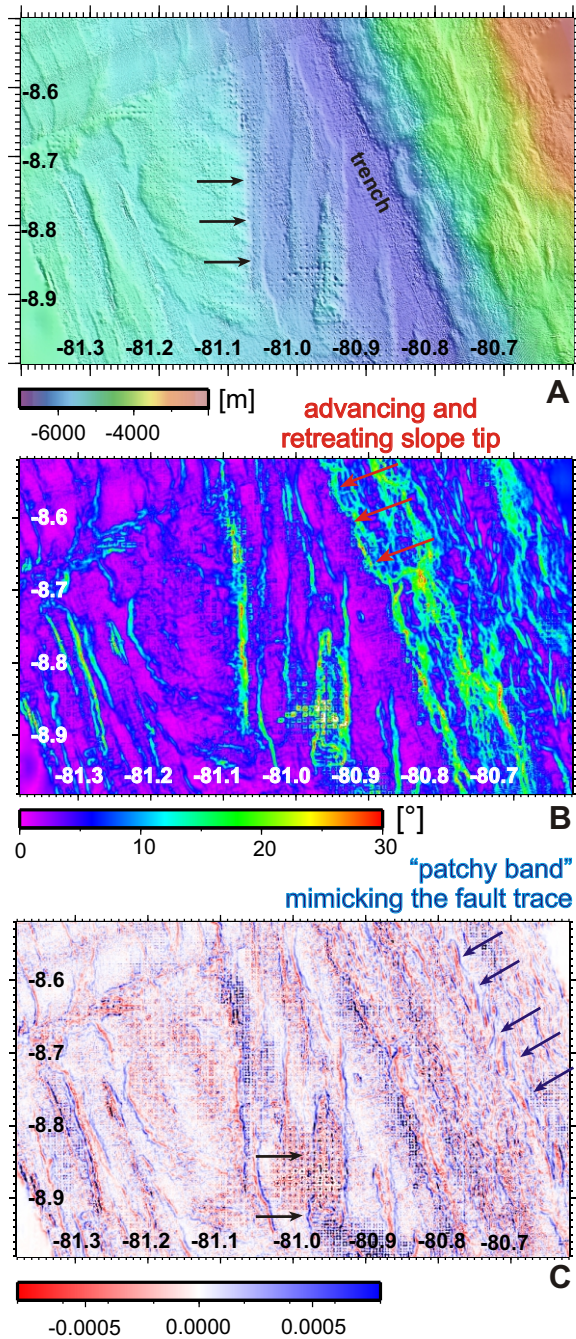
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.3



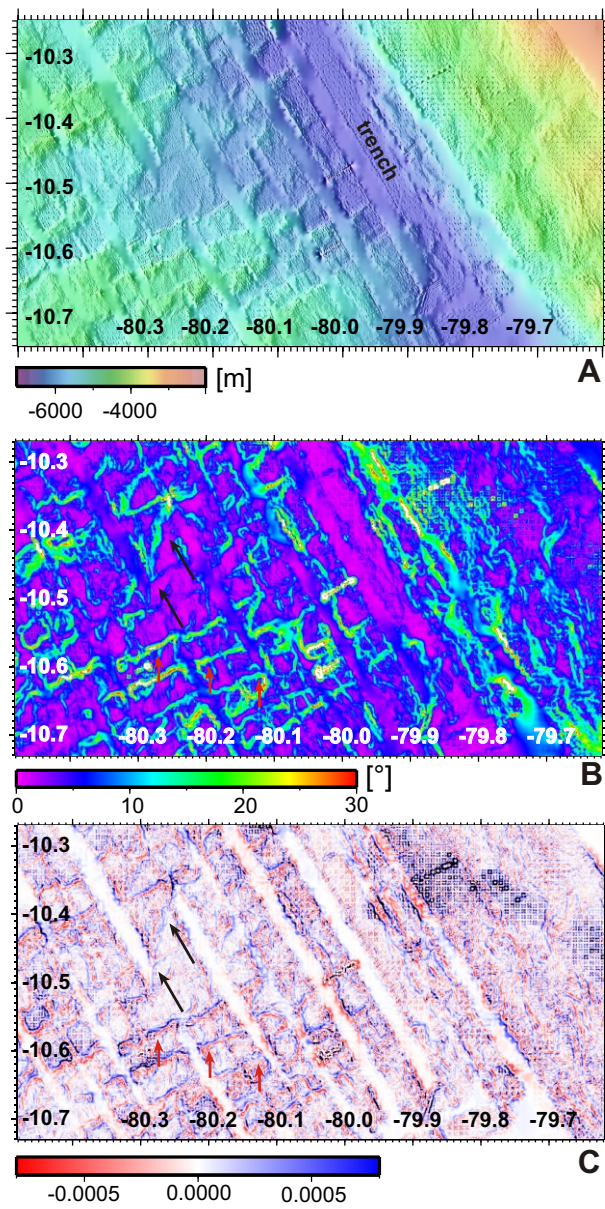
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.4



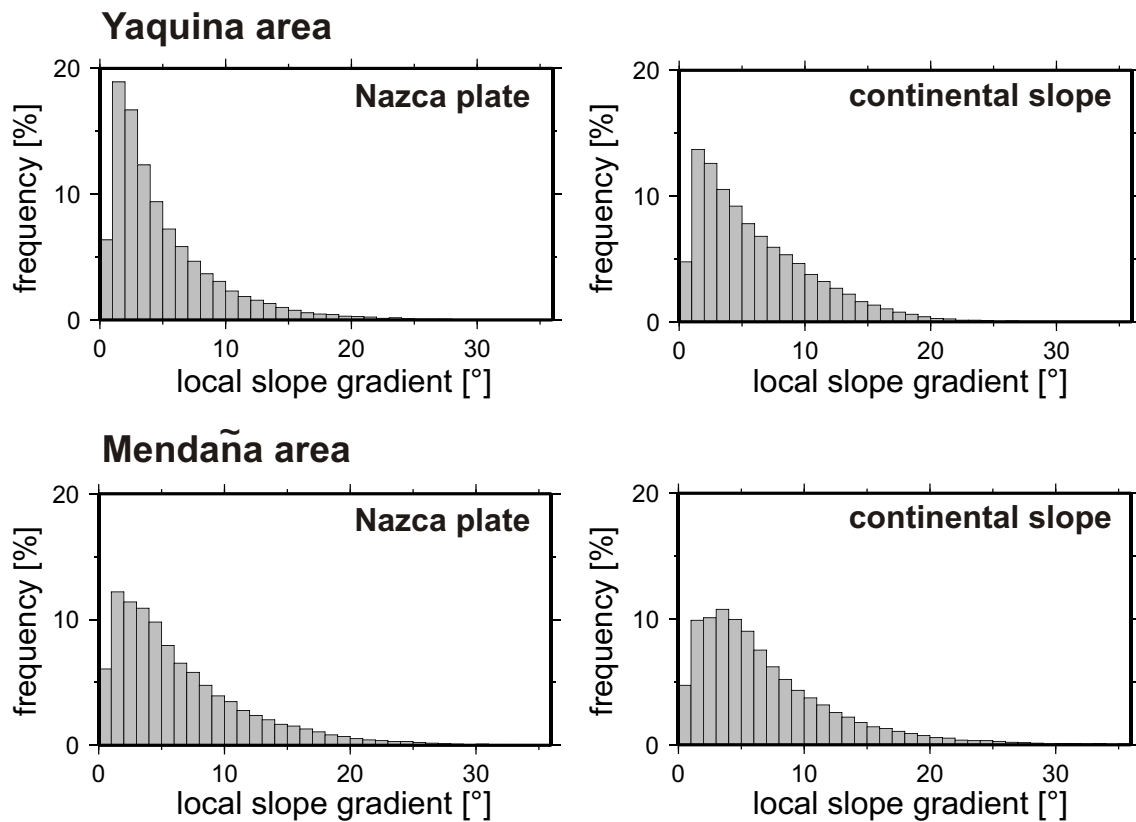
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.5



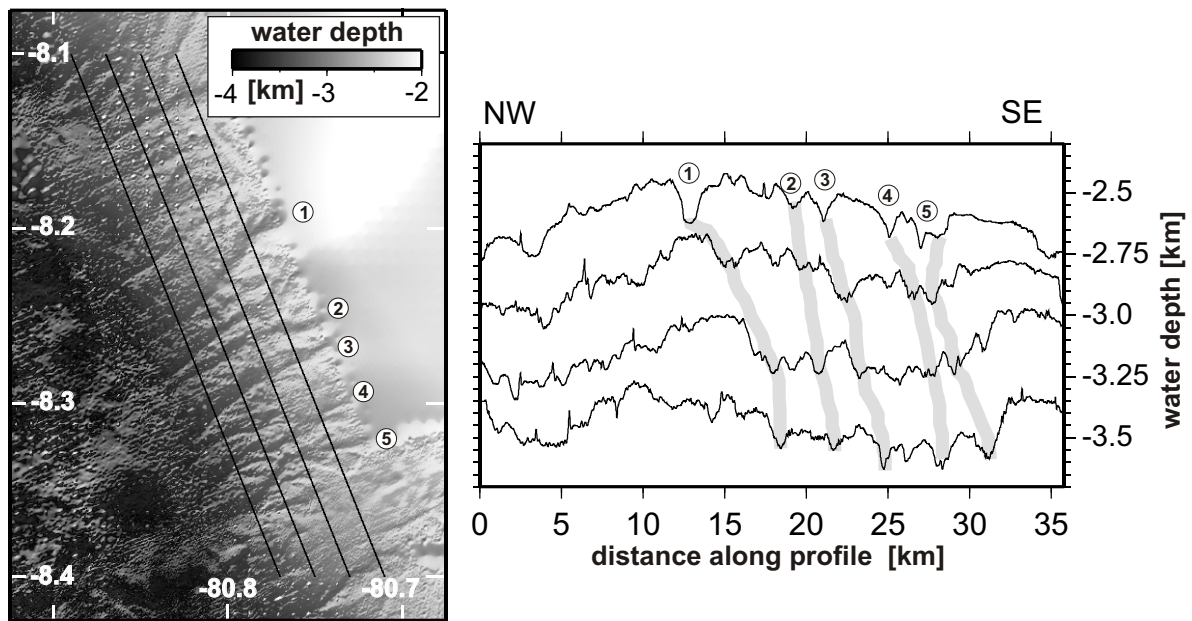
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.6



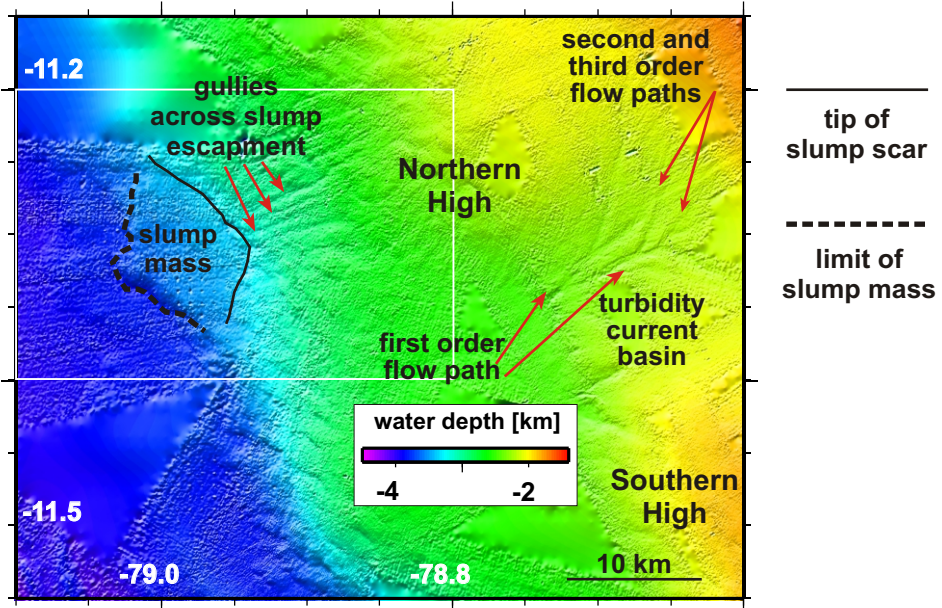
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.7



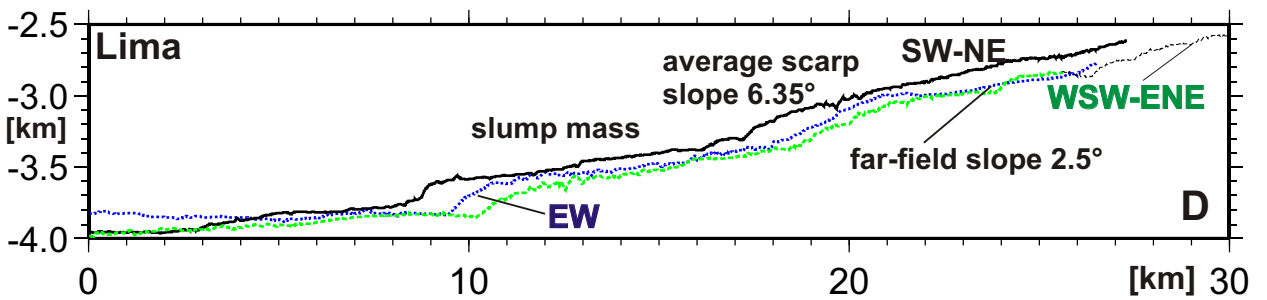
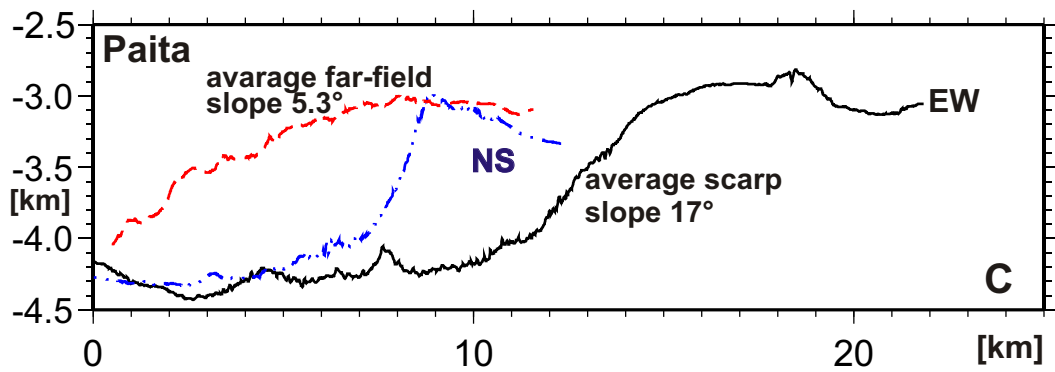
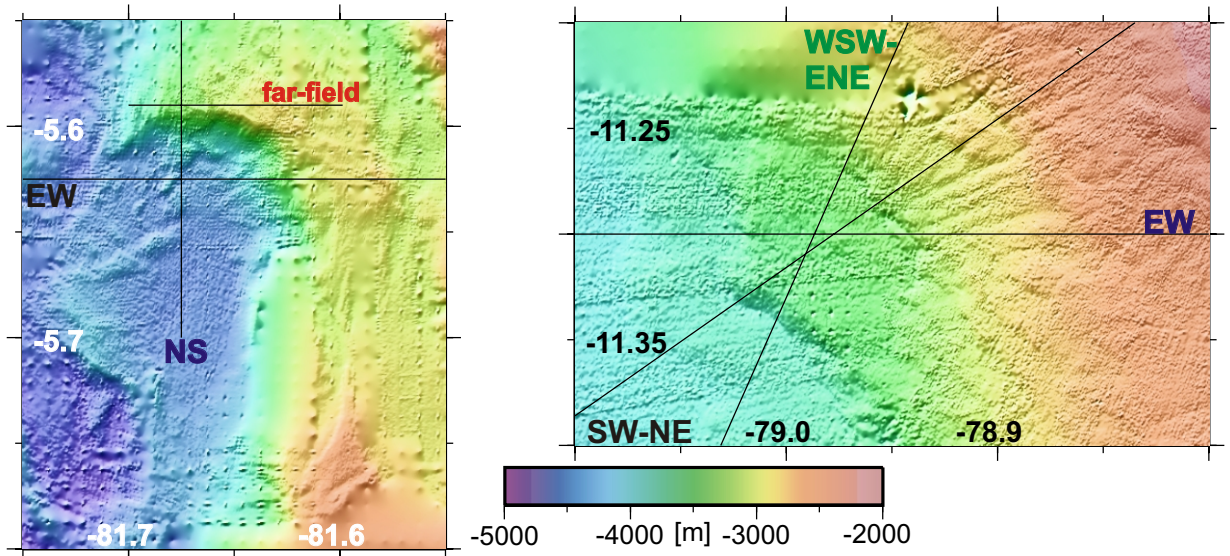
Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.8



Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.9



Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.10



Kukowski et al., MARGO 2008; doi:10.1017/j.margeo.2008.05.017Fig.11