

SUBMARINE LANDSLIDES ALONG THE NORTH ECUADOR – SOUTH COLOMBIA CONVERGENT MARGIN: POSSIBLE TECTONIC CONTROL

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Abstract

A morphometric analysis of submarine landslides on the continental slope of north Colombia – south Ecuador convergent margin provides insights into hazards, including mass movements locations, size of failures and location control. Bathymetric and seismic data acquired in 2005 revealed three distinctive types of locations with the occurrence of potentially tsunamogenic submarine landslides: 1) the erosive margin toe is characterized by three 5-6-km wide and up to 1500m high semi-circular scarps. The toe is also affected by a 35-km long area of linear scarps resulting from the imbrication of successive failures, 2) canyon walls are affected by five up to 500m high scarps, 3) the deformation front exhibits a 50x20 km potentially destabilized area characterized by intensive fracturation. All these features are controlled by active tectonics, Slope oversteepening is a key parameter facilitating the onset of slope failure for the two first types, and is associated with 1) seamount subduction, 2) subsidence related to basal erosion of upper plate, and 3) uplift along active tectonic structures. Regarding the third type, the destabilisation area is influenced by the intensive fracturing at the vicinity of a splay fault.

1. Introduction

Slope failures play a major role on sediment transport and sediment distribution on continental margins, and are largely responsible for shaping the seafloor of both deep sea and coastal environments. These mass-wasting events represent a hazard for e.g., offshore exploration safety, and communication cables. Coastal cities are exposed to a tsunami hazard if submarine slopes are affected by medium- to large-scale (over 5 km wide) collapses (McAdoo and Watts, 2004; von Huene et al., 1989). A good understanding of processes associated with submarine instabilities and their triggering factors is fundamental in order to quantify the hazard and mitigate the risk. To date, most studies have been carried out along passive margins (Canals et al., 2004; Evans et al., 1996) and volcanic islands (Masson, 1996; Masson et al., 2002). Triggering factors of submarine landslides include rapid accumulation of sediment, slope increase, sediment excess pore pressure, high physical stresses related to wave loading, tectonics and earthquakes (Hampton et al., 1996), eustatic sea-level variations, and gas hydrates dissociation (Maslin et al., 1998).

Regarding active margins, similar mechanisms were already reported, and tectonic activity is one of particular importance in triggering medium-scale (von Huene et al., 2000) to giant submarine landslides (Collot et al., 2001; Duperret et al., 1995). North Colombia – South Ecuador convergent margin has been explored in 2005 during

AMADEUS cruise on board of R/V *L'Atalante* (Collot et al., 2005), providing original data on the seafloor.

The principal aim of this paper is to map the areas of the margin undergoing mass wasting. We concentrated our study on failures which upper scarps are larger than 5 km, that could possibly generate catastrophic tsunamis (McAdoo and Watts, 2004). The second aim is to better constrain what parameters are controlling localization and triggering of medium- to large-scale, submarine landslides on study area.

To achieve these objectives, this study is based on submarine landslides identification using: 1) Multibeam swath bathymetry (150m resolution except along Patia/Mira canyon where data was reprocessed to obtain a resolution of 60m), 2) Six channels seismic data from the Amadeus cruise (AMA profiles), and 24- channels seismic data provided by the *Agencia Nacional de Hidrocarburos* (ANH profiles), and 3) 10-m long gravity cores.

2. Geological setting

The north Ecuador - south Colombia active margin (from N0° to N3°30) is located along the subduction margin of the Nazca and South America plates (fig. 1). The eastward convergence rate of the Nazca Plate is 54 mm/year (Trenkamp et al., 2002). The margin is the scene of intense seismicity with the occurrence of four of the greatest earthquakes of the twentieth century ($M_w > 7.7$) in the region (Mendoza and Dewey, 1984). The northern part of the margin (N1°30 to N3°30) is characterized by an accretionary wedge decreasing in width southward (Collot et al., 2006; Mountney and Westbrook, 1997). In contrast, the southern part of the margin shows a narrow slope (N0° to N1°30) related to tectonic erosion (Collot et al., 2002). The upper plate consists of an upper Cretaceous mafic basement overlain by Cenozoic sedimentary series (Jaillard et al., 1997). Offshore Colombia, the slope is incised by the Esmeraldas and Mira/Patia submarine canyons (Collot et al., 2005). (Fig. 1). Esmeraldas is V-shaped in cross section, sharply cutting the deformation front, thus indicating erosion is currently active. Patia and its tributary Mira are Z-shaped in map view and U shaped in cross-section, implying it has been less active than Esmeraldas, at least during the Holocene (Collot et al., 2005). The Ancon fault (Fig. 1) is a northeastward trending crustal scale fault which activity on the long term may reflect tectonics of the seismogenic zone (Collot et al., 2005).

3. Results

3.1 MARGIN TOE INSTABILITIES

3.1.1 Description

In the southern part of the margin (N0 to N1°30), the slope is 30-km wide between 200 and 3600 meter of water depth. The mean slope angle is about 6-7°. This narrow slope is affected by numerous sub-circular and linear scarps (Fig.1).

Sub-Circular scarps

Near 0°20'N of latitude (Fig. 2a) three semi-circular scarps, 5-6 km-wide, outline the top of a destabilized area covering about 300 km² and 22-km long. Scarps A and B are

about 1500 m high, with a slope angle of 30° . Scarp C is up to 750 m high and dips 25° westward. Arcuate lineations, exhibiting a concavity toward the trench overhangs the scarps (Fig. 2a). They are interpreted as creeping features. Moreover, a topographic knoll is present upslope from the scarps. Gravity core KAMA01, collected at the base of scarp B (Fig. 2a), consists of decimetric blocks of consolidated clay in a muddy matrix that are interpreted as a debris flow deposits.

Linear scarps

At about $0^\circ 55'N$ of latitude, a 35-km long section of the slope is affected by linear scarps up to 2000 m high (Fig. 2b). They are characterized by a sharp slope break, with a dipping angle increasing from 6 to 25° . From the bathymetric map analysis (Fig. 2b), we interpret the linear shape of the scarps as the results of several imbricated small-scale scarps corresponding to successive sliding events. Lineations, parallel to the main direction of the scarps are also present on the upper part of the slope (Fig. 2b). They could correspond to secondary normal faults due to the collapse of the margin or to possible creeping structures.

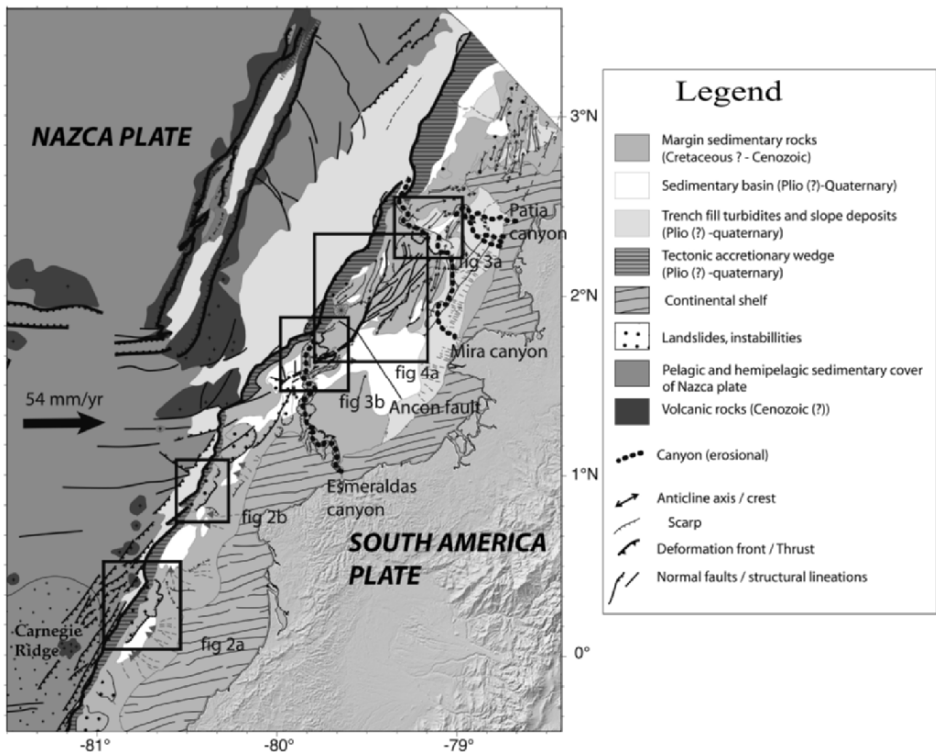


Figure 1. Structural map of North Ecuador - South Colombia margin. Black arrow is Nazca - South America plate convergence vector derived from (Trenkamp et al., 2002) GPS study. Black rectangles show localisation of bathymetric views of destabilization areas. Bold dotted lines show submarine canyons systems (modified from Collot et al., 2006).

3.1.2 Margin toe instabilities control

The origin of the sub-circular scarps is thought to result from the subduction of seamounts (Collot et al., 2005). The indentations shapes and the presence of bathymetric knoll landward of the scarps are similar to those described along the Costa Rica margin and unambiguously associated with seamount subduction (von Huene et al., 2000). Sandbox models also show similar morphological response of the seafloor to seamount subduction (Dominguez et al., 1998). This interpretation is supported by aligned seamounts located on the subducting plate a few kilometers in front of the scarps (Fig. 2a).

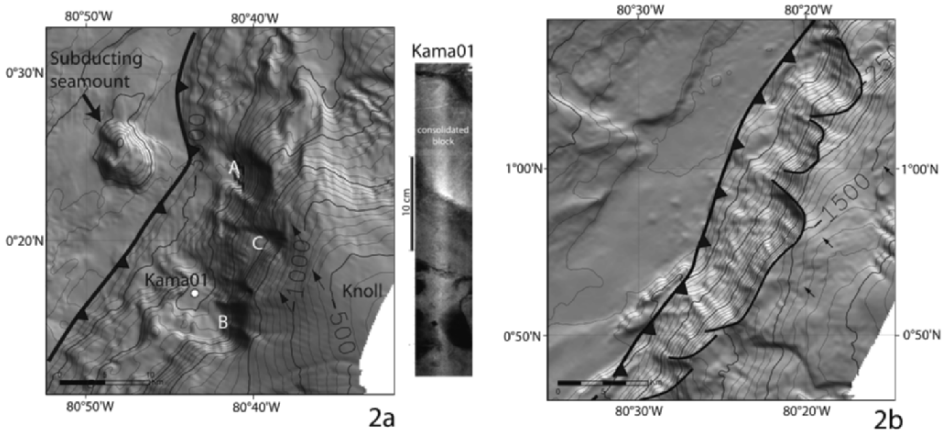


Figure 2. Seafloor bathymetric maps of margin toe failures. Bathymetric contour interval is 100m, grid size is 150m. Black arrows show parallel-to-the-scarps lineations. 2a) Circular scarps area: scarps are named A,B, and C. Kama01 is a Xray view from the sedimentary core with debris flow facies. 2b) Linear scarps area: black bold lines show scarps. Imbricated scarps on the SW corner lead to a general linear shape of the scarps.

The linear scarps are located at the base of the erosive margin (Collot et al., 2002). Their shapes are unlikely to be created by the subduction of a seamount as indentation or topographic knoll backward of the scarps are not present. Tectonic erosion are usually responsible for subsidence of the margin, as it was documented offshore Japan (Lallemand et al., 1992), or Peru (Sosson et al., 1994). In such a tectonic context, the lower slope is permanently oversteepened and undergoes failures (von Huene and Culotta, 1989). Oversteepening of the continental slope is likely to be the main factor leading to destabilization of the slope deposits, whilst the recurrent high-magnitude seismicity is believed to be the main trigger of sediment failure.

3.2 CANYON WALLS FAILURES

3.2.1 Description

The Patia/Mira canyons system

Three major slides (S1 to S3) (Fig.3a) are located close to the junction between the two canyons:

S1: A sub-rectangular scarp (8.5x5 km in map view and 500-m high) is located at the sharp bend of the Patia canyon (Fig. 3a). Hectometric blocks are located within the Patia canyon, downslope from the scarp. These deposits can be considered as a blocky

avalanche (S1) in accordance with the classification of (Mulder and Cochonat, 1996). The length of rough seafloor morphology of the canyon axis beneath the scarp lead us estimate a 18 km run-out distance for the avalanche. The slid blocks in the canyon axis formed a dam that trapped the sediment supply and caused an infilling of the canyon (Fig. 3a-3c). The dam still overhangs the canyon floor by 30 m.

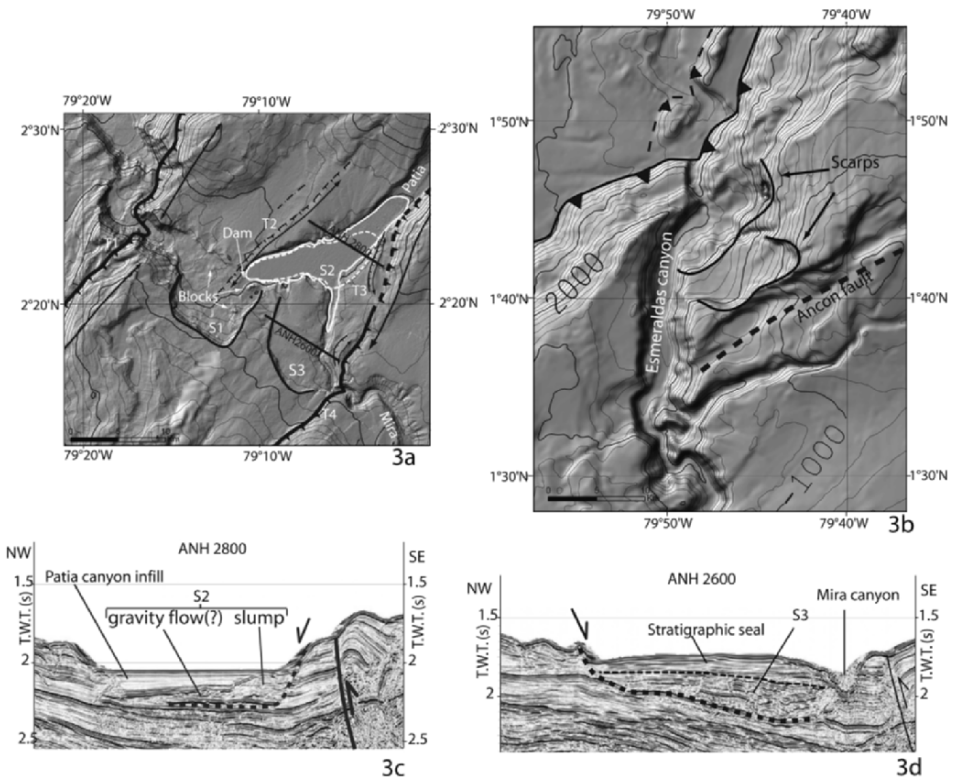


Figure 3. Bathymetric map from canyon walls scarps. Bathymetric contour interval is 100m, grid size is 60m for Fig. 3a, 150m for Fig. 3b. Black bold lines show scarps. 3a) Patia and Mira canyon walls failures. T1 to T4 are active thrusts. S1 to S3 are slides. White dashed line show buried S2 limits. White bold line show Patia canyon infill due to the dam. 3b) Esmeraldas canyon walls failures. Dashed line show location of Ancon fault. 3c) and 3d) Multichannel seismic profiles ANH2800 and ANH2800 across canyons junction area. Profiles are located on figure 3a).

S2: Seismic line ANH2800 shows tilted reflectors along a slip plane on the eastern wall of the Patia canyon (Fig. 3a). The reflectors are undisturbed at least close to the slip plane, but are getting disturbed and loose coherency further away. This structure (S2) is therefore interpreted as a rotational slump that possibly evolved into a gravity (mud?) flow. Its run-out distance is about 11 km, but must be greater as deposits in the canyon axis must have been eroded by the later overlapping S1 event. The scarp associated with slump S2 is buried beneath the canyon infill (Fig. 3c).

S3: A 12 km-wide, 100 to 200 m-high, amphitheater-like scarp is located at the junction of the Mira and Patia canyons (Fig. 3a). Seismic-reflection data (Fig. 3d) (ANH2600)

shows weakly deformed material at the toe of the scarp. Reflectors are not tilted, and the Skempton ratio h/l between the depth h and the length l of the slide (0,04) is lower than 0,15. This allows us to interpret S3 as a translational slide (Mulder and Cochonat, 1996). The run-out distance of the slide is not clearly established, but it does not exceed a few hundred meters. The slide and scarp are buried under younger levee deposits that smoothed the pre-existing relief (Fig. 3d).

Esmeraldas Canyon

The distal part of the Esmeraldas canyon is linear and oriented obliquely to the margin (Fig. 3b). Its walls are up to 1000-m high. Two 10-12 km-wide scarps are present along the right-hand side of the canyon (Fig. 3b). They are 400 m high, with a 30° slope angle. The run-out distance of the sliding material cannot be estimated.

3.2.2 Canyon walls failures control

Canyon walls are destabilized by the local oversteepening of the slope generated by strong axial incision. However, the evidenced submarine landslides on canyon walls occur on specific locations:

The Patia and Mira canyons have both a complex channel pathway controlled by the growth of active thrusts and folds (Collot et al., 2005) mainly parallel to the margin. They merge in a slope basin located between these structures. Four thrusts (T1 to T4) (Fig. 3a) are responsible for the uplift of topographic highs bounding the basin. S2 occurs directly in front of active thrusts T3 and T4 where the seafloor is locally oversteepened. The Ancon Fault, interpreted as a splay fault (Collot et al., 2004) crosses perpendicularly the Esmeraldas canyon axis and forms an anticline (Fig. 3b). The location of the slump scarps correlates to the steepest flank of the anticline activated by the splay fault.

These series of scarps are located in front or above active structures. That is why we consider these structures could play a role on the localization of landslides as it locally oversteepens the seafloor.

A sub-rectangular scarp as S1 is unusual for a gravitational failure. Its north-west and south-east walls are parallel to the trend of active thrusts (Fig. 3a). Hence we believe that the direction of these walls is tectonically controlled, mainly by a structural fabric that developed parallel to the tectonic structures. The south-west wall of the scarp is parallel to the canyon. Strong erosion occurring at the base of the concave flank of the canyon bend has oversteepened the slope angle, and thus has facilitated the occurrence of S1. Therefore, in that area, the oversteepening is also accentuated by tectonic uplift.

3.3 ANCON FAULT FEATURES

3.3.1 Description

In the prolongation of the Ancon fault (Collot et al., 2004), a 50x20-km area located on the deformation front is characterized by the presence of arcuate-to-the-slope ridges (Fig. 4) that consist of east-facing and west-facing scarps and counterscarps. The scarps defined a staircase-like morphology descending to the west. Seismic-reflection data

show that scarps are associated to sub-vertical normal faults affecting the sedimentary cover (Fig. 4b-4c). Some of the flats are small sedimentary basins with infilling showing fan-like structures (Fig. 4c). Moreover, the size of the area encompasses the entire slope.

3.3.2 Structural control

The fault network suggests the area could be a horse-tail structure associated to the Ancon fault. However, the study area has geo-morphological features closed to Deep-Seated Gravitational-Slope Deformation (DSGSD) as documented onland in mountain belts (Aglardi et al., 2001; Di Luzio et al., 2004). These features are: the presence of scarps and counterscarps, and arcuate structures facing downslope. The steepness of the faults suggests they are deep-seated structures, but poor seismic penetration prevents an estimation of their extent. The Ancon fault is likely responsible to intense faulting of the area, allowing the gravitational deformation on the fractures associated to the fault.

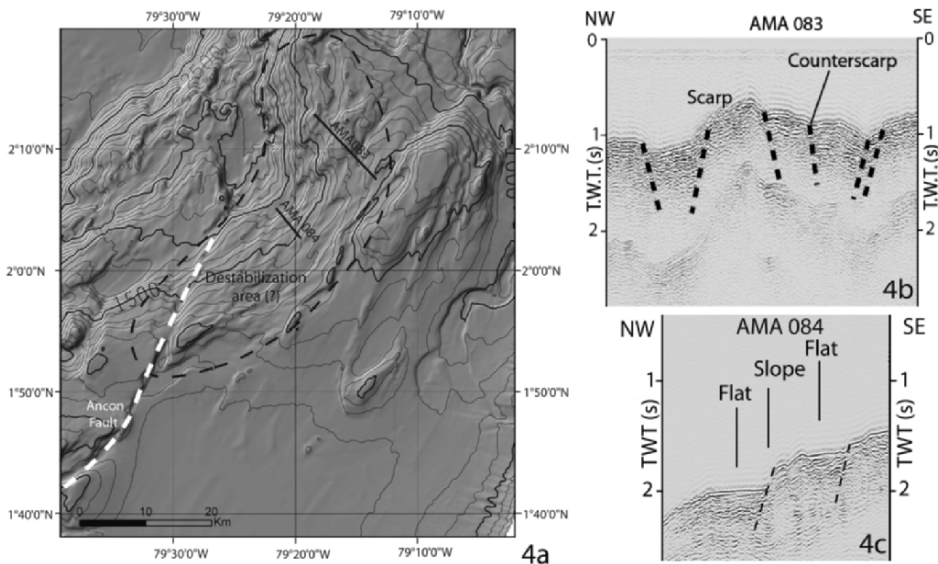


Figure 4. Bathymetric map and multichannel seismic reflection profiles across the possible giant destabilization area. Bathymetric contour interval is 100m, grid size is 150m. Black dashed line show the possible destabilistaion area. White dashed line show location of the Ancon fault.

4. Conclusions

On the North Ecuador – South Columbia active margin, medium (5-10 km) to large (50 km) - scale submarine failures have been observed 1) at the erosive margin toe (linear and sub-circular scarps), 2) along canyon walls (medium scale scarps), 3) in the vicinity of the Ancon fault (large scale margin destabilisation).

Destabilisation parameters:

- On the margin toe, the evidenced parameters controlling the localization of slope instabilities and the oversteepening of the margin are tectonically controlled. The

oversteepening of the slope is associated to seamounts subduction, and strong subsidence of the margin caused by basal erosion of the upper plate.

- On canyon walls, oversteepening is associated to uplift along active thrusts. Strong canyon incision is a parameter that can also weaken the canyon walls and generate collapses. It is however not the only factor on canyon walls, as the failures are mainly located along active structures. The two parameters are considered act together.

- In the forearc, the 50-km wide area that could be undergoing a slow deep-seated gravitational deformation is located on the prolongation of a major crustal fault affected by intensive fracturation. In that case the structural framework controls the margin destabilisation.

The triggering parameters can not be doubtlessly established, but tectonic oversteepening of the seafloor is facilitating the destabilisation. Earthquake induced ground shaking is also suggested for failures sliding triggering.

5. Acknowledgements

We thank the Institut de Recherche pour le Développement (IRD), the French GDR-Marges and ECOS-Nord program for funding this research, and the IFREMER and GENAVIR crew of the R/V *L'Atalante* for their logistic support during the AMADEUS cruise.

We thank the Agencia Nacional de Hidrocarburos (ANH) from Colombia for providing seismic profiles. We also thank Dr Lies Loncke and Dr Geoffroy Lamarche for their rapid and constructive review. This is contribution from GDR-Marges n°2175.

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