A coupled system of gravity tectonics and mass wasting processes in the Amazon Deep-sea Fan

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Abstract

Gravitational deformation affects the entire marine sequences of the Foz do Amazonas basin, including the Amazon Deep-sea Fan. During different stages of the margin's evolution, the sedimentary loading and bathymetric slope induced the formation of a linked extensional-compressional system, with remarkable fold-and-thrust belts running along the margin down to about 2100 m water depths, gliding on décollement surfaces. Gravity-related sea-floor relief can trigger slope failures along fold-and-thrust belts, leading to tectonically-induced mass movement deposits in the upper/middle Amazon fan, evidencing a sequential and long-lasting linking between gravitational collapse modes of deformation and mass movement.

Introduction

The entire marine sequence of the Foz do Amazonas basin, includin the Amazon submarine fan, is deformed by an upslope set of extensional faults and huge downslope fold-and-thrust belts considered to root into basal weak levels (e.g. Silva *et al.*, 1999; Cobbold et al., 2004). Concerning the Amazon submarine fan we lack chronostratigraphic and faciological details about the entire fan series, once most of the studies focus on the Quaternay fan section, involving deposition of channel-levees systems and mass transport deposits (e. g. Damuth *et al*,. 1988; Piper *et al.*, 1997a; 1997b; Maslin & Mikkelsen, 1997; Maslin *et al.* 2005). These studies recognize submarine mass wasting deposits as important elements in the fan's sedimentary construction, commonly correlated to climate-induced changes in sea level. On the other hand, the role of gravity-related structures in triggering slope failures was not until now addressed in the geographical frame of the Amazon fan.

We present here a refined map of gravity-related structures of the study area, based on 2D seismic interpretation. We analyse and describe as well, multi-scale gravitational collapses in the fan area, integrating sea-bottom relief due to megastructures with mapped slope failure features and shallow sediment slides, in order to asses possible links between different modes of gravitational processes (deformation and mass transport) on the Amazon fan.

Method

The available seismic data comprises about 15,000 km of 2D multichannel seismic reflection profiles (figure 1A). Seismic data include LEPLAC Survey, that comprises a super-regional seismic grid of 100 km, collected at 13 seconds recorded time by de Brazilian Navy and by PETROBRAS (with vertical resolution between 5-10 m), and additional industrial seismic grid of 10-20 km, provided by geophysical survey companies GAIA and FUGRO collected at 10 seconds recorded time with an approximate vertical resolution equally ranging from 5 to 10 m. Seismic data were interpreted on the software *Kingdom Suite®*.

Results

Results of 2D seismic analyses and their products allowed us to evaluate how gravity tectonics evolves and how it impacts sedimentation on the Foz do Amazonas basin.

Structural styles of thin-skinned tectonics in the Foz do Amazonas basin

Three main structural domains can be defined between the continental shelf and the deep basin. This structural zonation is composed by an upslope extensional domain (until 500 m water depth) linked via a translational zone to a downslope compressional domain (between approximately 900-2,100 m water depth). This gravitational *nappe* deforms the entire marine stratigraphic sequences of the Foz do Amazonas basin, across an area as large as 190 km wide, by about 300 km along strike, in a total of approximately 40,000 km^2 (da Silva 2008) (figure 1A).

Sliding of the sedimentary section took place along at least three main décollement surfaces and, apparently, at different stages of the margin's evolution. An ancient fold-and-thrust belt (poorly imaged on seismic profiles) slides on a *lower décollement level* in the central fan area. Major fold-and-thrust belts, running all along the upper Amazon fan (down to 2100 m) detach on an *intermediate* *décollement level* of regional extent. At local scale, antithetic normal growth faults detach on an *upper décollement level* and exert structural control on the segmentation of the fan's depocenters (figure 2).

The *compressional domain* located on the deep basin is composed of a series of thrust faults, most of which verge seawards, trend NW-SE and are grouped into thrust belts (figures 1, 2A and B). The most remarkable compressional structures are active ('modern") deep-water fold-and-thrust belts that run all along the upper Amazon fan that equally detach over an *intermediate décollement level*. The *intermediate décollement level* is probably Lower Paleocene in age (~65 Ma), correlatable with the base of the Paleocene-Eocene Marine Megasequence (65-40 Ma) of Silva *et al.* (1999) (figures 2A and B).The geometry and structural style of these thrust belts vary considerably along strike, following the development of two main structural compartments: the N*orthwestern* and the *Southeastern Compartments* (Oliveira *et al.*, 2005; da Silva, 2008; Reis *et al.*, submitted). In the NW Compartment, the majority of thrust faults is active and exhibits evidence of long-lasting deformation from multiple partially-overlapping thrusts. These faults affect the entire overlying sedimentary packaged, leading to the formation of several ponded basins (piggy-back basins) (figures 1, 3C and 3D). In contrast, along the SE Compartment, the modern thrust belt is restricted to a pair of active thrust faults assembled into a narrow compressional zone, considerably less shortened than in the NW Compartment (figures 1, 3A and 3DB) (da Silva, 2008).

The geometry of fold-and-thrust belts varies along strike, owing to lateral changes in the development of the Amazon fan's depocenters. Depocenters are significantly more complex at the NW Compartment due to differential sedimentary loading, exhibiting evidence of long-lasting deformation from multiple partially-overlapping fronts that resulted in further shortening and its impact on the bathymetry (figures 1B and 2A). A map of depth to an *upper décollement level* (located close to the base of the Amazon fan succession, figure 3) shows that the margin's main depocenters are isolated between upslope extensional faults and the highly-arcuate thrust faults in the deeper basin (sedimentary depocenters labeled D1 and D2 in the time isopach map of figure 1B).

Impact of gravity tectonics on sea-floor relief and mass wasting in the Amazon fan

Distinct degrees of structural development between the NW and SE Compartments are also expressed by equally distinct morphological features and mass wasting processes at the Amazon fan.

The active compressional system responds for major morphological impact on the Amazon fan (Araújo, 2008). At the NW Compartment, the fold-and-thrust belts are capable of affecting sea-floor relief as roughly continuous lineaments for distances of over 100 km (between 1,300-2,100 m deep) (figure 1). Active thrust faults can reach up the sea-floor causing major bathymetric impact at the submarine fan scale, forming fault scarps up to about 500 m high (figures 3C and 3D). Contrastly, at the SE Compartment, thrust belts are largely deactivated and are located at shallower water depth, running between approximately 900-1400 m as a narrow zone rarely larger than 10 km and continuous for no more than a few tens of km (figures 1 and 2B). Associated structural styles are variable along strike, with the prevalence of zones of sea-floor structural uplift due to folding and/or faulting, with just a pair of active thrust faults that can eventually reach up the sea-floor to form local fault-related scarps up to 200 m high (Araújo, 2008). Structural sea-floor uplit can yet result in a flexure of sedimentary bedding along fold limbs, capable of unleveling sea bottom as ramp-like features as high as hundreds of meters (up to 300-350 m) over horizontal distances of just a few kilometers (figures 3A and 3B).

A series of slope failure features and displaced sediment deposits were seismically recognized along fold-and-thrust belts of the NW and SE Compartments.

At the SE Compartment, slope failure features can be defined by faulted blocks (about 200-250 m thick) in downslope continuity to upslope unfailed layers, laid directly onto structural ramps (figures 1 and 3A). Locally, detached faulted-rotated blocks (about 200-250 m thick) can leave behind erosional scars up to 200 m in height (figure 3B). Downslope mobilized sediments show are dominated by folded and compressed sediment slides, in units as thick as 600 m (figures 3A and 3B). These facies features support their interpretation as slides that have been variably folded and compressed so that they became generally thicker dowslope. Seaward of the SE Compartment, slided masses can make up an upper mobilized layer up to approximately 300-600 m thick (depending on the geographical location) and were mapped in the study area downslope to about 2,600 m water depths (figures 1, 3A and 3B).

A distinct scenario is found on the NW Compartment, where the majority of headslide areas are faulted scarps (as high as 500 m) vertically coincident with thrust faults, forming markedly sinuous erosional traces of headwall scars for distances over tens of km, which may occasionally evolve into upslope erosional scarps by isolated retrogressive events (figures 1, 3C and 3D). Displaced sediments are characterized by widespread seismically massive units showing internal transparent to chaotic facies, and only local interbedded facies. These features support their interpretation as predominant debris flow deposits variable thickness (in the order of 150-250 m) (unit a in figure 3C) implying more intensively re-deposition. Locally, slide scars seem to have been evacuated to a much higher degree where displaced masses derived from upslope disrupted features have overridden previous allochthonous deposits and slid away downslope (figure 3D). Seaward of the NW Compartment, highly-deformed and displaced sedimentary units were mapped downslope to about 3,000 m water depths, making up an upper mobilized layer of approximately 500-600 m thick (figures 1, 3C and 3D).

Allochtonous masses were mapped as two laterally continuous areas of 10,000 km^2 and 8,000 km^2 located immediately seaward of the compressional belts of respectively the NW and SE Compartments (figure 1A). These areas correspond to *submarine slide complexes* of regional extent, rather than to individual slided masses or slide events. Although gliding levels in each slide complex were laterally correlated by crossing seismic lines, limitation of seismic coverage, as well as seismic resolution, do not allow an adequate identification of individual slide masses or events. The same reasoning applies to the distal limits of the each submarine slide complexe (placed at approximately 2,600-3,000 m water depths) that correspond merely to the offshore coverage of available closely-spaced seismic lines (**figure 1**A).

Features and deposits mapped in the slide complexes show that slope failure initiation and subsequent development of mass transport are unequivocally associated with tectonically-induced sea-floor relief. These are key results that allow for the first time to tie surficial and subsurficial mass wasting processes in the area (concerning here the upper sequences to a maximum of 600 m thick) to gravity tectonics that deforms the entire marine sequence of the basin (Araújo, 2008; Reis *et al.*, submitted). Based on regional seismic analysis, figure 3 summarises a sequential development of gravitational collapse linking different degrees of fold-and-thrust belt compression, its impact on sea-bottom morphology and finally different patterns of displacement and disruption of mass transport deposits mapped on the upper-middle Amazon fan. Buried slope disrupted features and large slide deposits of regional extent are also recognized along the entire vertical succession of the Amazon fan seaward of the compressional fronts, indicating that a coupled mechanism of gravity tectonics and mass wasting has been recurrently operating in the Amazon fan (for example, ***c*** and ***bsd*** in figure 3). Mapped slide complexes are also geographically coincident with part of the MTDs previously mapped in the Amazon Fan (e.g. Damuth *et al*,. 1988; Piper *et al.*, 1997a; 1997b; Maslin & Mikkelsen, 1997; Maslin *et al.* 2005). The currently knowledge suggest that MTDs in Amazon fan were primarily related to climatic-induced sea level changes (e.g. higher sedimentation rates and/or gas hydrates dissolution). However our results point out that gravity tectonics is a triggering mechanism of slope instability that has also to be taken into account for the investigation of mass wasting processes in the Amazon submarine fan. A thorough understanding of how these processes are coupled and how they evolve in time and space certainly require further detailed investigation.

Conclusions

Analyses of 2D seismic data carried out in this work provided us with new insights into how gravity tectonics operates and evolves in the Foz do Amazonas basin, as well as on how it induces sea-floor relief capable of triggering mass wasting on the Amazon fan.

(1) Thin-skinned structures were driven by gravity in a linked extensional-compressional system and by sedimentary loading. The geometry of fold-and-thrust belts varies along strike, owing to lateral changes in the development of the Amazon fan's depocenters. Depocenters are significantly more complex at the NW Compartment due to differential sedimentary loading, exhibiting evidence of long-lasting deformation from multiple partially-overlapping fronts that resulted in further shortening and its impact on the bathymetry.

(2) This study also reveals that two regional submarine slides complexes, ranging between 8,000-10,000 km^2, were triggered by sea-floor disruptions induced by gravitational compression that forms the fold-and-thrust belts on the Foz do Amazonas basin. Consequently, significant volumes of mass transport deposits on the Amazon fan are tectonically-induced.

(3) Multi-scale gravitational collapses occur at the Amazon fan by a coupled mechanism of gravity tectonics and mass wasting, which may indicate a long-term mode of slope instablities, with consequences for the depositional pattern and stratigraphic succession of the Amazon fan, composed by channel-levees systems interbedded with recurrent mass movement deposits.

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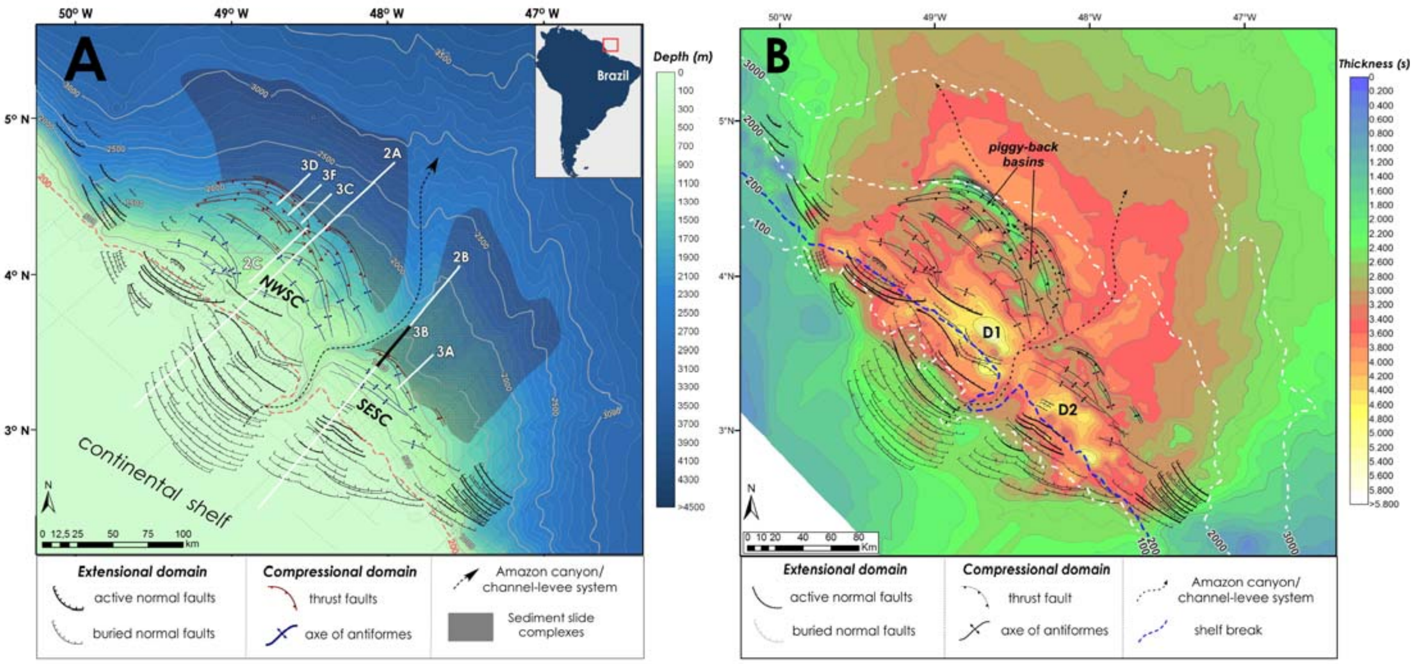

Figure 1: A- Structural map of gravity-related structures in the Foz do Amazonas basin-Brazilian equatorial Atlantic margin, with location of seismic data grid (from Reis *et al.*, submitted). Numbers refer to figures presented in this work (NWSC= Northwest Structural Compartment, SESC= Southeast Structural Compartment). Bathymetric data are from Smith & Sandwell (1997) and from compilation by the Brazilian Navy. B-Conjugated structural map and sediment isopach map (time depth to the upper décollement level, see figure 2) across the upper-middle Amazon fan, central Foz do Amazonas basin. D1 and D2 are the main margin's sediment depocenters for the considered time interval (modified from da Silva, 2008).

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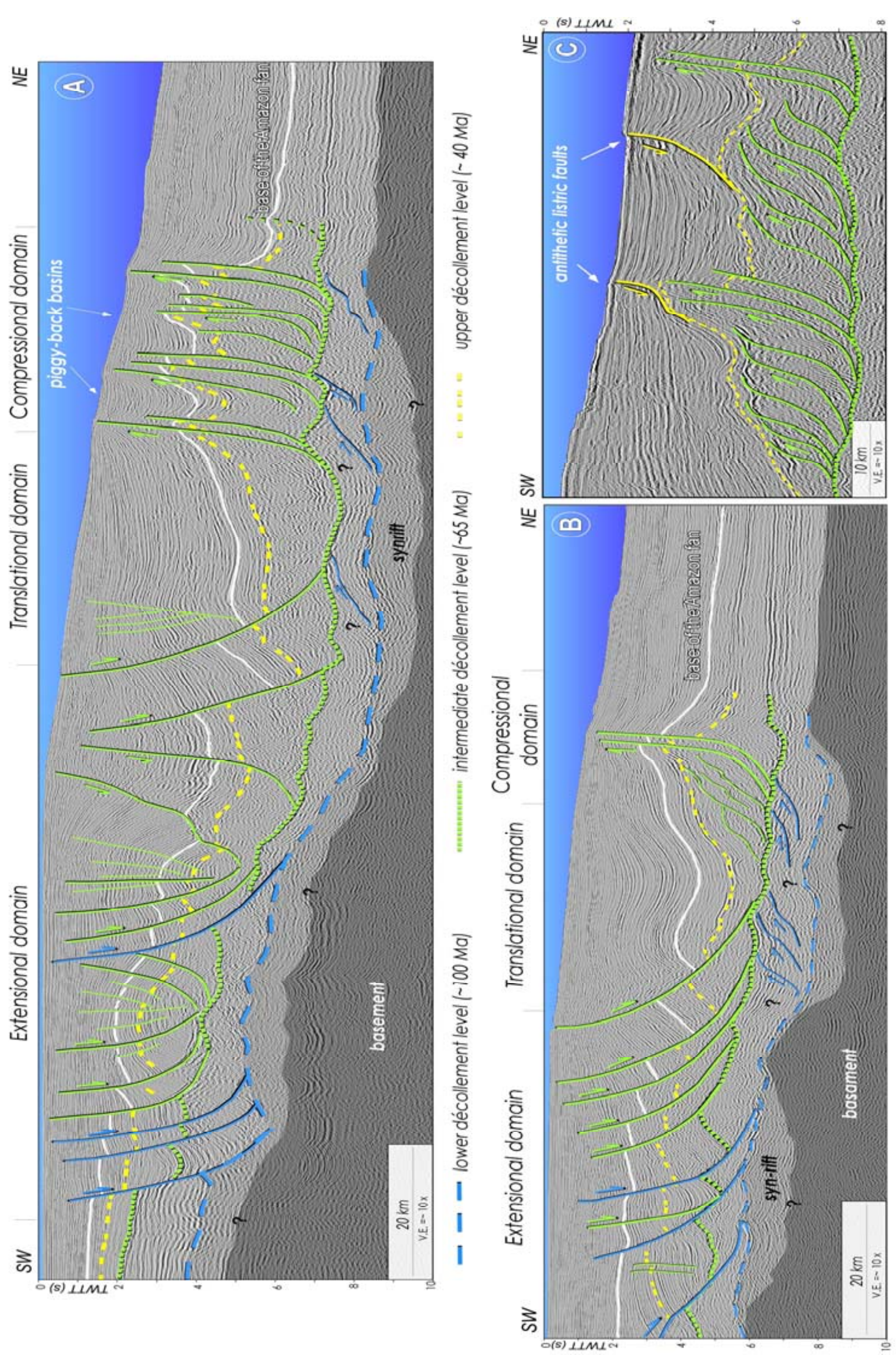

Figure 2: Interpreted dip seismic lines illustrating the linked extensional-compressional system gliding over basal décollements across the Northwest (A) and the Southeast Structural Compartiments (B) of Foz do Amazonas basin. An extract of seismic line in C shows antithetic growth normal faults that detach over an upper décollement level of local extent (from Reis *et al.*, submitted). See figure 1 for locations.

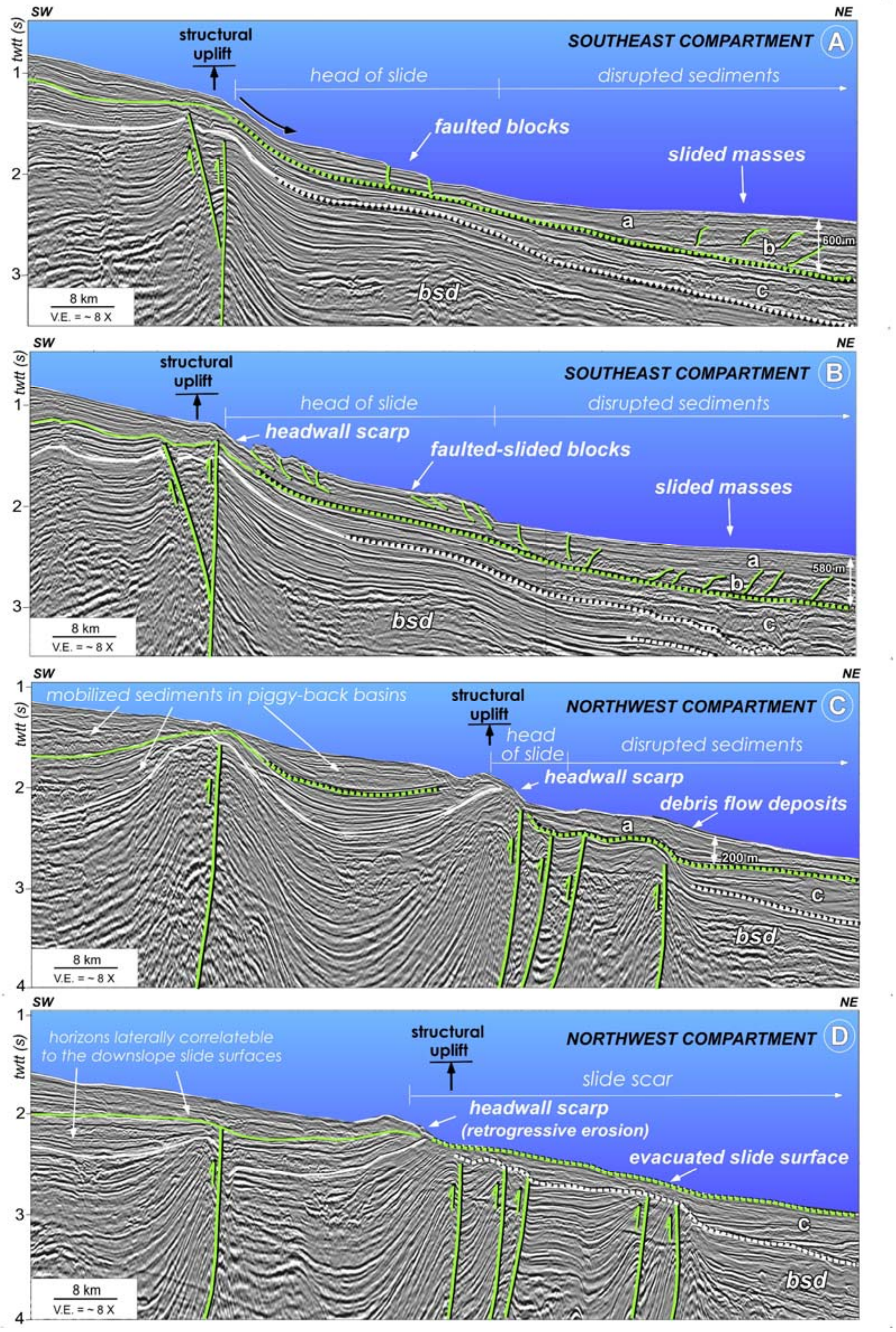

Figure 3: Sequential development of mass transport deposits from the initiation of slope failures (A) to the complete slid away of mobilised masses (D) (from Reis *et al.*, submitted). Increasing seabed disruption from A to D responds to variable morphological impact of tectonically-induced sea-floor reliefs (dashed lines are inferred décollement levels; ***a***, ***b*** and ***c*** correspond to seismic facies or units; ***bsd*** corresponds to buried sediment slides). See figure 1 for locations.