Two-scale gravitational collapse in the Amazon Fan: a coupled system of gravity tectonics and mass-transport processes

A. T. REIS1*, R. PEROVANO2, C. G. SILVA2, B. C. VENDEVILLE3, E. ARAÚJO2, C. GORINI4 & V. OLIVEIRA2

1Grupo Geomargem-Faculdade de Oceanografia/UERJ, Rua São Francisco Xavier, 524, 4º Andar, bl E, Maracanã, Rio de Janeiro, RJ, CEP 20550-013, Brazil
2Departamento de Geologia-Lagemar/UFF, Av. Litorânea, s/n, Boa Viagem, Niterói, RJ, CEP 24210-346, Brazil
3UMR 8157 Géosystèmes, Université de Lille 1, Bât. SN5, USTL, 59655, Villeneuve d’Ascq cedex, France
4UMR CNRS 7193 Evolution et Modélisation des Bassins Sédimentaires, Université Paris 6 Pierre et Marie Curie, 4 place Jussieu, case 117, Tour 56-57, 75252 Paris cedex 05, France

*Corresponding author (e-mail: antonio.tadeu@pq.cnpq.br)

Abstract: Gravity tectonics affects the entire marine sedimentary sequence of the Foz do Amazonas basin, including the topmost Amazon Fan. During the various stages of the margin’s evolution, the sedimentary loading and bathymetric slope induced the formation of a linked extensional–compressional system in which gravitational fold-and-thrust belts form significant structural features on the continental slope. Seismic analysis carried out in this study shows that sea-floor relief created along these thrust belts can trigger recurrent mass-transport deposits in the upper–middle Amazon Fan, suggesting a long-lasting linkage between gravity tectonics and mass-transport processes throughout the sedimentary evolution of the Amazon Fan.

Supplementary material: Uninterpreted seismic sections are available at http://www.geolsoc.org.uk/SUP18393.

The Foz do Amazonas basin (also called the Amazon Mouth basin) is the largest offshore sedimentary basin located on the Brazilian Equatorial Atlantic margin (Fig. 1a). This basin has been the target of systematic exploration in recent decades, because of the potential occurrence of oil plays in deep-water marine sequences. Basinwide, the Amazon Deep-sea Fan (referred to hereafter as the Amazon Fan) has built out as a prominent and thick sedimentary prism about 10 km into the deeper basin since the Late Miocene (Figueiredo et al. 2007, 2009). Both the basin and its topmost fan stratigraphic successions (c. 10 Ma) have been affected by features of gravitational collapse at different time and space scales (Fig. 1).

The entire marine sequence of the basin is deformed by an upslope set of extensional faults and downslope gravitational fold-and-thrust belts considered to root into basal weak levels (e.g. Silva et al. 1999; Zalán 2005). Although these structures affect large areas of the basin, they are not well discussed in the scientific literature. In the study area, as most of the geological and geophysical investigations have been carried out by oil companies, very little information has reached the public domain and important aspects of gravity tectonics remain open for study.

The same scarcity of information applies to the stratigraphic organization of the Amazon Fan since the Late Miocene. The fan was built primarily by huge volumes of terrigenous sediments carried out to the sea by the Amazon River (Figueiredo et al. 2007), but we lack chronostatigraphic details about the entire fan series, as most of the studies on the Amazon Fan have focused on the Quaternary fan section, involving deposition of channel–levee systems and mass-transport deposits (e.g. Damuth & Embley 1981; Damuth et al. 1988; Maslin & Mikkelsen 1997; Piper et al. 1997a,b; Maslin et al. 2005). These studies recognized submarine mass-transport deposits (MTDs) as important elements in the fan’s Quaternary sedimentary construction, commonly correlated to climate-induced sea-level changes. On the other hand, the role of gravity tectonics in triggering mass-transport processes has not until now been addressed in the geographical frame of the Amazon Fan.

In this paper, we present a refined map of gravity tectonic structures of the study area, based on 2D seismic interpretation. We also analyse and describe a two-scale system of gravitational collapse in the fan area by integrating sea-bottom relief caused by gravity tectonic structures with mapped slope failure features (e.g. erosional scars, fault scarps, faulted blocks; Mulder & Cochonat, 1996) and shallow mass-transport deposits (e.g. slide blocks, sediment slides and slumps, debris flows; Evans et al. 1996; Mulder & Cochonat, 1996), to assess possible links between gravity tectonics and mass-transport processes on the Amazon Fan.

Data and methods

The available seismic data comprise about 15 000 km of 2D multichannel seismic reflection profiles (Fig. 1). The seismic data include a super-regional seismic grid of 100 km spacing and an industrial seismic grid of 10–20 km spacing (Fig. 1): the first consists of the LEPLAC Survey lines collected at 13 s recorded time interval by the Brazilian Navy and by PETROBRAS (vertical resolution between 5 and 10 m); the second grid, collected at 10 s recorded time interval (vertical resolution between 5 and 10 m) was provided by the geophysical survey companies GAIA and FUGRO. Seismic data were interpreted using the software Kingdom Suite®.
Bathymetric data used in this study comprise the compilation of regional bathymetric data of the Foz do Amazonas basin extracted from ETOPO1 (Smith & Sandwell 1997), and a higher resolution bathymetric grid of the upper-middle Amazon Fan that had been previously compiled from different sources by the Brazilian Navy, including the LEPLAC Survey, PETROBRAS, the Geophysical Data System (www.ngdc.noaa.gov/mgg/geodas) and the General Bathymetric Charts of the Oceans (www.gebco.net).

Seismic analysis was conducted based on the general principles of seismic stratigraphy to: (1) identify major structures and horizons; (2) define seismic facies indicative of depositional processes (slope failure features and mass-transport deposits); (3) generate structural and thickness contour maps of selected intervals. As we did not have access to well data, time correlations proposed for interpreted seismic lines are derived from correlation with published data of Silva et al. (1999).

**Geological setting**

The Foz do Amazonas basin covers an area of about 268 000 km², extending to c. 3000 m water depth, located on the northwestern part of the Brazilian Equatorial margin (Figueiredo et al. 2007). The basin evolved in a context of both wrenching tectonics, kinematically related to ancient transform movements, and compressional tectonics related to the history of Andean uplift, which reorganized the catchment basin of the Amazon River (Hoorn et al. 1995; Matos 2000). The syn-rift sequence is
composed of Neocomian to Albian fluviol-deltaic, lacustrine and marine strata (Caciporé Formation), infilling pull-apart half-grabens (Figueiredo et al. 2007). Open-marine clastic deposition started in the Late Albian (c. 102 Ma) with deposition of deep-water mudstones and siltstones (Limoeiro Formation) that lasted until the Late Palaeocene. This was succeeded by a Selandian to Tortonian (between c. 62 and 11.3 Ma) mixed carbonate–siliciclastic platform (Marajo and Amapá Formations) with laterally equivalent deep-water calcilutites and mudstones (Travosas Formation). Tectonically driven changes in fluvial laterally equivalent deep-water calcilutites and mudstones (11.3 Ma; Figueiredo et al. 2007). This sequence includes shoreline facies (Tucunare´ Formation) and the Amazon Fan series, composed of continental slope fine sand and clay facies (Pirarucu Formation) and deep-water mud facies (Orange Formation) (Figueiredo et al. 2007).

Previous studies on gravity tectonics in the Foz do Amazonas basin

Silva et al. (1999) were the first to map gravity tectonic structures across the Foz do Amazonas basin and to associate them with a linked extensional–compressional system gliding on weak overpressured shales. Deformation was considered to have been induced mainly by gravity spreading as a result of the sedimentary progradation and loading of the Amazon Fan. Gravity-related structures were linked to two distinctive basalt décollement levels. Most of the basinward-dipping listric faults located on the inner to mid-shelf root into a décollement level at the top of the upper Cretaceous Marine Megasequence (c. 100 Ma), whereas those closer to the shelf edge root into a shallower décollement that is at the base of the Palaeocene–Eocene Marine Megasequence (c. 65 Ma). An ancient gravitational fold-and-thrust belt (poorly imaged on seismic profiles) slides on the basalt décollement level in the central area, whereas the most conspicuous fold-and-thrust belts on the mid-slope region sole out in the shallower décollement.

Cobbold et al. (2004) and Oliveira et al. (2005) pointed out a structural asymmetry along the strike of the gravitational fold-and-thrust belts, leading Oliveira et al. (2005) to propose a structural segmentation into two major compartments: a larger and structurally complex NW Compartment, and a smaller and structurally immature SE Compartment. The along-strike variations of structural styles have been attributed to compaction-induced overpressure caused by lateral changes in the development of the margin’s depocentres as a result of the Amazon Fan deposition (Silva et al. 1999; Oliveira et al. 2005). Cobbold et al. (2004), on the other hand, advocated that the along-strike structural variability of thrust belts, instead of being related to compaction, responds primarily to enhanced hydrocarbon-induced overpressure on the NW fan area, which coincides with the location of an inferred pod of Cenomanian–Turonian source rock. The two explanations (compaction-induced and hydrocarbon-induced overpressure) do not seem to be mutually exclusive.

The Amazon Fan

The Amazon Fan is one of the largest river-fed mud-rich submarine fan systems in the world, depositing over an area of 330 000 km². It extends from the shelf break over 1100 km northeastwards to about 4800 m water depth (Damuth & Kumar 1975; Damuth et al. 1988). For the upper fan water depths extend to about 3000 m and the Amazon Canyon is a major morphological feature, which appears as a deeply incised valley of up to 600 m depth. However, the scientific literature does not provide studies concerning the stratigraphic and sedimentary architecture of this large turbidite system since its early development in the Late Miocene. Most of the previous investigations focused on the Quaternary upper and middle fan and were based on high-resolution seismic data and sediment samples recovered by the Ocean Drilling Program (e.g. Damuth et al. 1988; Flood et al. 1991; Maslin & Mikkelsen 1997; Piper et al. 1997a,b; Maslin et al. 2005).

The upper 500–800 m of the Amazon Fan consists of overlapping channel–levee systems (100–200 m thick) grouped into major levee complexes that were formed by periodic channel avulsions during sea-level lowstands (Damuth et al. 1988; Lopez et al. 2005). MTDs are also important sedimentary components of the fan, covering extensive areas of the upper-middle fan, and can be as large as 200 km downslope and 100 km wide. Each MTD (slumps, slides and debris flows) can result in remobilized sediment deposits as large as 15 000 km² and reaching a thickness of up to 200 m (Damuth & Embley 1981; Damuth et al. 1988; Flood et al. 1991; Maslin et al. 2005). Most of the surficial and subsurface MTDs are recent, dated to either 41–45 ka or 35–37 ka, and were associated with Quaternary sea-level lowstands (Maslin & Mikkelsen 1997; Piper et al. 1997b; Maslin et al. 2005). The younger MTDs (11–14 ka) are associated with the last sea-level rise (Maslin & Mikkelsen 1997; Maslin et al. 2005). Catastrophic mass-transport processes on the Amazon Fan are considered to be caused probably by enhanced sediment supply and gas-hydrate dissociation during rapid drops in sea level, whereas during transgression and sea-level highstands the rise of hydrostatic pressure and migration of depocentres would be the main causes of slope gravitational instabilities (Maslin & Mikkelsen 1997; Piper et al. 1997b; Maslin et al. 2005). Piper et al. (1997a) cited gravity tectonics (referred to as ‘shale diapirs’) as another possible cause of mass-transport processes in the Amazon Fan but did not explore this hypothesis.

Results

We present below the results of 2D seismic analyses to evaluate how gravity tectonics evolves and how it affects sedimentation in the Foz do Amazonas basin. The results are organized into two main sections: (1) structural styles of gravity tectonics in the Foz do Amazonas basin; (2) impact of gravity tectonics on sea-floor relief and mass-transport processes in the Amazon Fan.

Structural styles of gravity tectonics in the Foz do Amazonas basin

The analysis of 2D seismic lines carried out in this study allowed us to refine the structural framework of gravity tectonics previously mapped in the Foz do Amazonas basin (Silva et al. 1999; Cobbold et al. 2004; Oliveira et al. 2005). Three main structural domains were defined between the continental shelf and the continental slope: an upslope extensional domain extending to 500 m water depth is linked, via an intermediate translational domain, to a downslope compressional domain located between c. 900 and 2100 m water depth. This extensional–compressional gravitational system deforms the entire marine stratigraphic sequence of the Foz do Amazonas basin, across an area as wide as 190 km by about 300 km along strike, over a total area of c. 40 000 km² (Fig. 1).
The updip extensional domain, located between the midcontinental shelf and the upper slope, is characterized by both seaward- and landward-dipping listric normal faults with strike orientation in a general NW–SE direction, stratigraphic wedges and rollover anticlines, as well as minor antithetic planar normal faults (Figs 1 and 2a, b). Most listric faults are concave seaward-dipping normal growth faults with single fault planes extending up to 80 km in strike direction; they are more or less regularly spaced, with an average distance between faults of 3–8 km (Fig. 1). On the continental shelf, proximal normal faults are mostly now inactive, whereas closer to the shelf break and upper slope, listric faults can reach the sea floor and form fault scarps as high as 150–180 m (Figs 2a, b and 3a). A few listric faults, located in the continental shelf area, sole out into a lower décollement surface. As inferred by correlation with published seismic data of Silva et al. (1999), this lower décollement level is probably upper Cretaceous in age (c. 100 Ma), lying at the base of the upper Cretaceous Marine Megasequence (100–65 Ma) (Fig. 3a and b). However, the majority of synthetic and antithetic normal growth faults, including all active faults located at the shelf edge and upper slope, sole out into an intermediate décollement surface; this surface is probably lower Palaeocene in age (c. 65 Ma), being correlatable with the base of the Palaeocene–Eocene Marine Megasequence (65–40 Ma) of Silva et al. (1999) (Fig. 3a and b). Considering the submarine fan area, the location of these extensional structures varies along strike: to the NW, normal faults lie between the mid-shelf and about 500 m water depth, whereas to the SE they extend from the mid-shelf to the shelf edge (c. 200 m water depth) (Figs 1 and 3a, b). Finally, antithetic normal growth faults can also occur in the deeper basin (see translational domain below). These faults sole out into an upper décollement surface, probably lower Oligocene in age (c. 40 Ma), as it seems to be correlatable with the base of the Oligocene Marine Megasequence (40–25 Ma) of Silva et al. (1999) (Fig. 3c).

The compressional domain, located in the upper fan, is composed of a series of thrust faults that verge seawards, strike NW–SE and are grouped into seaward-convex thrust belts (Figs 1 and 2c, d). Gravitational fold-and-thrust belts that run along the upper Amazon Fan are active ('modern') compressional structures detaching directly over the intermediate décollement surface (Fig. 3a and b). The geometry and structural style of

![Fig. 2. Seismic examples of structural styles of gravity tectonics in the Amazon Fan. (a–d) representative large-scale examples of structures across the extensional and compressional domains; (e, f) detailed views that highlight local high relief (see Fig. 1 for location). BSR, bottom-simulating reflector for gas hydrates; twtt, two-way travel time.]
Fig. 3. Interpreted dip seismic lines illustrating the linked extensional–compressional system gliding over basal décollements across (a) the NW and (b) the SE Structural Compartments of the Foz do Amazonas basin. (c) Extract of a seismic line showing antithetic normal growth faults that detach over an upper décollement level of local extent. (See Fig. 1 for location.)
these thrust belts vary considerably along strike, following the development of two main structural compartments: the NW and the SE Compartments. In the NW Compartment, the majority of thrust faults are active and exhibit evidence of long-lasting deformation from multiple partially overlapping thrusts (Fig. 1). These faults affect the entire overlying sedimentary package, leading to the formation of several ponded basins (piggy-back basins) (Figs 2c, d and 3a). In contrast, along the SE Compartment, the modern thrust belt is restricted to a pair of active thrust faults assembled into a narrow active compressional zone, being considerably less shortened than in the NW Compartment (Figs 1 and 3b). An earlier and inactive gravitational fold-and-thrust belt of regional extent also detaches directly over the intermediate décollement surface. It consists of a zone of up to 80 km width of closely spaced stacked thrust sheets comprising imbricate structures. The imbricate structures are restricted to a stratigraphic section between the intermediate and the upper décollement levels (Fig. 3b and c). These thrust faults do not propagate upward into the overlying sedimentary section, but form a palaeo-thrust belt buried under the slope (Fig. 3b and c). An even older fold-and-thrust belt, located under this palaeo-thrust belt, slides over the lower décollement level, but it is so poorly imaged on seismic profiles that its structural style cannot be determined (Fig. 3a and b).

Further shortening of the NW Compartment is also reflected in the way compartments are linked to each other. Methods of section restoration to estimate the amount of horizontal displacement of deformed sequences were not employed in the present study. However, structural analyses and barymetric data suggest that structural compartments are linked by relay ramps along which the Amazon canyon is structurally controlled, until c. 1400 m water depth, beyond which the canyon decreases its average 600 m vertical relief and changes into channel–levee systems. Relay ramps imply some sort of transfer movement (in a general SW–NE direction) accommodating distinct rates of shortening. Mapping of strike-slip structures is, however, somewhat complicated at this location because of gaps in the seismic grid (Fig. 1).

The translational domain connects the upslope extension to the downslope compression in a relatively undisturbed mode, across areas up to 50–60 km wide. Although it seems to act as a dominantly translational sedimentary cover detaching over the intermediate décollement level, this domain exhibits features and structures indicative of sparsely distributed deformation, such as detachment folds, rollover antilines and associated syntectonic strata (an example of the last is shown in Fig. 3b). Deformation is also illustrated by the antithetic growth normal faults that occur as local extensional structures in the transitional zone. These faults step over a stratigraphic horizon located near the top of the palaeo fold-and-thrust belt that seems to act locally as an upper décollement surface (Fig. 3c).

A first-order linkage between structural zonation and deposition of the clastic wedge of the Amazon Fan is highlighted by isopach maps. A map of depth to the upper décollement level shows that the margin’s main depocentres are fault-bounded, isolated between upslope active extensional faults and the downslope highly arcuate thrust faults (sedimentary depocentres labelled D1 and D2 in Fig. 4). A series of overlapping thrust faults frame the outer limits of the wider D1 depocentre in the NW Compartment, and the pair of active thrust faults that characterizes the SE Compartment frames the outer limits of the shorter D2 depocentre. Active normal growth faults form the upslope boundaries of maximum sedimentary thickness of both depocentres (Fig. 4). Strata in these depocentres thicken both between antiformal limbs and towards extensional faults (Fig. 3b), and there record coeval sedimentation and deformation. Antithetic listric normal faults that occur in the central part of the depocentres result in sea-bottom morphologies (Fig. 3c) that exert structural control on segmentation of depocentres (Fig. 4).

Impact of gravity tectonics on sea-floor relief and mass-transport processes in the Amazon Fan

Among gravity-related structures at the scale of the Amazonas Fan, active fold-and-thrust belts have a major morphological impact. Overlapping thrust sheets are arranged as lineaments tens of kilometres long, forming continuous zones of faulted and folded sea-bed on the upper Amazon Fan (to c. 2100 m water depth). However, this structurally induced sea-floor relief varies considerably along strike (sediment thickness in this section corresponds to an estimated seismic velocity layer of 1800 m s⁻¹).

In the NW Compartment, compressional belts occur in water depths between 1300 and 2100 m, showing single thrust faults up to 60 km long and 5–10 km apart. The whole compressional system can affect sea-floor relief as roughly continuous lineaments for distances of over 100 km, along a zone of up to 50–70 km width (Fig. 1). Active thrust faults can reach the sea floor and have a major bathymetric impact on the upper submarine fan, forming fault scarps up to 500 m high. The fault scarps can be isolated features or occur as series forming a step-like high relief (Fig. 2f). Conversely, in the SE Compartment, thrust belts are largely now inactivated and are located at shallower water depths, between c. 900 and 1400 m (Fig. 1). The active thrust belt spans a narrow zone rarely wider than 10 km and is continuous for no more than a few tens of kilometres. The associated structural style is variable along strike, with the prevalence of zones of sea-floor structural uplift as a result of folding and/or faulting (Fig. 5a); locally, active thrust faults can reach the sea floor, forming fault-related scarps up to 200 m high (Fig. 5b). Although these features are not as significant as the spectacular relief mapped in the NW Compartment, structural sea-floor uplift can nevertheless result in flexure of sedimentary bedding along fold limbs, capable of elevating the sea bottom into ramp-like features as high as hundreds of metres (up to 300–350 m) over horizontal distances of only a few kilometres (Figs 2e and 5a, b).

A series of slope failure features and mass-transport deposits were seismically recognized along the fold-and-thrust belts of both the NW and SE Compartments. The main criteria for recognition of mass-transport processes were the existence of headwall features (erosional scarps and slide or rotated blocks; Evans et al. 1996; Mulder & Cochonat 1996) and the presence of transparent to chaotic seismic facies with clear basal detachment surfaces (Mulder & Cochonat 1996; Canals et al. 2004; Sultan et al. 2004; Evans et al. 2005; Frey-Martinez et al. 2006).

Seaward of the SE Compartment, mass-transport deposits were mapped in the study area downslope to around 2600 m water depth and can make up an upper remobilized sediment layer up to c. 300–600 m thick (Figs 1 and 5a, b). Slope failure features are developed along the sea-floor structural uplift that flanks the lineaments of the fold-and-thrust belt (Fig. 1). Slope failure features can be defined by faulted blocks (about 200–250 m thick) in downslope continuity to upslope unfailed layers that pass laterally to sea-bed structural uplifts (Fig. 5a). Typical headwall features are developed along isolated segments of sea-floor uplift where the downside movement of detached rotated blocks (c. 200–250 m thick) can leave behind erosional
scarps up to 200 m high (Fig. 5b). In all cases, slide and faulted blocks are replaced 2–5 km downslope by mass-transport deposits exhibiting a set of acoustic features that can be grouped into two main types of seismic facies (considering the seismic resolution of available data), units a and b, which exhibit distinct signs of sediment displacement (Fig. 5a and b). In most places, unit b is a well-defined basal unit (Fig. 5a and b) composed of highly reflective although discontinuous internal reflectors that have been apparently folded and faulted. These features support the interpretation of this basal unit as slide sheets that have been variably folded and compressed so that they become generally thicker downslope (Canals et al. 2004; Evans et al. 2005; Frey-Martínez et al. 2006). The base of this unit is represented in many places by a continuous and seismically well-defined detachment surface. Unit a is the upper unit, consisting of a continuous layer of rather chaotic to transparent seismic facies, which can be indicative of debris-flow deposits (Evans et al. 2005), with the presence of local parallel-layered facies interpreted as internal preserved sediment blocks (Fig. 5a and b).

Seaward of the NW Compartment, mass-transport deposits were mapped downslope to about 3000 m water depth, making up an upper remobilized layer c. 500–600 m thick (Figs 1 and 5c, d). However, a somewhat distinct scenario of slope failure features and mass-transport deposits is found adjacent to the highly deformed fold-and-thrust belts of the NW Compartment (Fig. 1). Headwall scarps are defined by discontinuous and sinuous traces of thrust faults for distances over tens of kilometres. Fault scarps may be as high as 500 m, particularly along

Fig. 4. Combined structural map and sediment isopach map (time depth to the upper décollement level; see Fig. 3) across the upper–middle Amazon Fan, central Foz do Amazonas basin. D1 and D2 are the margin’s main sediment depocentres for the time interval considered.
the most convex seaward trace of fold-and-thrust belts. These fault scarps may in some cases evolve into upslope erosional scarps by retrogressive erosion (Fig. 5c and d). However, toward both extremities of the convex trace of fold-and-thrust belts, headwall scarps are less well expressed (c. 50–70 m high), being gradually replaced by sea-bed flexures that result in ramp-like features laid onto fold limbs, similar to those observed seaward of the SE Compartment, as already shown in Figure 5a and b. Seaward of the toe of fault scarps, mass-transport deposits are characterized by seismically transparent to chaotic facies, with only local interbedded facies. These features support their interpretation as predominantly debris-flow deposits (Canals et al. 2004; Evans et al. 2005; Frey-Martínez et al. 2006) of variable thickness (c. 150–250 m), infilling local depressions caused by folding and faulting (unit a in Fig. 5c). Earlier mass-transport deposits are represented by slide deposits that glided along deeper detachment surfaces (unit c in Fig. 5c and d).

Allochthonous sediments identified seaward of both the NW and SE Compartments of the Amazon Fan, as illustrated in Figure 1, correspond to two laterally continuous areas of respectively 10 000 km² and 8000 km² extent. These areas correspond to submarine mass-transport complexes of regional extent and make up an upper remobilized layer that can be c. 500–600 m thick. Although gliding levels in each mass-transport complex were laterally correlated by crossing seismic lines, the limited seismic coverage, as well as seismic resolution, do not allow an adequate identification of single mass-transport deposits or mass-transport events. The same limitations apply to the undefined distal limits of each submarine mass-transport complex (c. 2600–3000 m water depth), which correspond merely to the limits of the offshore coverage of available closely spaced seismic lines (Fig. 1).

Discussion

Structural analyses carried out in this study show that a palaeo fold-and-thrust belt is buried under the modern upper-middle slope of the Foz do Amazonas basin, whereas the currently active gravitational fold-and-thrust belt is located in a toe-of-slope setting (Figs 1 and 3a, b). Extensional faults present a similar seaward structural zonation, with inactive normal faults tending to be buried under the mid-shelf and active normal faults being located on the outer shelf and upper slope (Figs 1 and 3a, b). In addition, portions of the palaeo fold-and-thrust belt located just seaward of the modern shelf-slope break are taken into extension by active normal faults, which are characterized by thick growth sections (Fig. 3a and b). The isopach map shown in Figure 4 also illustrates that the main depocentres are fault-bounded and located close to the most active normal growth faults of the outer shelf–upper slope. This structural zonation is similar to that observed in the Niger Delta, where the structural and depositional systems have migrated basinwards as a consequence of the delta progradation (e.g. Damuth, 1994; Cohen & McClay 1996; Hooper et al. 2002).

In this context, the structural complexity and size of the NW and SE Compartments of the Foz do Amazonas basin were interpreted to have evolved under the increasing influence of the sedimentary loading of the Amazon Fan, coinciding with lateral changes in the development of its main depocentres. Although the Amazon Fan’s series corresponds to only 10% of the elapsed time (c. 10 Ma) since open-marine deposition started in the Late Albian (c. 102 Ma), it represents more than 50% of the siliciclastic volume deposited in the basin since then, forming a clastic wedge about 10 km thick (Figueiredo et al. 2007). Gravitational fold-and-thrust belts are significantly more complex to the NW of the basin, exhibiting evidence of long-lasting deformation from multiple, partially overlapping fronts that have a major impact on the bathymetry (Figs 1, 2f and 3a). Simple conceptual models presented below propose possible scenarios for the structural development of distinct styles of fold-and-thrust belts by relating different degrees of deformation (shortening) to the evolution of the basin’s sedimentary infilling, notably after the onset of the Amazon Fan construction (Fig. 6).

Within the SE Compartment, the compressional zone consists essentially of deactivated imbricate slices forming closely spaced stacked thrust sheets that detach over the intermediate décollement level; they are restricted to a basal sedimentary package buried under the slope (Fig. 3b). This structural configuration points to an early stage of deformation involving gravitational collapse of originally undisturbed layers. Associated slide and compression would have resulted in a succession of thrust sheets forming a large and highly deformed fold-and-thrust belt, as illustrated in Figure 6a. A comparable modern analogue is represented by the thrust belts described in the Orange Basin, Namibia (Butler & Paton 2010). Subsequently, but still before the Amazon Fan started to be formed, continuous sediment deposition led to further syndepositional compression, fault steepening and reactivation of thrust faults, causing the entire sedimentary pile to thicken, and to drape folding of the overlying syntectonic layer as a result of shearing stresses exerted along two décollement levels (the intermediate and the upper décollement surfaces) (Fig. 6b). An example of a similar early gravitational fold-and-thrust belt is represented by the deep-water thrust belts found in the Pará–Maranhão basin of the Brazilian Equatorial Atlantic margin (Zalán 2005).

Within the NW Compartment, structural styles of fold-and-thrust belts suggest the occurrence of phases of deformation similar to those proposed above for the SE Compartment. However, the preferential development of the major fan’s depocentres in the NW Compartment resulted in a thicker and larger syntectonic sedimentary wedge (Fig. 4). Enhanced sedimentary loading in this compartment caused further shortening and the syn-fan reactivation of existing gravitational thrust sheets that propagated upward; as a consequence, faulting of entire sedimentary sequences occurred over large areas, forming the wide and mostly active fold-and-thrust belts that characterize the NW Compartment (Fig. 6c). The same sequence of deformation seems to have occurred within the SE Compartment, where, although sedimentary loading (depocentre D2) was capable of reactivating the existing thrust sheets, most of them have been preserved as a palaeo fold-and-thrust belt (Fig. 6a). In this case, faulting of the overlying sedimentary cover was accommodated along a pair of thrust faults, which form the narrow active belt framing the SE Compartment (Fig. 3b).

Distinct degrees of structural development observed in the NW and SE Compartments are also expressed by equally distinct morphological features and mass-transport processes on the Amazon Fan. Submarine mass-transport complexes are located

Fig. 5. Sequential development of mass-transport deposits from (a) the initiation of slope failures to (d) the complete sliding away of remobilized masses. Increasing sea-bed disruption from (a) to (d) corresponds to the variable morphological impact of structurally induced sea-floor relief (dashed lines are inferred décollement levels; a, b and c, seismic facies or units; bsd, buried sediment slides). (See Fig. 1 for location.)
immediately seaward of the gravitational compressional belts. Slope failure features and seismic facies of mass-transport deposits indicate that slope failure initiation and subsequent development of mass-transport deposits is unequivocally associated with structurally induced sea-floor relief. Based on regional seismic analysis, Figure 5 summarizes a sequential development of gravitational collapse linking different degrees of fold-and-thrust compression, its impact on sea-bed morphology, and the different patterns of displacement of mass-transport deposits, as mapped on the upper–middle Amazon Fan. Adjacent to compressional structures of the SE Compartment, slope failure features are defined by slide or rotated blocks that detach from fold limbs caused by the sea-floor structural uplift. Downslope mass-transport deposits are dominated by folded and compressed sediment slides forming units as thick as 600 m (Fig. 5a and b). In contrast, adjacent to compressional structures of the NW Compartment, the majority of slope failure features are headwall fault scarps (as high as 500 m) vertically coincident with thrust faults; basinward, they are followed by seismically homogeneous, thinner debris-flow deposits (transparent to chaotic seismic facies units), resulting in units as thick as 150–250 m (Fig. 5c and d). In some cases, slide scars can be developed to a much higher degree as mass-transport deposits slide away downslope leaving behind large slide scars (Fig. 5d). The seismic facies as well as the thickness of the mapped units indicate that, seaward of the NW Compartment, redeposition was more intense and gravitational slope instabilities were more frequent than in the seaward area of the SE Compartment (Fig. 5). The occurrence, close to the sea floor, of instability and deformation features had been previously detected in the Niger Delta (e.g., Cohen & McClay 1996; Hovland et al. 1997). In this same environment, Sultan et al. (2007) have recently recognized the role of compressional structures in generating submarine slope failures and mass-transport deposits in the Niger Delta. In the Amazon Fan, the coupling between gravity tectonics and mass-transport processes, as well as their evolution through time and space, still require further investigation. None the less, the results discussed above introduce new elements that allow, for the first time, a direct link to be established between gravitational processes that operate at distinct spatial and temporal scales: gravity tectonics induces regional compressional movement that forms fold-and-thrust belts involving the entire marine sequence of the basin; folding and thrust faulting creates sea-floor relief that triggers mass-transport deposits.

The main emphasis in this paper was to highlight connections between gravity tectonics and mass-transport processes occurring...
in the upper sequences of the Amazon Fan. The identified submarine mass-transport complexes are up to 300–600 m thick and correspond to areas of between 8000 and 10 000 km$^2$ extent. These mass-transport complexes could not be chronostatigraphically constrained but are possibly placed within the Pliocene–Quaternary stratigraphic window (Piper et al. 1997a,b). They are also geographically coincident with some of the MTDs of similar extent that have been mapped in the upper 200 m section of the Amazon Fan (e.g. Damuth et al. 1988; Maslin & Mikkelsen 1997; Piper et al. 1997a; Maslin et al. 2005). It has been suggested that, in the Amazon Fan, the formation of the previously mapped MTDs was primarily related to climate-induced sea-level changes caused by higher sedimentation rates and/or gas-hydrate dissolution. However, our results reveal that compressional movements caused by gravity tectonics have been operating as a recurrently triggering mechanism for mass-transport processes in the Amazon Fan (Fig. 7). Buried slope mass-transport deposits of regional extent are recognized throughout the succession of the Amazon Fan seaward of the compressional fronts, indicating that a coupled mechanism of gravity tectonics and mass-transport processes has been operating since the onset of the Amazon Fan in the Late Miocene (e.g. facies c and hsd in Fig. 5).

Conclusions

Analyses of 2D seismic data have provided new insights into how gravity tectonics operates and evolves, and how it induces sea-floor relief capable of triggering mass-transport processes on the Amazon Fan, as follows.

(1) Thin-skinned tectonic structures were driven by gravity in a linked extensional–compressional system and by local sedimentary loading. The geometry of fold-and-thrust belts varies along strike, owing to lateral changes in the development of Amazon Fan depocentres. These are significantly more complex in the NW Compartment as a result of differential sedimentary loading, exhibiting evidence of long-lasting deformation from multiple partially overlapping fronts that resulted in further shortening and an associated impact on bathymetry.

(2) Translation 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 along the upper Amazon Fan (down to 2100 m), detach on an intermediate décollement level of regional extent. At a local scale, antithetic normal growth faults detach on an upper décollement level and exert structural control on the segmentation of the fan’s depocentres.

(3) This study also reveals that, on the Amazon Fan, two regional submarine mass-transport complexes, c. 8000–10 000 km$^2$ in area, were triggered by gravitational compression of fold-and-thrust belts of the Foz do Amazonas basin. Consequently, significant volumes of mass-transport deposits on the Amazon Fan are structurally induced.

These results show that in the Amazon Fan a two-scale system of gravitational collapse occurs through a coupled mechanism of gravity tectonics and mass-transport processes. This coupled mechanism may indicate the long-term occurrence of structurally induced mass-transport processes with consequences for the
depositional pattern and stratigraphic succession of the Amazon Fan, which comprises interbedded channel–levee deposits and recurrent mass-transport deposits.

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