Multi-direction Flow in a Mass-Transport Deposit, Santos Basin, Offshore Brazil

L.B. Ashabranner, E.K. Tripsanas, and R.C. Shipp

Abstract The complex Quaternary Rebelde Slide is located on the northeastern corner of the Sao Paulo Plateau at the base of the upper continental slope in water depths of 1,600–1,700 m. This mass-transport deposit (MTD) is up to 300 m thick, 10 km wide where confined, 36 km long, and is buried beneath 50–65 m of hemipelagic drape. The Rebelde Slide is unusual because it appears to have flowed parallel to the slope. The majority of the failure is confined to a contouritic moat that runs along the base of the upper continental slope. The sliding surface of the failure is undulating, and coincides with the top of an underlying sediment wave. The Rebelde Slide consists of three components. Each one is characterized by different structural characteristics and direction of movement, as if the entire interval collapsed under its own weight on a multi-directional sliding surface. The coincidence of the sliding surface of the Rebelde Slide with the source area of fluid-expulsion features observed near the moat suggests failure along a zone of overpressured, geotechnically weak layers.

Keywords Mass-transport deposit • contourite • sediment drifts

1 Introduction

Most sediment failures tend to occur on specific layers of low shear-strength commonly referred to as “weak” layers. These weak layers can be sand intervals with high water content (e.g., Tripsanas et al. 2008), or relatively overpressured mud-prone intervals (J. Newlin, personal communications, 2009). Most examples of sediment failures in literature are from unidirectional slopes that result in the formation of simple (e.g., Gulf of Corinth failures in Hasiotis et al. 2004) or complex mass movements (e.g., Storegga slide in Bryn et al. 2005). Very few studies exist on the

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development of failures in areas with complex multi-directional slopes (e.g., Moscardelli et al. 2006)]. Such failures are comprised of several, multi-directional flow components.

This study investigates an unusual MTD that exists at the intersection of the upper continental slope and the Sao Paulo Plateau, approximately 200 km southeast of Rio de Janeiro (Fig. 1). The Rebelde Slide is an example of a complex failure that has evolved on the multi-directional slope environment of a contouritic (sediment-drift) deposit. The purpose of this study is to describe the morphology, internal character, and depositional processes of this unusual MTD. Additionally, this study explores the relationship to an underlying sediment-drift complex, establishes a model for progression of the failure, and speculates on possible triggering mechanisms.

The study area is covered by high quality 3D post-stack time migrated seismic data. Geco-Prakla Exploration Services conducted the non-proprietary 3D survey in 2000. Dissemblance volumes (also known as coherency volumes) based on correlation coefficients between traces in a user-defined matrix around each trace were used to facilitate interpretation.

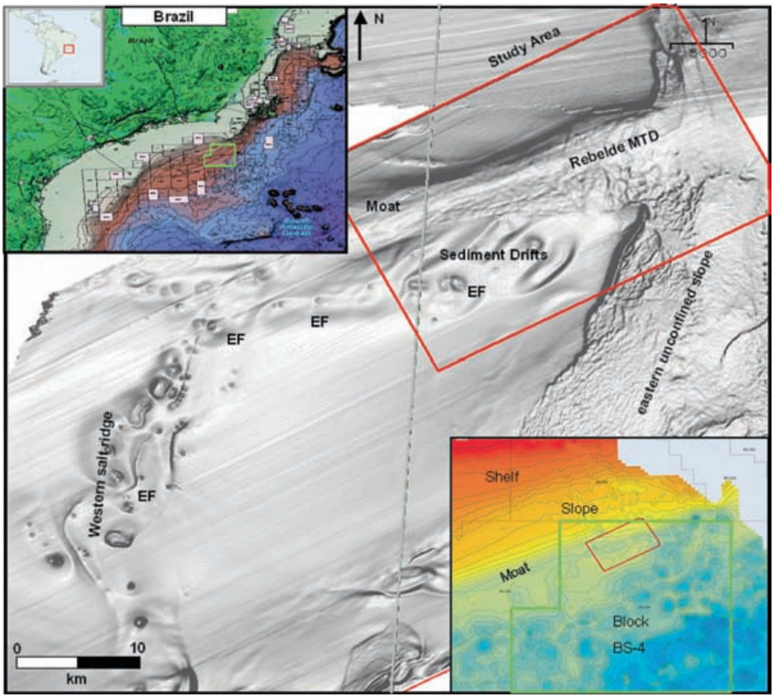

Fig. 1 Seafloor dip map of the Santos Basin, offshore Brazil. Study area is approximately 200 km south of Rio de Janeiro and is positioned at base of the upper continental slope. Upper left inset is a location map, the BS-4 concession block is outlined in green. Lower right inset: a sea-floor relative bathymetry map (*red is shallow, blue is deep*). Study area is outlined in red. EF: expulsion features.

2 Geological Setting

The dominant source of clastic sediment input into the Santos Basin was an ancestral river system that focused sediment into the northern and central parts of the basin during the Late Cretaceous and Paleogene (Modica and Bush 2004). This depositional pattern was altered as the river system was tectonically redirected to the north into the Campos basin during the Oligocene. This resulted in a starved and eventually drowned Santos continental shelf. The diversion of the dominant clastic source away from the Santos Basin resulted in a Late Tertiary to Holocene section consisting predominately of marine muds.

The study area is located at the base of the upper continental slope (Fig. 1), and is characterized by complex seafloor morphology. The western and central parts exhibit predominantly smooth morphology, punctuated by the occurrence of fluid-expulsion features (pockmarks). In the west, a north-south trend of pockmarks and undulating topography is related to an underlying salt ridge. At the base of a slope, sediment waves, pockmarks and an east-west trending depression or "moat" characterize the seafloor. This base of slope depression and sediment wave complex is interpreted as a large sediment drift (H. Lu, personal communications, 2005), with the prominent east-west depression interpreted to be a contouritic moat. The eastern part of the study area consists of a southeasterly inclined slope that is characterized by a rugose topography, attributed to near surface MTDs. This rugose topography is also found to extend westward into the contouritic moat along strike to the continental shelf and represents the seafloor expression of the Rebelde Slide.

3 Results

3.1 Structural Characteristics

The Rebelde Slide occupies a contouritic moat, is up to 300 m thick, is at water depths of 1,600–1,700 m, and is buried under 50–65 m of hemipelagic sediment (Figs. 2 and 3). Underlying the MTD is a thick sequence of undulating sediment-drift deposits. A northeast-southwest salt-rooted fault zone is truncated at the base of the MTD (Fig. 3b). The base of the Rebelde Slide consists of three elongated depressions. The eastern-most depression is open at its eastern boundary and connects with the unconfined inclined eastern slope (Fig. 2a).

The Rebelde Slide can be subdivided into three major components (A, B, and C) characterized by different types of movement and sediment remobilization (Fig. 2b). The A component is 20 km long, 1.9–3.3 km wide, occupies two elongated depressions in the moat, the western depression (WD) and the eastern depression (ED) (Fig. 2a). It has a wedge-like shape, which thins from 250 m in the east to less than 150 m to the west. Analysis of seismic traverses indicates that the A component is

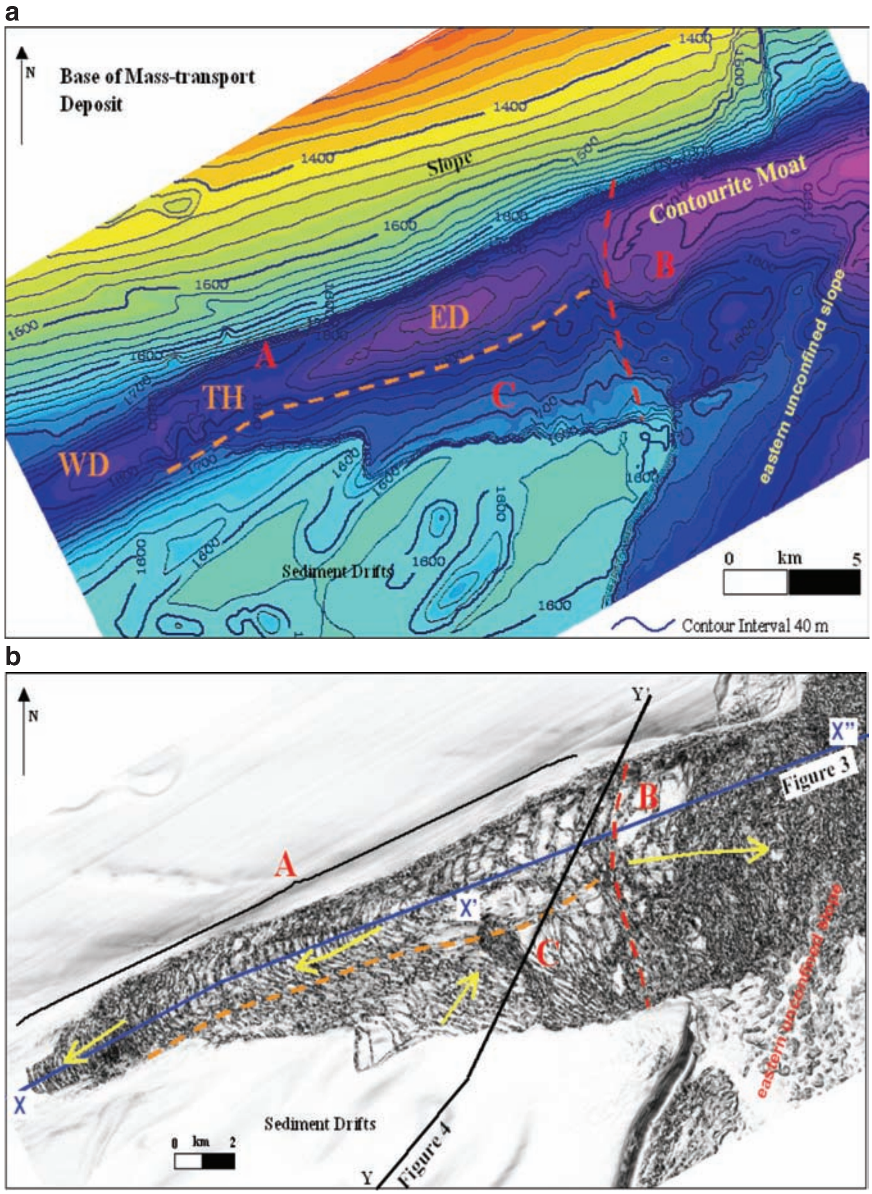

Fig. 2 Map view of the Rebelde Slide. (**a**) A structure map of the basal surface of the failure (*green line in Figs. 3 and 4*). The main components (A, B, C) are identified. The basal surface of component A is defined by underlying sediment drifts with a western depression (WD), a central area of topographic high relief (TH) and an eastern depression (ED). (**b**): A flattened dissemblance slice 100 ms above the base of the failure. Yellow arrows indicate flow direction. Dashed lines represent the boundaries between the components in both images.

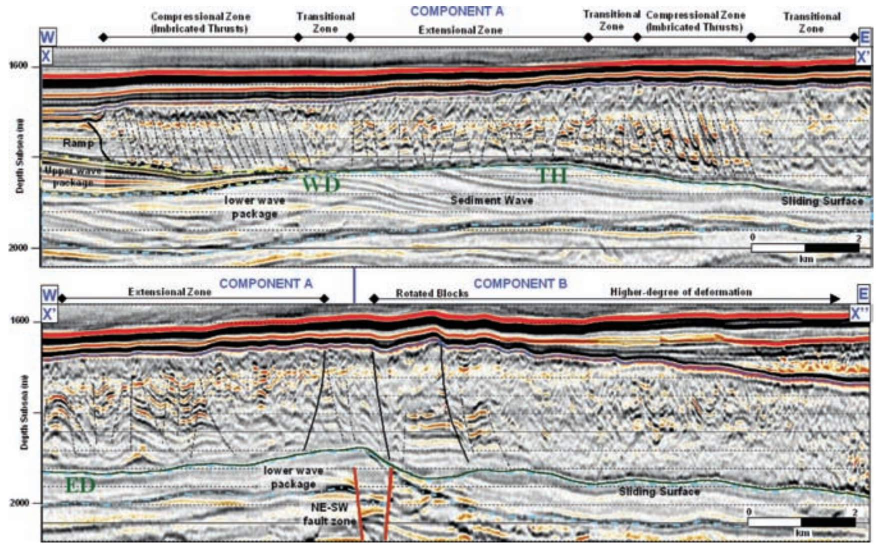

Fig. 3 A seismic traverse down the length of the moat, see Fig. 2 for line of section: X–X′ upper image and X′–X″ lower image. The compressional western terminus of the A component is shown in upper image. The upper wave package is outlined in yellow dashed lines (*western edge of upper image*) and the lower wave is outlined in dashed blue lines. Transition to the B component is shown in lower image. WD: western depression, TH: topographic high, ED: eastern depression. Underlying northeast-southwest faults in brown.

composed of a complex of alternating compressional and extensional zones (Fig. 3). Internal reflections, correlated to the stratigraphy of the pre-failed sediments, are preserved in this component, and provide a very useful tool for the assessment of the fragmentation of the failed sediment mass. The compressional zones are characterized by imbricated thrusts, which in map view form crescent-shaped compressional ridges. Two compressional zones (2 and 3.5 km long) are observed in the A component, one at the western terminus and another (2 km long) on the western flank of the eastern depression (ED on Fig. 2a). Two extensional zones (4.5 and 6 km long) are observed, one along the western flank of the central area topographic high relief (TH on Fig. 2a) and the other along the eastern flank of the eastern depression (ED). Fragmentation of the strata in both of the extensional zones resulted in the formation of alternated horst and graben-like structures. The downward bending of the reflections in the down-dropped blocks indicates collapse of the strata at these locations, which is in agreement with the stretching of the sediment prism. The dissemblance slice in Fig. 2b shows that sliding blocks in the extensional zones form arcuate bands, indicating that the movement along the axis of the A component was larger (up to 1 km) than at its edges. Transitional zones (1–2 km long) exist between the compressional and extensional zones, across which the change in sediment-remobilization style occurs. Two transitional zones occur at the center of the elongated basal depressions, and are characterized by a more incoherent seismic signature, implying a much higher degree of fragmentation and/or plastic deformation of the sediment at these locations. The transitional zone at the topographic area of high relief (TH on Fig. 2a) is characterized by a complex fragmentation, having extensional and compressional features that are antithetic to those of the extensional and compression zones to the west and east, respectively.

The B component occupies the eastern unconfined part of the Rebelde Slide, and is up to 300 m thick. The junction between the A and B components is coincident with the underlying salt-rooted fault zone. Four large coherent blocks are present above and on the eastern flank of the fault zone (Figs. 2b and 3). In some areas these blocks display stratified continuity with the underlying strata that suggest minimal movement. East of these blocks, the seismic character becomes incoherent, indicating a larger degree of sediment fragmentation and/or plastic deformation. This component is unconfined to the east and becomes indistinguishable from the confluence of larger, regional failure complexes on the eastern unconfined slope.

The C component of the Rebelde Slide is 16 km long, 3.5 km wide and up to 250 m thick, and occupies the southern part of the failure (Fig. 2). Near the walls of the moat along the southern margin, this component consists of back-tilted rotated blocks (Fig. 4). Clusters or individual stratified blocks, similar to those from the extensional zones of the A component, lie along the northern part of this component and alternate with incoherent seismic zones. It is separated from the A component at its northern boundary through a 100–500 m thick, transitional or shear zone, in which several lineations are observed in the dissemblance data (Fig. 2b). This zone has a semitransparent seismic character and an undulating surface, resembling lateral ridges (Fig. 4). Thrust fault-like features are also observed in this transitional zone.

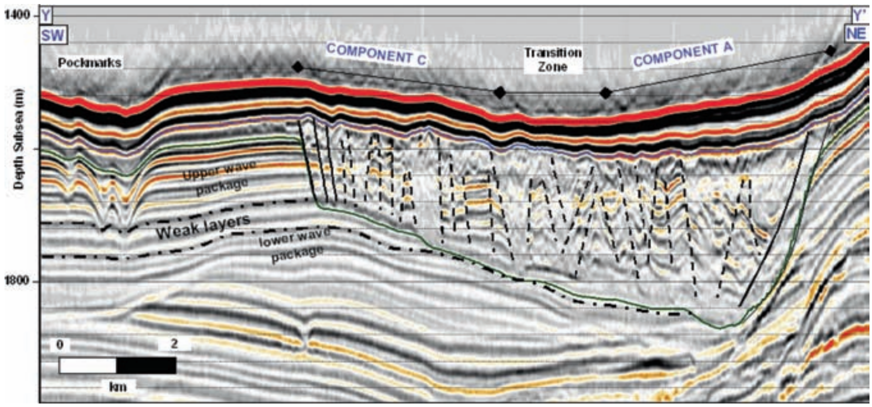

Fig. 4 Seismic traverse Y–Y′ (see Fig. 2b for line of section) through the C component, the transition zone and the A component. Green surface is sliding surface (*map view of surface in Fig. 2a*). Black-dashed lines represent the boundaries of the 'weak' zone.

3.2 Stratigraphic Characterization

The Rebelde Slide has been developed on a large sediment-drift deposit, and is confined to the strike-oriented moat (Fig. 2). Two packages of sediment waves are observed that correlate to the basal sliding surface of the Rebelde Slide (Figs. 3 and 4). The upper sediment-wave package is present only at the western edge of the failure, and is expressed by high-amplitude reflections that onlap the lower package. Large parts of this sediment package have been remobilized and incorporated into the Rebelde Slide (Fig. 4). The lower package is up to 200 m thick and consists of eastward migrating sediment waves, in which the upper boundary is characterized by an undulating surface (Figs. 2 and 3).

The sliding surface of all components that form the complex Rebelde Slide immediately overlies this lower sediment wave. Many pockmarks observed around the moat (Figs. 1, 2, and 4) appear to originate from a 20–25 m thick zone of parallel seismic reflections (dashed lines, Fig. 4). This zone can be traced to the Rebelde Slide, where it coincides with the sliding surface and the top of the lower sediment wave.

4 Discussion

The Rebelde Slide consists of three major components, each one of which is characterized by different geometric characteristics. The A component is confined to the contouritic moat and consists of multiple extensional and compressional zones (Fig. 3). Failures with similar characteristics have been classified by Frey-Martinez et al. (2006) as confined failures. The eastward dipping thrusts (Fig. 3) in combination with the westward pointing arcuate ridges (Fig. 2b) indicate a westward movement for this component. The only exception occurs in the transitional zone along the western flank of the topographic area of high relief (TH on Figs. 2a and 3) that separates the eastern and western depressions (Figs. 2a and 3). This transitional zone is characterized by extension to the west and compression from the east, which is expressed by thrusts that are antithetic to the thrust of the eastern compressional zone (Fig. 3). These characteristics suggest that there was a local eastward motion in the A component. However, it is not certain whether this motion took place during or after the development of the Rebelde Slide.

The B component comprises the eastern part of the Rebelde Slide, and is separated from the A and C components by a basal scarp coincident with the underlying fault zone. Moderately deformed, coherent blocks, which grade vertically and laterally to higher-deformed sediment with floating blocks to the east, indicate an easterly flow direction for the movement of this component (Fig. 3). Based on this observation, the B component is interpreted to have an eastward, unconfined, and emergent flow. Beyond the confines of the contouritic moat, the B component becomes indistinguishable from the larger regional MTDs.

The C component evolves from the collapse of the southern wall of the moat and consists of rotated blocks near the head-scarp, which evolved into coherent sliding blocks separated from each other by zones of higher sediment deformation (Fig. 4). Through the orientation of the blocks, a northeasterly to easterly motion is indicated for the C component (Fig. 2b). The C component is separated from the A component by a 100–500 m thick zone that is characterized by presence west-northwest to east-southeast lineations in dissemblance time slices (Fig. 2b). In seismic traverse, this zone is expressed by an incoherent and semi-transparent acoustic character and thrust-like features (Fig. 4). This transitional zone is interpreted as a zone of collision and shear between these two components, which led to the easterly diversion of the northeasterly flowing C component.

All components of the Rebelde Slide occur over the same sliding surface, which corresponds to the top of an underlying sediment wave package (Figs. 3 and 4). This condition in combination with the colliding and shearing boundaries of the Rebelde A and C components suggests that each component of this complex failure occurred simultaneously. The coincidence of this sliding surface with the layer from which the expulsion features are sourced suggests that the Rebelde Slide was caused by simultaneous failure along an underlying geotechnically "weak" zone, a zone that was likely comprised of relatively overpressured, under-compacted formations. A similar mechanism has also been proposed for other failures occurring in sediment-drift deposits (e.g., Afen Slide in Wilson et al. 2004). Such a mechanism can explain the different types and directions of motion taking place in a single failure, where the entire section collapsed under its own weight after loosing its basal support. The pre-failed slope inclination and that of the underlying weak layers probably determined the direction of motion.

Two triggering mechanisms are proposed for the loss of basal support in Rebelde. The first possible triggering mechanism is through the cyclic loading of weak layers through an earthquake. In the Gulf of Corinth, Greece, an earthquake resulted in the liquefaction of a sand layer that resulted in the formation of multiple sediment failures and sand volcanoes (Papatheodorou and Ferentinos 1997). Earthquakes in passive margins are rare events but not absent. A good example is the 1929 "Grand Banks" earthquake that resulted in the development of multiple failures in the passive eastern Canadian continental margin (Piper et al. 1999). A second possible triggering mechanism is the migration of gas through faults and its accumulation in a zone of higher permeability (e.g., Frey-Martinez et al. 2009).

5 Conclusions

The composite Rebelde Slide has developed in a contouritic moat, and consists of three major components, each one of which is characterized by different type of sediment deformation and direction of motion.

The sliding surface of the Rebelde Slide coincides with the top surface of an underlying sediment wave.

Pockmarks around the moat are interpreted as fluid-expulsion features, which are sourced by a thin (up to 25 m thick) stratigraphic interval. This interval coincides with the sliding surface of the Rebelde Slide.

The development of the Rebelde Slide is attributed to loss of basal support of a "weak" underlying zone.

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