Geophysical Journal International

Geophys. J. Int. (2010) **183,** 1151–1164 doi: 10.1111/j.1365-246X.2010.04827.x

A 3-D morphometric analysis of erosional features in a contourite drift from offshore SE Brazil

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Accepted 2010 September 26. Received 2010 September 25; in original form 2010 May 6

SUMMARY

A contourite drift from offshore Brazil is mapped in detail and investigated using state-of-the-art 3-D seismic data. The aim was to review the relevance of erosional features in contourite drifts accumulated on continental slopes. Topographically confined by growing salt diapirs, the mapped contourite ridge is limited by two erosional features, a contourite moat and a turbidite channel, showing multiple slide scars on it flanks. Associated with the latter features are thick accumulations of high-amplitude strata, probably comprising sandy/silty sediment of Miocene to Holocene age. The erosional unconformities are mostly observed in a region averaging 3.75 km away from the axes of a channel and a moat, whose deposits interfinger with continuous strata in central parts of the contourite drift. The multiple unconformities observed are mostly related to slide scars and local erosion on the flanks of the drift. This work demonstrates that the existence of widespread unconformities within contourite drifts on continental slopes: (1) may not be as prominent as often documented, (2) are often diachronic and interfinger with correlative hiatuses or aggraded strata in axial regions of contourite drifts. Although less widespread than regional, or ocean-scale unconformities, these diachronous features result in significant hiatuses within contourite drifts and are, therefore, potentially mappable as relevant (regional-scale) unconformities on 2-D/3-D seismic data. Thus, without a full 3-D morphometric analysis of contourite drifts, significant errors may occur when estimating major changes in the dynamics of principal geostrophic currents based on single-site core data, or on direct correlations between stratigraphic surfaces of distinct contourite bodies.

Key words: Geomorphology; Continental margins: divergent; Sedimentary basin processes; South America.

1 INTRODUCTION

Published seismic and sedimentological data on continental margins have stressed the close proximity of turbidite and contourite depositional systems (Mulder *et al.* 2003; Llave *et al*. 2006; Molina *et al.* 2010). Slope features such as, for instance, rising salt diapirs can divert deep geostrophic currents, cause overescavation of contourite channels and generate erosional features, furrows and moats (e.g. Gulf of Cadiz; Garcia *et al*. 2009). In turn, when across-slope processes dominate over along-slope sediment flows, turbidite deposits may overprint the accumulation of contourite drifts. The opposite process occurs in areas of strong along-slope currents: turbidite flows can be deviated, feeding contourite drifts whenever along-slope current flows are strong enough to redistribute seafloor sediment (e.g. Faugères *et al*. 1999; Mulder *et al.* 2003, 2006; Viana *et al.* 2007). Within these mixed depositional settings, the interaction between submarine flows generates diverse erosional features, which effectively mark the principal paths of significant currents affecting the continental slope (Garcia *et al*. 2009).

A point of agreement to some authors using classical seismic-stratigraphic tools, i.e. correlating stratigraphic unconformities in a basinwide scale, is that the effect of contour currents on the seafloor is often marked by unconformities that reflect global hydrological events; (e.g. Llave *et al.* 2007; Rebesco *et al.* 2007). These unconformities: (1) are thought to be traceable at the scale of contourite drifts (e.g. Campos Basin, Espírito Santo Basin, Hatteras Drift, North Rockall Trough, Weddell Sea, Argentine Basin), (2) are typical of all the drift types existing in nature and (3) mark a significant difference between turbidite units and contourite drifts (Faugères *et al.* 1999; Knutz & Cartwright 2003; Viana *et al.* 2003; Maldonado *et al*. 2005; Duarte & Viana 2007; Koenitz *et al*. 2008). Sediment drifts are commonly delimited by contourite channels, moats and furrows, which have been invariably interpreted as localized erosional features with little effect other than forming channelled paths for sediment redistributed along-slope (Rebesco *et al.* 2007; Garcia *et al*. 2009). Such a view contrasts with that of other authors, who consider many of the common seismic stratigraphic methods utilized in turbidite systems not to be fully applicable to contourite deposits (Faugères *et al*. 1999; Stow *et al.* 2002a). In particular, current regimes acting diachronously on a continental margin may impose difficulties when dating basal and intradrift unconformities. Despite this limitation, most studies still consider

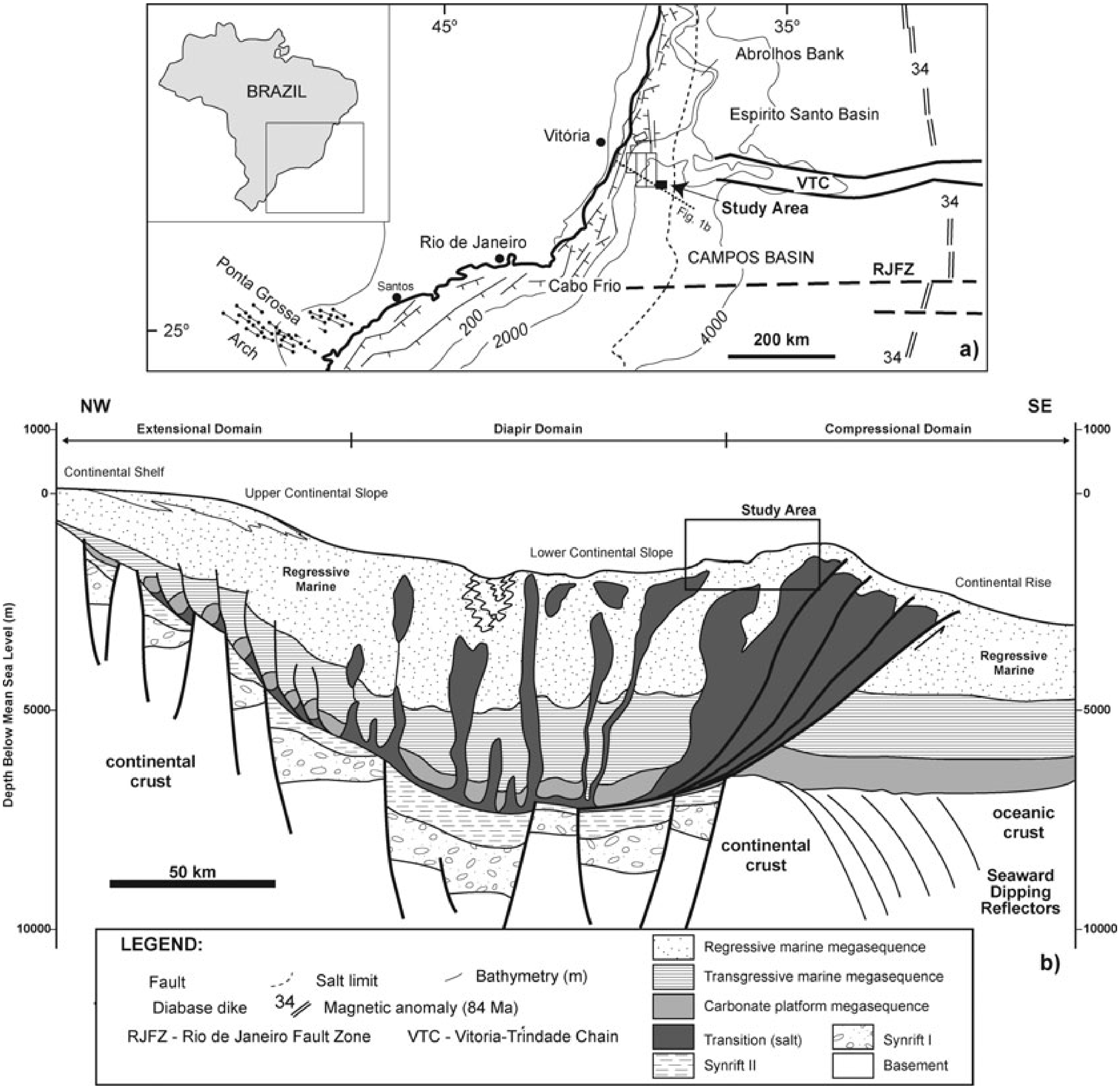

Figure 1. (a) Map of the southeast Brazilian margin showing the location of the Santos, Campos and Espírito Santo basins in relation to main fault zones. The location of the interpreted 3-D seismic volcume is highlighted in the figure. (b) Relative location of the study area on the continental slope east of Espírito Santo. The interpreted seismic volume is located at the base of the continental slope in an area of significant halokinesis and toe compression, both associated with gravitational collapse of the upper/mid slope regions above thick Aptian salt (Demercian *et al*. 1993). Panel (b) modified from Fiduk *et al.* (2004).

plausible to date regional changes in current regime by correlating seismic-stratigraphic surfaces at the scale of a continental margin, particularly in deeper abyssal regions, even when scarce ties with well data are available (e.g. Maldonado *et al.* 2005; Koenitz *et al*. 2008; Molina *et al.* 2010).

This paper uses a 3-D seismic volume from southeast Brazil (Espírito Santo Basin) to assess the spatial significance of internal unconformities within a contourite drift deposited on the base of a continental slope (Fig. 1). The interpreted data depict the internal geometry of confined contourite drifts. Confined drifts are characterized by presenting mounded or elongated shapes, two distinctive moats (or channels) along both margins, and are sparsely documented in the literature (Faugères *et al*. 1999). The interpreted seismic volume shows the distribution of erosive features in contourite systems to be of paramount importance to understanding the oceanographic conditions leading to the deposition of contourite drifts, but more equivocal (and varied) than previously interpreted. In spite of the oceanographic changes that occurred in the South Atlantic during the Late Neogene (Duarte & Viana 2007; Molina *et al.* 2010), the studied contourite drifts show no relevant unconformities in their axial region, with relevant stratigraphic unconformities on seismic data being confined to a region 3.75 km away (in average) from an observed moat and a submarine channel. This work also shows that erosional moats comprise regions of current

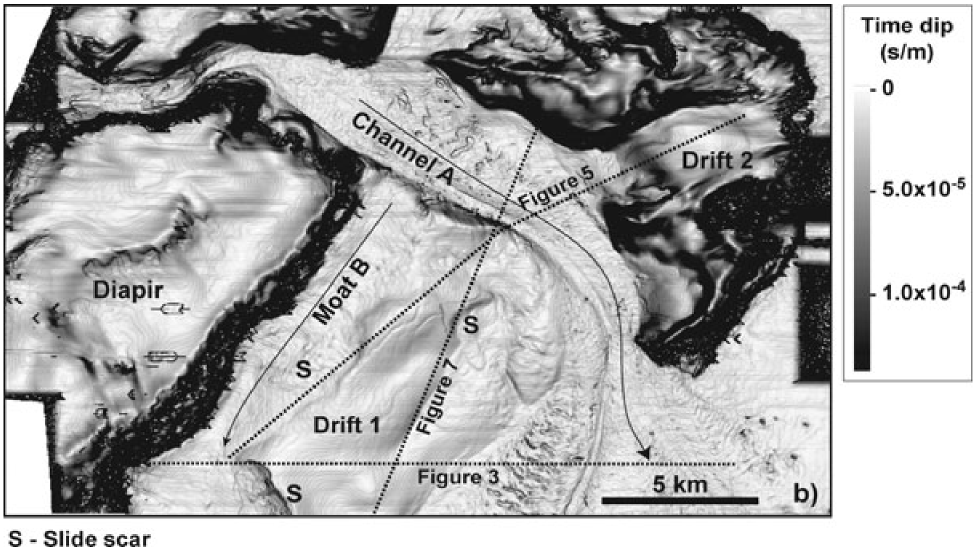

Figure 2. Dip map of seafloor in the study area showing principal topographic and depositional features. Drift 1 is located at the centre of the map. Drift 2 occurs towards the northeast corner of the study area.

winnowing and seafloor instability that may lead to the accumulation of relatively coarse-grained deposits, even towards axial regions of contourite drifts.

This paper starts with a presentation of the methods and data sets used, followed by a section on the geological setting of the study area. The Late Cenozoic hydrology of the Espírito Santo Basin is then summarized, prior to a principal section devoted to seismic stratigraphy and morphometric analyses. At the end of the paper are discussed the significance of 'regional' unconformities in contourite drifts, and a comparison with contourite systems on other continental margins is undertaken.

2 METHODS AND DATA

3-D seismic data from an area covering 791 km^2 of the continental slope of southeast Brazil (Espírito Santo Basin) are used in this work (Figs 1 and 2). The interpreted seismic volume has an inline spacing of 12.5 m and was acquired with a 6 × 5700 m array of streamers within a 12.5 m × 25 m bin grid. Data were sampled in intervals of 2 ms, for a nominal fold of 56. Data processing included resampling, amplitude recovery, time-variant filtering, and predictive deconvolutions, prior to stacking and 3-D pre-stack time migration using the full Kirchoff algorithm. Data from DSDP Sites 355/356 (Kumar *et al*. 1977) and 515 (Barker 1983; Barker *et al*. 1983) indicate *P*-wave velocities of 1.6 km s^{-1} for the studied interval. In parallel, vertical seismic resolution is of ∼20 m based on the signal frequency for the interval in question.

Main countourite drifts were identified, their tops and bases marked on seismic data, and their geometries compared with adjacent strata deposited by turbidite systems (Figs 2 and 3). For the purposes of this paper, three horizons of a Late Cenozoic contourite ridge were mapped in detail, Horizon 1 at the base of Drift 1, Horizon 2 in the interior of the same drift, and the seafloor reflection (Fig. 3). Attribute maps were computed in specific intervals and in between the mapped horizons. Later in this work, seismic data from a 3-D volume in the Rockall Trough (see Knutz & Cartwright 2003) are used to illustrate the diachronicity of unconformities in contourite ridges from other continental margins.

3 HYDROLOGIC SETTING

The hydrologic setting of southeast Brazil is characterized by the presence of several water masses, which are commonly grouped in four main currents. As the study area is located in depths between 2375 and 2860 m, it is within the area of influence of the Deep Brazil Current (Viana 2002). This current displaces South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW) at depths below 2000 m. Displacement of Antarctic Bottom Water (AABW) occurs below the Deep Brazil Current, that is, beyond 3000 m water depth (Duarte & Viana 2007).

Previously to this work, Viana (1998) and Viana & Faugères (1998) proposed a model for deep-water circulation in the Campos Basin over the last 50 000 yr, based on analysis of sedimentary and geochemical data from piston cores. The analysis of sediment texture and composition, sedimentary internal structures, isotopic data, biostratigraphic samples and 14C dating were, according to the authors, corroborated by C, O and Cd/Ca isotopic studies performed by Costa (2000).

Most of the continental slope of southeast Brazil records alternating north- and south-flowing deep-water currents in time (Viana 2002). During the Last Glacial Maximum (or maximum lowstand) between 24 and 13 kyr BP, the lower slope was temporally occupied by the southward extension of the Glacial North Atlantic Intermediate Water (GNAIW), a relatively nutrient-depleted, slow southward-flowing water. Near the Pleistocene/Holocene boundary (15–9.5 kyr BP) the GNAIW was replaced by a strong intermediate depth circulation, the upper Southern Ocean Water (SOW)/Antarctic Intermediate Water (AAIW). At the beginning of the Holocene, due to the ice melting in the northern hemisphere, the re-appearance of NADW is observed on the lower slope, below which pelagic marl of Holocene age is deposited. At the time, the southward intrusion of NADW limited the AAIW to the middle slope. Subsequent sea level rise during the Holocene is recorded by a shift in the core of the Brazil Current towards the upper slope, accompanied by a relative decrease in its intensity and by a regional (topographic) constriction of the flow against the base of the shelf edge. Both AAIW and NADW kept their position flowing respectively over the middle and lower slope (Viana 2002; Fig. 4).

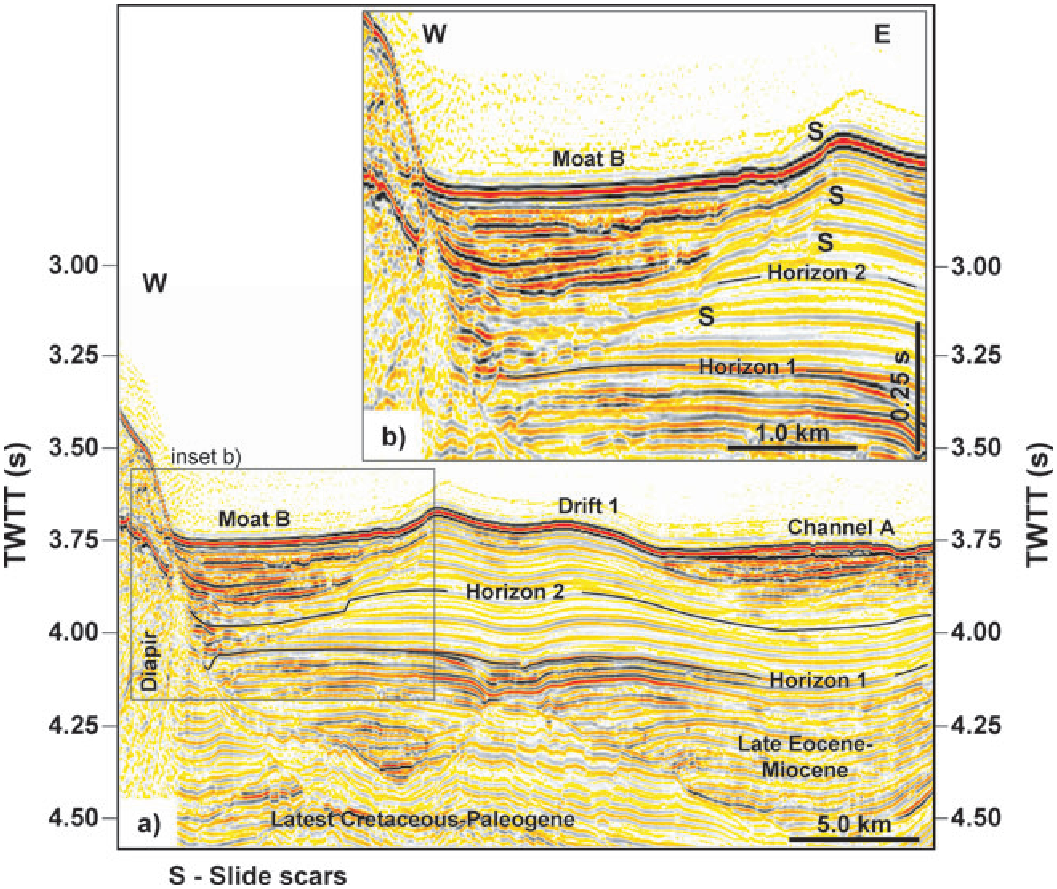

Figure 3. Selected seismic section showing the internal character of contourite drifts in the study area and the lateral extent of erosional unconformities within them. (a) East–west profile showing the morphology of Drift 1 and adjacent contourite Moat B and Channel A. (b) Inset of the seismic profile in (a) depicting Moat A and associated slide scars in detail.

Across-slope sediment transport is known to occur on the east-facing southeast Brazilian margin since the Early Cenozoic and, more markedly, within Upper Oligocene to Holocene channel systems (Viana *et al.* 2003; Moreira & Carminatti, 2004; Fig. 4). Some of these channel systems are known to have fed contourite drifts located on the distal part of mixed turbidite-contourite systems (i.e. below 2000 m water depth), showing multiple unconformities since the Early Miocene (Viana *et al.* 2003).

4 GEOLOGICAL SETTING

The study area is located at the base of the continental slope of the Espírito Santo Basin, within a region of salt diapirism related to a compressional domain. In this domain, post-salt units are compressed onto the continental rise in a complex process of gravitational collapse of the entire southeast Brazilian margin (Chang *et al.* 1992; Demercian *et al*. 1993; Mohriak *et al.* 2008; Fig. 1b). Seismic and stratigraphic evidence indicates that bottom currents deposited extensive contourite drifts through different climatic and oceanographic conditions, particularly during the Miocene and the Holocene (Silveira *et al*. 2000; Duarte & Viana 2007). Local tectonics was manifestly complex during the same time period, with widespread halokinesis deforming the continental slope significantly (Fiduk *et al*. 2004; Alves *et al*. 2009). Halokinetic movements on the southeast Brazilian margin have been related to thin-skinned extension due to gravitational gliding of post-salt strata over Aptian evaporites (Demercian *et al*. 1993). In the Espírito Santo Basin, significant salt deformation is primarily recorded in the Early Cenozoic, synchronously with the uplift of the proximal margin and the emplacement of the Abrolhos Bank (Fiduk *et al*. 2004; Fig. 1). However, halokinesis is shown to have peaked during the Late Cenozoic in most of the Espírito Santo Basin, particularly in its intermediate and distal continental slope (including the study area) where developed salt diapirs, allochthonous salt canopies and fairways occur and deform the seafloor (Fiduk *et al*. 2004; Figs 1b and 2). Topographic changes on the seafloor have also promoted variations in the geometry of contourite drifts in upper slope areas as recorded, for instance, in the Santos Drift System (Duarte & Viana 2007). These morphological changes in the slope were accompanied by variations in sea level during the Quaternary. Consequently, during the Holocene sea level highstand the weakening of the Brazil Current resulted in the deposition of muddy sand on the slope. Furrows, longitudinal scours and related bedforms were locally developed on the uppermost slope as a response to local variation in sediment texture and bottom current intensity (Viana 2002). The middle and lower slope sedimentation are respectively marked by the firmground and the pelagic marl.

5 SEISMIC STRATIGRAPHY OF INTERPRETED DEPOSITIONAL SYSTEMS

On the Brazilian margin, contourite units comprise transparent, mostly wavy deposits marked by laterally migrating packages and

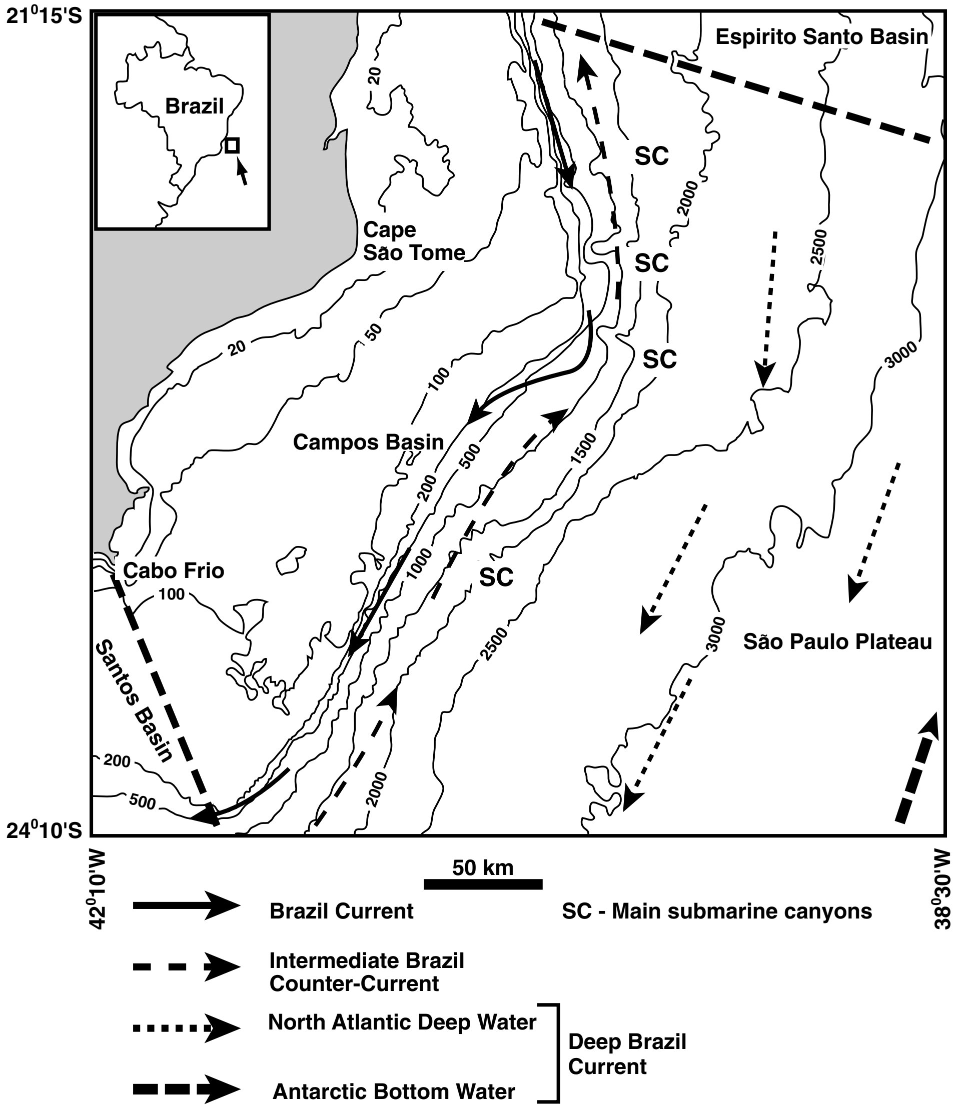

Figure 4. Regional map of the southeast Brazilian margin showing the circulation paths of modern contourite currents. Modified from Viana (2002).

wavy relief on the seafloor (Viana *et al.* 2003; Rebesco *et al.* 2007). Based in the stratigraphic frameworks of Viana *et al*. (2003) and Fiduk *et al*.(2004), we interpret three main seismic units in the study area:

5.1 Late Cretaceous–Palaeogene

Late Cretaceous to Palaeogene strata show low- to moderate-amplitude reflections significantly deformed by narrowly spaced normal faults (Fig. 3). The thickness of the unit varies from less than 0.25–1.5 s twt in the interpreted block. Stratigraphic data from Fiduk *et al*. 2004) indicates the unit as comprising Cretaceous carbonate units and distal slope deposits.

5.2 Late Eocene–Miocene

The Late Eocene to Miocene is characterized by the extensive deposition of mass-transport and channel deposits (Fiduk *et al*. 2004; Alves *et al*. 2009). In the study area, it comprises chaotic to subparallel internal reflections of high to moderate amplitude. A wavy erosional base occurs on its base, onto which onlap is visible (Fig. 3). The thickness of the unit varies from less than 0.1 to 0.7 s twt in the study area (Figs 3 and 5).

5.3 Pliocene–Quaternary

Strata interpreted as representing the Pliocene–Quaternary include, in the study area, alternating channel-fill deposits and accumulated sediment drifts (Figs 3 and 5). Low-amplitude strata are interpreted to comprise contourite drifts. Chaotic to high-amplitude reflections with poor continuity comprise channel and moat-fill deposits. An erosional unconformity onto which onlap is observed marks the base of the unit (Fig. 5). Its thickness varies from 0.25 to 0.75 s twt.

6 SEISMIC MAPPING

6.1 Basal unconformity (Horizon 1)

The unconformities that occur within the studied contourite drift are illustrated in Figs 3 and 5. The oldest unconformity, Horizon 1,

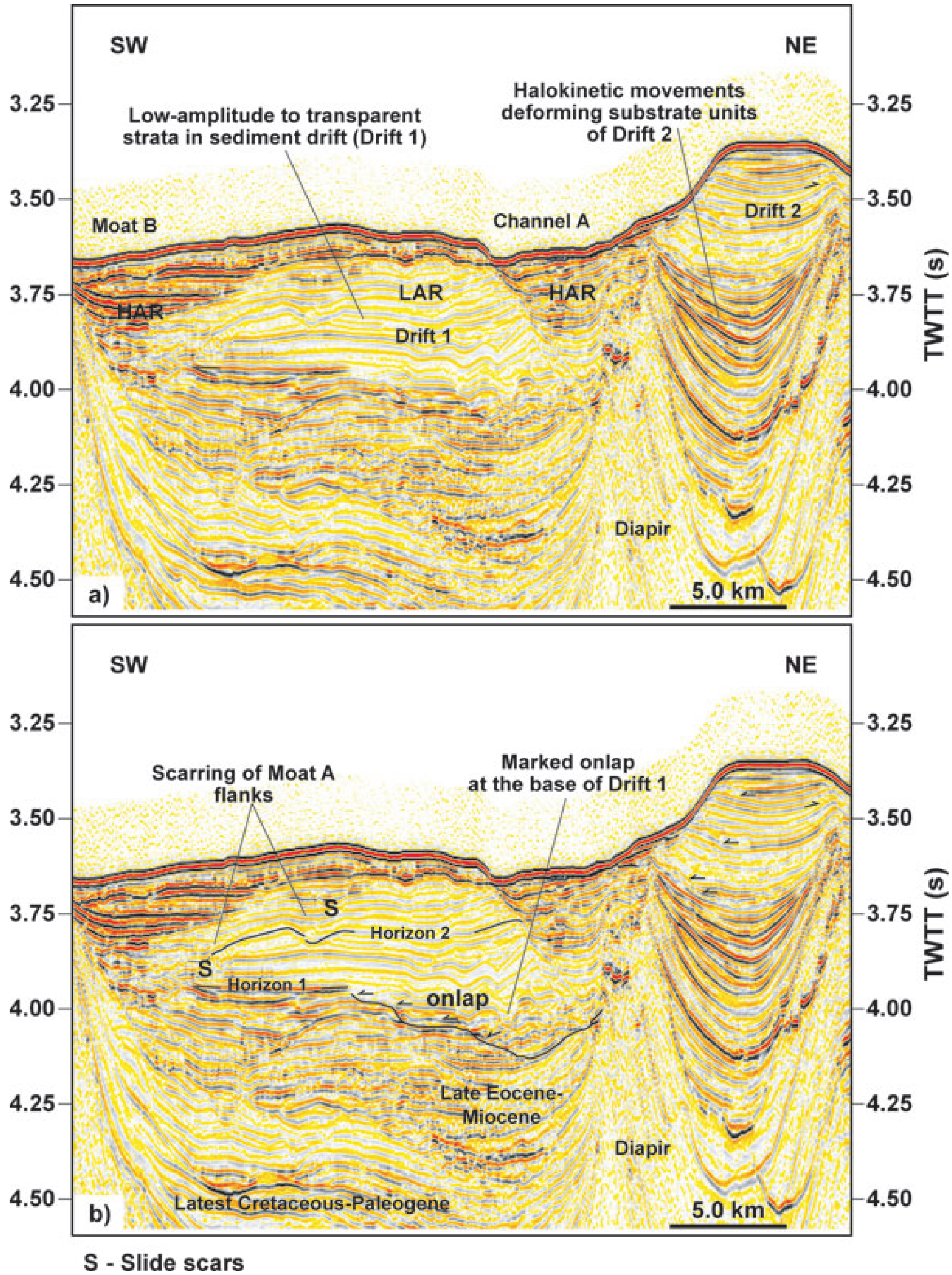

Figure 5. Internal geometries of Drift 1 (confined drift) and Drift 2 (detached drift). Note the marked onlap on an irregular basal unconformity in Drift 1. Location of the seismic sections in Fig. 2.

marks the base of Drift 1, which shows marked by onlap of the overlying reflections in the drift. The horizon also marks a change from continuous, low-amplitude reflectors within the studied contourite drift to discontinuous strata in the Late Eocene–Miocene unit. At places, Horizon 1 expresses an angular unconformity marked by truncation of underlying southeasterly dipping reflectors (Fig. 5).

The morphology of Horizon 1 is shown in Fig. 6, where a rms amplitude map of the horizon is compared with twt structure and isochron data. The rms amplitude map in the area of the 3-D seismic survey reveals a surface marked by polygonal faulting (Fig. 6c). A continuous succession of low-amplitude reflections occurs on top of Horizon 1 until a second irregular surface (Horizon 2) showing marked erosion towards the borders of Drift 1, is observed (Figs 3 and 5). Above Horizon 2, sectors marked by slumping and local erosion are observed on seismic data (Fig. 7). The slumped zones correspond to local instabilities on the flanks of the interpreted sediment Drift 1. Towards the adjacent contourite moat and channel, secondary onlap onto the flanks of the sediment drift occurs towards the seafloor.

6.2 Drift geometry

The studied Drift 1 is shown as a northeast–southwest oriented feature, presenting low- to moderate-amplitude internal reflections thickening towards the axis of the drift (Fig. 6b). Typically, two erosional channels flank the contourite drift to the east and west.

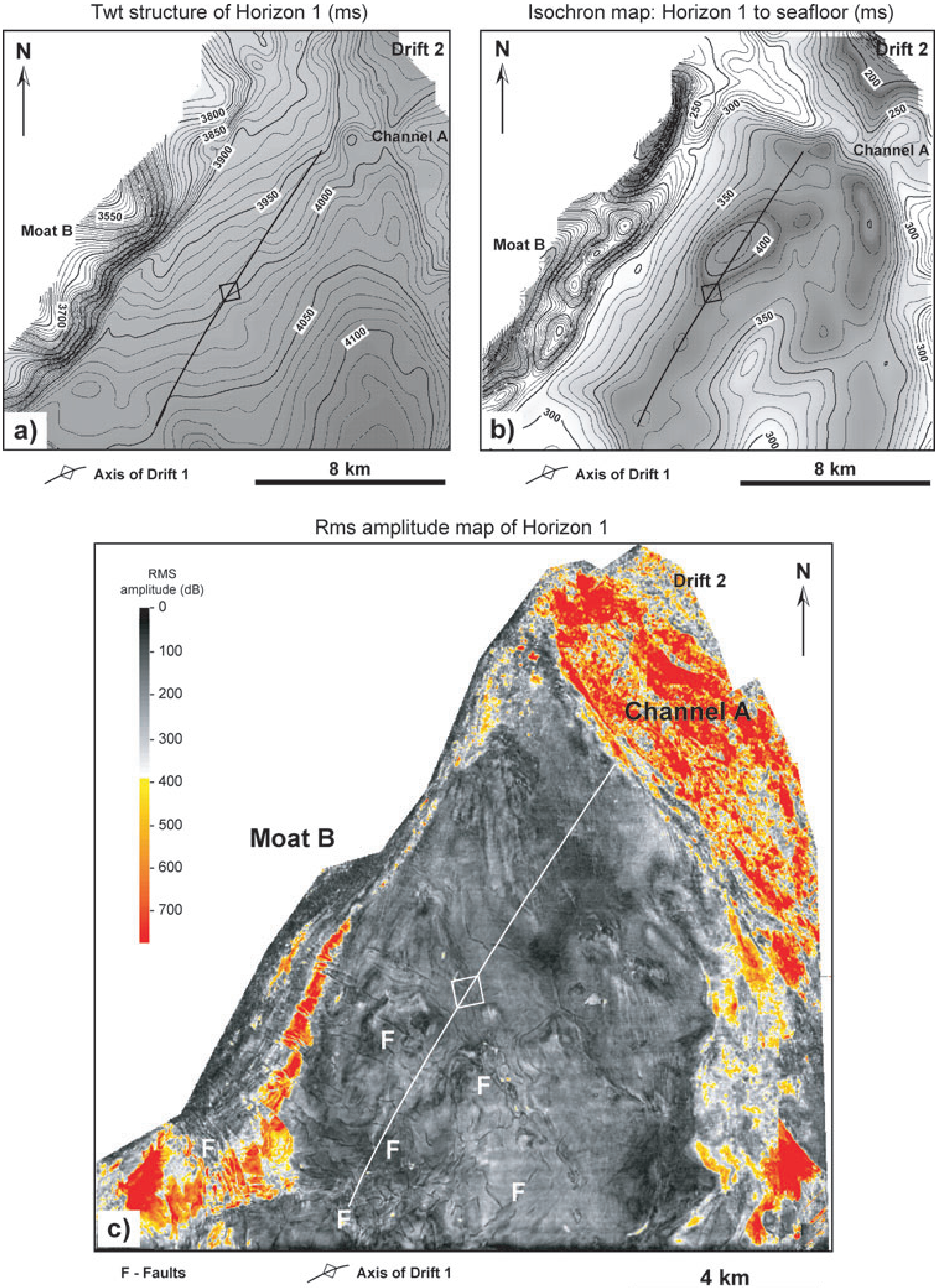

Figure 6. Selected two-way time structure, isochron and rms amplitude maps from Horizons 1 and 2. (a) Twt structure map of Horizon 1, highlighting the regional southeastern tilt of Horizon 1. (b) Isochron map of strata between Horizon 1 and the seafloor, underlining the constructive (i.e. relatively thicker) nature of strata within Drift 1. (c) Rms amplitude map of Horizon 1 showing the location of vertically propagated faults intersecting the base of Drift 1. Values in (a) and (b) in milliseconds.

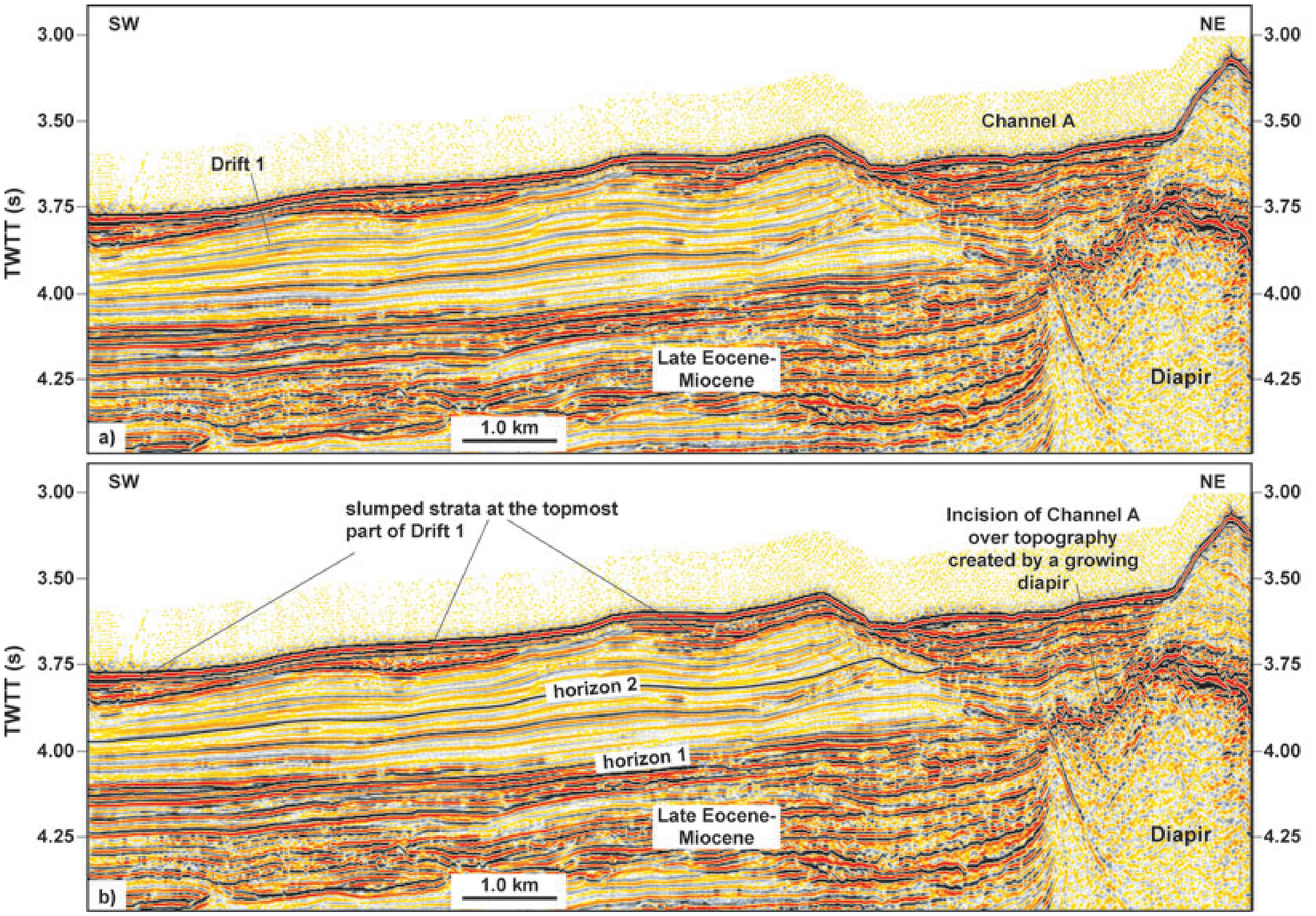

Figure 7. Seismic profile depicting the morphology of slumped strata on the top of Drift 1. These are commonly shown as regions with higher amplitude and number of zero crossings on attribute maps (see Figs 8 and 10). See Fig. 2 for location of the seismic profile.

Based on the isochron data shown in Fig. 6(b), the studied contourite drift shows uniform axial growth above Horizon 1, with the flanking Channel A and Moat B occurring in the study area since the onset of drift deposition. The geometry of the subcropping units, truncated by the studied contourite drift, shows very mild southeast tilting, which was essentially complete by the time of initiation of Drift 1 (Fig. 6a). Minor faulting occurs towards the southwest, suggestively in association to the vertical propagation of older fault families (Fig. 6c).

In contrast, Drift 2 comprises an isolated (mounded) drift *sensu* Faugères *et al*. (1999) confined by a salt ridge (Figs 2 and 5). This isolated drift is not faulted but shows moderate deformation at this base, likely related to the growth of salt diapirs at depth (Fig. 5).

6.3 Erosional features (slump scars, channels and moats)

The submarine channel and moat occurring in the study area show irregular truncation surfaces at their base and, overall, a V-shaped geometry of incision into the underlying strata (Figs 5 and 7). This erosional event, leading to the formation of the two erosional features, is interpreted to have be synchronous with the onset of deposition within Drift 1 and continued until the present-day.

7 MORPHOMETRIC ANALYSIS

Figs 3 and 5 illustrate the internal character of the two interpreted contourite ridges. Drift strata are shown as mounded sediment ridges with low- to moderate-amplitude reflections (Fig. 3). The bulk of the observed contourite drift is composed of low-amplitude, continuous subparallel reflections showing little evidence of erosion. However, erosional surfaces are only locally visible in the entire study area. Also, a significant amount of internal reflections continue uninterruptedly into adjacent erosional moats and channels (Fig. 3). Irregular reflections and local erosional surfaces are observed in regions adjacent to Moat B (Fig. 2). Considering the dip-map in Figs 2 and 8, these erosional surfaces are related to the presence of small slides on the flanks of the growing contourite drift. Underneath the erosional moats and areas of seafloor instability—marked by slide scars on dip-maps—high-amplitude reflection (HAR) contrast with the bulk of strata in the contourite drift, comprising low-amplitude deposits (LAR).

The units interpreted in this paper do not show marked v-shaped erosion within adjacent contourite channels and moats (Fig. 3a). In addition, there is (i) a marked lateral continuity of internal reflections within the imaged contourite drift, (ii) a uniform reflection pattern in axial parts of the drift, characters contrasting with the uncontinuous gull-wing geometry of channel-levee deposits (Rebesco *et al.* 2007). Correlations between the seismic stratigraphic units in Fiduk *et al*. (2004) and Alves *et al*. (2009) indicate a probable (and diachronous) latest Oligocene/early Miocene age for the basal strata in the imaged contourite drift (surface R1 of Viana *et al.* 2003).

Comparisons among the interpreted seismic data an 2-D seismic data from Akhmetzhanov *et al*. (2007), and the depositional models of Viana *et al*. (2007) suggest that: (1) LARs essentially

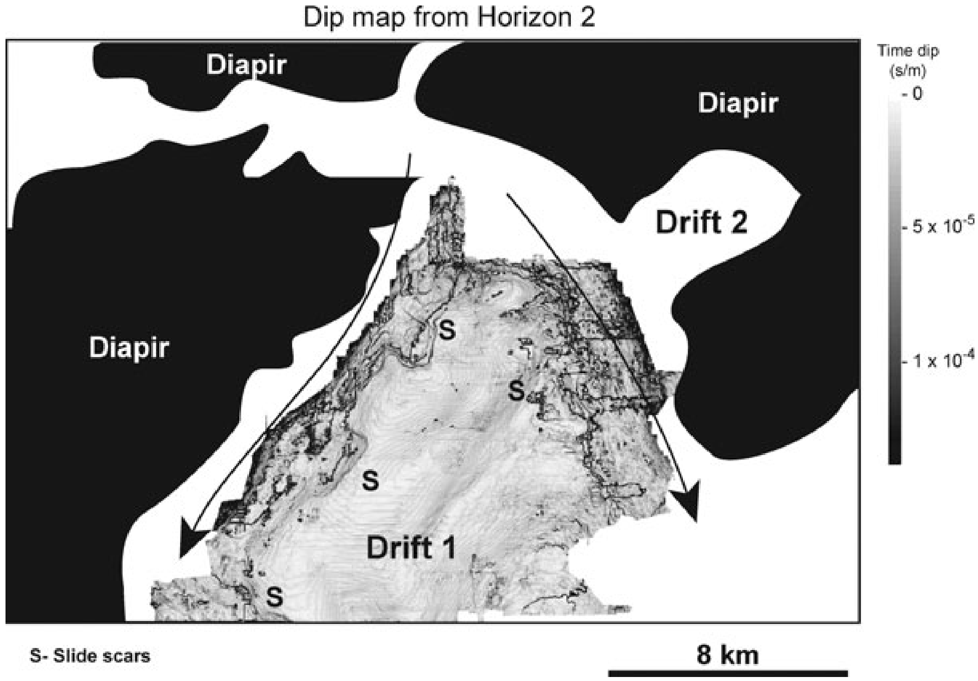

Figure 8. Dip map showing the relative location of erosional features (slide scars, moats, contourite channels) in Horizon 2. Note that the persistence in time of slide scars on strata flanking Moat B and Channel A, as modern features also show marked erosion in these latter regions.

represent concordant mud-rich strata intercalated with minor sandy/silty deposits in axial regions to the contourite drift; (2) HARs represent coarser-grained strata deposited within erosional channel and moats. Chaotic reflections are locally associated with slide scars, thus indicating the existence of interbedded slide deposits within the contourite drift. Attribute data shows high-amplitude reflections within the observed erosional features to extend laterally into the contourite ridges with no significantly change in reflection geometry or continuity (Fig. 3). In contrast, significant erosion on the margin of the moats is shown by vertically stacked irregular surfaces and erosional truncation of seafloor strata.

8 QUANTIFICATION OF SEISMIC ATTRIBUTE DATA

Principal diagnostic parameters were used in the quantification of seismic attribute data: (i) lateral continuity of HAR in adjacent areas to main channels and moats, (ii) the number of zero crossings within the contourite drift (a proxy for reflection frequency) (Brown 1999), (iii) energy half-time for the interval corresponding to Drift 1 (Figs 5 and 9). Rms (root-mean square) amplitude data provides an approximation to reflection strength. Rms amplitude tends to be more effective than absolute amplitude because the high amplitudes are boosted by the squaring (Brown 1999). Maps showing the number of zero crossings indicates how many zero crossings occur between two mapped horizons, thus indicating layering and the presence of hard continuous strata, normally sands or carbonates (Brown 1999). Energy-half time computes the time required for the energy contained within a time interval to reach one half of the total energy contained within the entire interval. As energy half-time values are from 1 to 100, a window of 100 ms in length, with half of the energy dispersed in the first 10 ms, will present a value of 10 (Brown 1999). Several studies concluded on the direct relationship between the presence of sandier deposits in depth and the number of zero crossings and energy half-time (Brown 1999).

Channel A located towards the east of the principal sediment drift comprises an east–southeast striking submarine channel. Moat B occurs towards the west of the drift. Both are bounded by growing halokinetic structures (Diapir 1 and 2). In Fig. 9(b) is shown the regional distribution of number of zero crossings, which correlate well with presence of HARs in the contourite system. Most of these HARs are located in regions of slumping and erosion on the flanks of Drift 1, as shown on the dip map of Fig. 9. Notably, in Fig. 10 are plotted the values showing how laterally extensive are HARs in relation to the axes of principal erosional features, that is, the maximum distance to the axes of erosional features one can expect the occurrence of sandy material. The data collected from rms amplitude maps at the seafloor, 75 ms below the seafloor and 200 ms below the seafloor show the extension of HAR to range from 1.9 to 7.0 km away from the axes of Channel A and Moat B. Significantly, average values approach 3.75 km for both Channel A and Moat B (Fig. 10a).

9 DISCUSSION

9.1 Reassessment of 'regional' unconformities in contourite drifts

A key character of the investigated contourite drifts is that the nature and morphology of the mapped erosional surfaces contrast sharply with the unconformities documented in most contourite drifts (e.g. Maldonado *et al.* 2005; Llave *et al*, 2006; Koenitz *et al*. 2008). In fact, a principal unconformity is only observed at the base of the imaged contourite drift (Horizon 1, Fig. 7). This latter observation has significant implications to the current depositional models for contourite deposits, which essentially consider the existence of regional margin-scale unconformities in most drifts. These unconformities are interpreted as reflecting major shifts in oceanographic conditions, and current direction, through time (Maldonado *et al.* 2005; Koenitz *et al*. 2008). The interpreted 3-D volume shows that

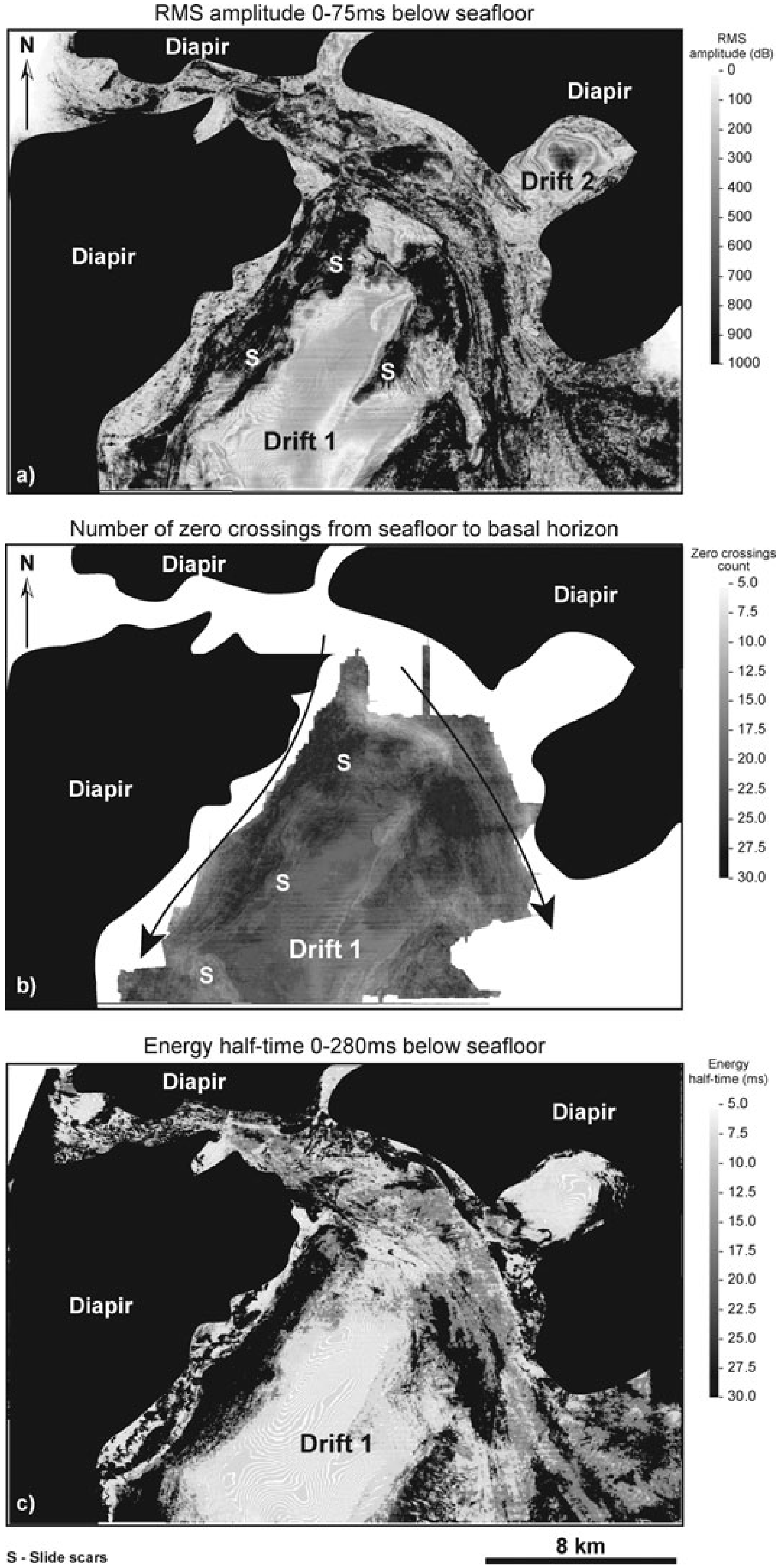

Figure 9. Relevant attribute data from Drifts 1 and 2. (a) Rms Amplitude data from an interval 0–75 ms below the seafloor. (b) Number of zero crossings between the base of the contourite and the seafloor, highlighting the location of continuous high-amplitude strata (i.e. with higher number of zero crossings) in Drift 1. (c) Energy-half time data for the interval 0–280 ms below the seafloor. Compare with Figs 8 and 9(a).

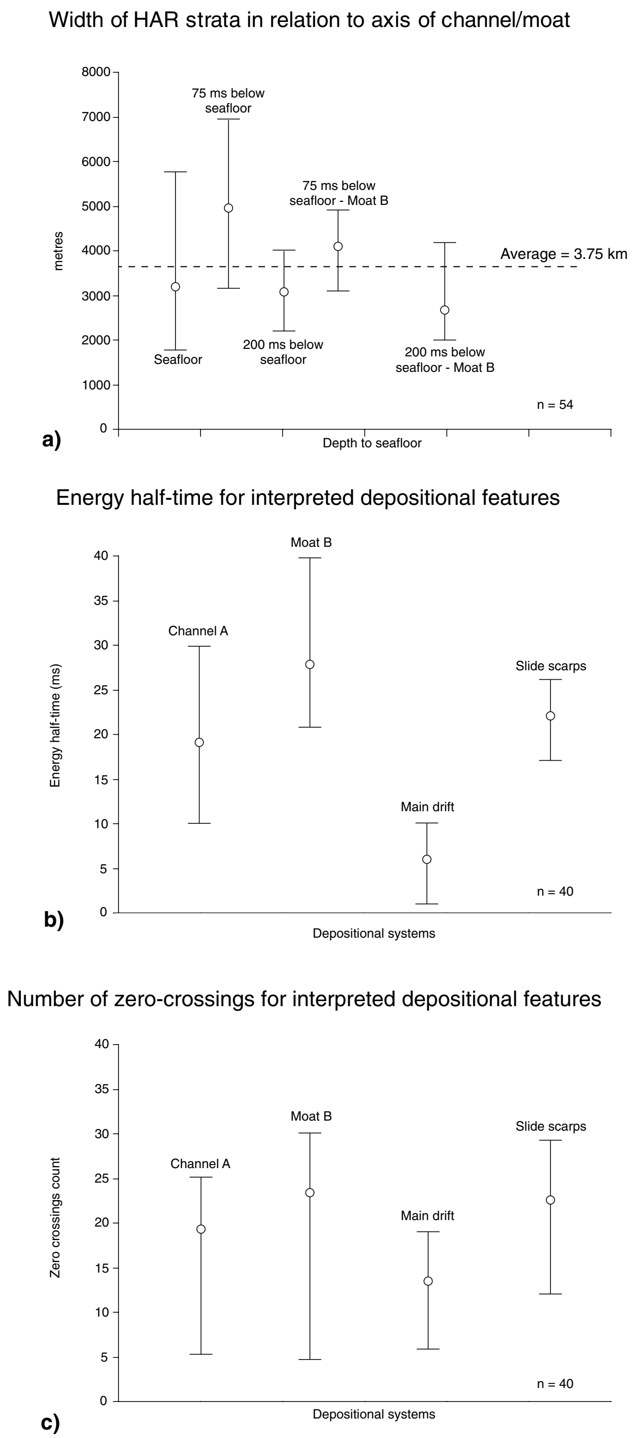

Figure 10. Graphs showing the (a) lateral extension of erosional unconformities for specific intervals in Drift 1. (b) Energy-half time values for depositional/erosional features in Drift 1. (c) Distribution of zero-crossings for specific depositional/erosional features in Drift 1.

(multiple) unconformities can be pervasive within contourite drifts deposited on the continental slope, thus with the potential to hinder regional drift-to-drift correlations on a basin scale. In addition, the basal unconformity (Horizon 1) in the study area is markedly diachronous (Fig. 7). As a comparison, drifts of similar age in the Santos Basin (Santos Drift) show at least six main Miocene-Pliocene internal unconformities separating distinct sequences (Duarte & Viana 2007).

The interpreted 3-D seismic volume points out to instability processes on the seafloor as one of the principal factor controlling the morphology and internal character of contourite drifts. Instability processes are specifically implied in the local degradation of drift deposits and in the generation of local depositional hiatuses not entirely equivalent to strata within the contourite drift (Figs 3 and 5). As a result, internal unconformities in the studied contourite drift are only significant in a region approximately 3.75 km distant from the axes of the principal channel/moats. There is no significant onlap of channel-fill deposits onto such slide scars which, in turn, seemed to recur in time as the contourite drift accumulated (Fig. 7).

Considering that most of sediment drifts on continental margins are accumulated in regions adjacent to topographic features, as a response to a loss in sediment-transport capacity of contour currents when passing though topographic barriers on the slope (Faugères *et al*. 1999) it is suggested, based on the interpreted seismic survey, that a significant portion of interpreted 'regional' unconformities within contourite drifts can be related to episodic shifts in current velocity and location or, instead, to evolving seafloor topography in tectonically active areas. However, as contourite channels/moats comprise the locus of seafloor erosion and instability, localized erosion of drift strata is a common event on the flanks of developing drifts, thus generating stratigraphic hiatuses not related to significant interruptions or changes in current flow. In parallel, progradation and buildup of distinct contourite drifts in specific parts of the margin can wrongly lead to regional correlations of otherwise diachronous surfaces. In essence, the observed channel and moat are shown as depositional areas mostly comprising lower net-to-gross ratios, with active seafloor destabilization contributing to sediment redistribution. Consequently, attribute and dip data in Figs 8 and 9 permit the distinction of three main zones in the contourite drift: (i) erosional moats and channels, comprising up to 300 ms of HARs, potentially comprising low net-to-gross ratios of sediment, (ii) an instability front on the flanks of the growing sediment drift, which comprises mass-HARs (low net-to-gross) strata and (iii) a central region where LARs and vertical aggradation of sediment prevails (Fig. 11).

9.2 Comparison with giant open-sea contourite drifts

An important conclusion of this paper relates to the recognition of the lateral extent of HARs (sand/silty) strata within contourite drifts deposited on the continental slope. Various sediment sources must be considered when explaining the accumulation of contourite drifts: (i) pelagic-hemipelagic (which come from multiple sources) turbidity currents from adjacent slopes, and bottom currents with local erosion and longer-distance transport, (ii) stratified nepheloid layers in regions of high organic productivity, in with sediment entrained in the nepheloid layers is deposited by currents decelerated by isolated obstacles (Stow *et al.* 2008). These sediment sources can accumulate coarse-grained sediment in sediment drifts that are, in principle, accumulating finer particles (Masson *et al.* 2010). The larger part of sediment being transported into the study area uses submarine channels and canyons dominated by turbidity currents. Also, slope instability comprises an important erosional process acting on a moving topography, controlled by halokinetic movements at depth. Consequently the interpreted seismic survey reveals that a considerable part of channel strata is composed by mass-wasted material distinctly reworked by bottom currents, but that aggradation

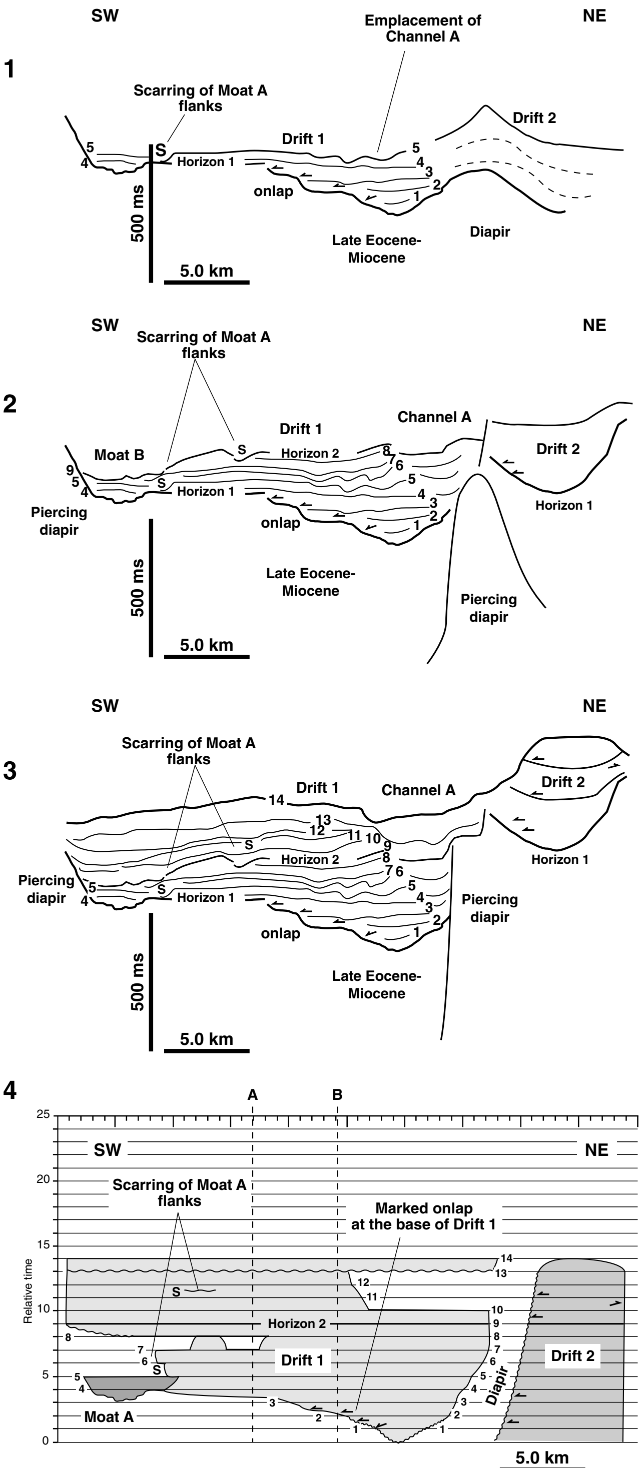

Figure 11. Diagrams illustrating the structural evolution of the study area, based on seismic profile in Figure 5. Diagram 1–3 represent the principal evolution phases of the interpreted contourite drifts 1 and 2. Diagram 4 indicates the corresponding Wheeler diagram (Wheeler 1964) for the seismic the Brazilian continental slope. Points A and B indicate two of the sites where most of the contourite drift 1 can be drilled. However, the basal portion of Drift 1 is missed due to the diachronous nature of it base (Horizon 1).

of sediment occurs in the channel axis in parallel with the core of contourite drifts (Figs 3 and 11). This also contrast with the location of coarse-grained sediment in the Rockall Trough and Southwest Iberia (Akhmetzhanov *et al*. 2007), known to occur in axial regions of contourite channels.

Large mounded drifts have been described in deep-water regions such as Antarctica (Maldonado *et al.* 2005, 2006; Koenitz *et al*. 2008), the Greenland margin (Arthur *et al*. 1989; Hunter *et al*. 2007), the Indian Ocean (Schlüter & Uenzelmann-Neben, 2007, 2008). On the Argentine abyssal plain, at least three large-scale drifts (Zapiola, Argyro and Ewing) have been identified at the present seafloor (Ewing & Lonardi 1971; Flood & Shor 1988). In the same region, Molina *et al*. (2010) recognized the importance of giant mounded fields in abyssal areas to the recognition of variations in the flow regimes of the North Atlantic Deep Water and Antarctic Bottom Water. The latter authors consider mounded drifts in open, deep marine environments to differ from those in continental slopes, in which the core current migration is not confined by the slope physiography, and therefore, there is no resulting erosion of sediment and drift construction on the opposite side (e.g. Llave *et al*. 2001, 2007; Carter & McCave 2002; Stow *et al.* 2002b; Carter *et al.* 2004; Maldonado *et al.* 2005), similarly to examples in the North Rockall Trough (Knutz & Cartwright 2003) and in the Campos Basin (Viana *et al.* 2003; 2007).

In contrast to open-sea conditions, the formation of contourite drifts on continental margins is specifically related to the existence of focused sediment sources, which are then deviated along the pathway of deep oceanic boundary currents (Faugères *et al*. 1999). The scale of these large open-sea contourite drifts is of several hundreds of kilometres, contrasting sharply with the few dozens of kilometres in drift length observed in the study area. The external morphology of open-sea drifts as such offshore Argentina is characterized by a steep sides and a gently dipping, smooth aggrading side with prograding reflections (Molina *et al.* 2010). This asymmetric morphology was generated by erosion of the steep side by periodic, invigorated, bottom-water currents, and its interpretation with important regional implications in palaeocurrent reconstructions. Therefore, the accumulation of fine-grained sediments occurs preferentially along the edge of the flow axis as a result of reduced shear stress within the benthic boundary layer. Abrupt shifts from erosion/non-deposition to rapid sediment accumulation observed on seismic data require a decrease in bottom water flow speed accompanied by an increase in sediment supply (Knutz & Cartwright 2003). Also, density gradients between different water masses are also crucial to variations in shear stress.

In the Weddel Sea, combined turbidite-contourite levees involved distinct processes also recorded in the study area (Michels *et al.* 2001). Sediment suspensions were generated on the shelf or the upper continental slope by turbidity currents and moved gravitationally down the continental slope, where they were rapidly channellized in a system of channels and gullies. Both turbidity currents and adjacent water plumes had the ability to entrain sediment and erode along the channel thalweg, depending on the density contrast with surrounding water masses. Sedimentation rates were different in the Weddel Sea during late Quaternary glacial and interglacial periods. The last glacial shows sedimentation rates up to 30 times higher than during the Holocene (e.g. Weber *et al.* 1994), because the sea level was significantly lower and the grounding line of the Antarctic ice sheet in the southernmost Weddell Sea was located at the shelf edge so that glacial debris was directly discharged to the slope (Grobe & Mackensen 1992; Anderson & Shipp, 2001).

No such processes have been recorded on the subtropical southeast Brazilian margin. However, slope plastered sand sheets occur in upper slope regions, elongated along the slope topography and characterized by high amplitude seismic reflections (Viana 2002). Contourite drifts are themselves fed by submarine channels crossing the upper and middle slope regions. Offshore Brazil, the action of contour currents can also overcome the importance of gravity currents where continental supply is reduced.

Based on the interpreted 3-D seismic volume, it is suggested as diagnostic features in contourite channel-drift systems on continental slopes: (i) scarce (or even absent) onlap ot channel-fill strata onto marginal deposits; (ii) the presence of aggrading drift successions at the centre of the drift; (iii) marked instability of drift strata in adjacent areas to the contourite channel/moat, with this latter area of instability essentially marking the limit of coarse-grained strata in the system. This setting contrasts with the aggrading nature of (turbidite) channel levees—known to redistribute sand through large areas of the seafloor—or the v-shaped erosion of seafloor strata by turbidite canyons. Therefore, preferential areas for drilling comprise axial areas of contourite drifts, where sedimentation is evidently more continuous (Fig. 3). However, these same areas are not guaranteed as the regions where the oldest drift strata occurs, as illustrated in Fig. 11, a character that promotes the necessity of selecting different drilling sites according to its objective, either by: (i) sampling of the drift-onset deposits, or (ii) documenting stratigraphic variations within the contourite drift.

10 CONCLUSIONS

A confined contourite system was investigated using 3-D seismic data, thus allowing the investigation of the principal depositional processes controlling its accumulation.

The existence of multiple unconformities within active contourite drifts was investigated and, in contrast to the published literature, the 3-D-seismic analysis undertaken in this paper reveals that erosion is limited to an average distance of 3.75 km away from erosional channels or moats. Erosional moats and channels are shown as areas of sediment accumulation, although in a smaller degree than central parts of the drift, with stacked strata often interfingering with strata within the drift. In contrast to submarine channels, no sediment levees are observed in contourite channels.

These latter characteristics can hinder regional correlations based on single-site core data collected in individual drifts. Moreover, site-specific well data can lead to significant errors when estimating major changes in the dynamics of principal geostrophic currents. This poses problems when selecting drilling sites on continental slopes, as the regions where internal stratigraphic unconformities occur may (i) only document local erosional events; (ii) be away from drift-onset regions on the margin and (iii) be influenced by local variations in current regime, particularly in tectonically active parts of the continental slope.

ACKNOWLEDGMENTS

The authors thank permission conceded by CGG-Veritas to publish this work. T. Mulder and three anonymous reviewers are thanked for their comments on a previous draft of this work.

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