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The economic importance of contourites

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Abstract: The importance of contour currents in shaping and building continental margins has long been accepted. Their economic implications and the stratigraphic framework in which they are developed remain largely unknown. Data retrieved from sidescan sonar images, seismic profiles and their attribute maps, as well as sea-floor coring, boreholes and the few known outcrops around the world, suggest that bottom currents can locally develop large deposits of relatively coarse-grained sediments. Accumulation of coarse-grained deposits under the influence of bottom currents requires sediment availability, a geologically persistent strong circulation regime and a favourable physiographic setting both for enhancing the currents and for hosting the sediments. The hydrocarbon exploration of oceanic depositional systems demands a better understanding of the role of bottom currents and their implications for petroleum systems such as reservoir and sealing rocks. Such understanding implies additional alternatives for the definition of exploration targets and prospect risk reduction. Correlating seismic anomalies from 3D mapping with core and well logging data reveals the depositional geometry and sedimentological characteristics of coarse-grained contourites. Fine-grained drifts can locally and regionally develop large and thick accumulations, which have an important seal potential for trapping hydrocarbon.

Recent decades have been marked by an increasing number of publications on the recognition and characterization of contourite systems. The great majority of these systems were recognized through high-resolution 2D seismic data locally complemented by sea-floor coring and drilling. Despite the controversy surrounding their lithological characterization, modern contourites have been identified in almost all oceans around the world, and also in confined seas and lakes (see references given by Faugères & Stow 1993; Faugères *et al.* 1993, 1999; Stow & Faugères 1998; Stow *et al.* 2002; and, for lacustrine drifts, Johnson *et al.* 1980; Johnson 1996; Ceramicola *et al.* 2001; Gilli *et al.* 2005).

The difficulties in determining reliable facies characteristics of the interaction between oceanic bottom circulation and sedimentary processes (Viana *et al.* 1998; Stow *et al.* 1998), besides the controversies related to the palaeoceanographic–stratigraphic control on the intensity of thermohaline currents, and to the poorly known economic applications of contourites, relegated these deposits to a secondary rank of interest in the spectrum of deep-sea sediments. The accumulation of oil reserves found in turbidite reservoirs has driven most of the attention of deep-water research, leading to the evolution of facies model concepts (Normark 1970, 1978; Bouma *et al.* 1985; Mutti & Normark 1987, 1991; Normark & Piper 1991; Mutti 1992; Mutti *et al.* 1999, 2003; Piper & Normark 2001), supported by industrial 3D seismic data, well logging, imaging and coring, and corroborated by outcrop field studies. However, contourites not associated with oil-bearing reservoirs have remained a subject of more academic studies, based on traditional shallow penetration high-resolution seismic 2D data and sea-floor piston coring.

The development of swath bathymetry and the widespread utilization of 3D seismic data, which are being gradually transferred to academic centres, provides a wider understanding of the geometry of contourite deposits, related bedforms and possible relationship with coarse-grained accumulations. Nevertheless, these systems are still perceived as a controversial deep-water deposit, where the tractive effects of gravity- or density-driven turbulent flows are the preferred option for explaining the construction of some sedimentary records, which could also be the product of contour currents. Stow *et al.* (1998) presented a discussion on fossil contourites stressing the point that several deep-water deposits described in the literature as contourites could be better considered as fine-grained turbidites. Those workers presented a series of criteria that would help to clarify contourites preserved in the rock record. These criteria have been widely applied, and some outcropping contourites described using such criteria were presented in the Geological Society Memoir on contourites edited by Stow *et al.* (2002).

In the late 1970s to early 1980s, influenced by the suggestion made by Mutti *et al.* (1980) that some rippled, top-truncated, medium- to fine-grained sand-rich oil-bearing horizons of Eocene age in

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the Campos Basin could constitute contourite sands, the interpretation of other similar deposits, mostly in Oligocene–Miocene age, deep-water sediments, became more frequent in the Campos Basin. Contourite reservoirs are also suggested as occurring in the North Sea (Enjorlas *et al.* 1986). Nevertheless, the recognition of such deposits remains controversial, mostly because of the lack of unequivocal criteria. After that period, concomitantly with the increasing number of fine-grained contourite systems identified in several deep-water settings (see Faugères *et al.* 1999, for references), the attention given to contourite deposits as potential reservoirs remained low.

During the 1990s, papers by Shanmugam *et al.* (1993), Stanley (1993) and Stow *et al.* (1998) tried to redeem the importance of sandy contourites as potential hydrocarbon reservoir rocks. The recognition of palaeoceanographic–climatic changes recorded by contourite rocks was also identified as a crucial application for contourite studies (Faugères & Stow 1993; Robinson & McCave 1994). The continuous expansion of petroleum exploration towards deeper water is responsible for introducing some important new aspects in the study of contourites: the analysis of slope stability areas subjected to strong contour currents and the development of thick fine-grained deposits acting as local to basin-wide sealing rocks.

This paper proposes a broad discussion on the economic implications resulting from the occurrence of contourites in the sedimentary record. We focus on two main aspects: (1) the possibilities of contourites playing an important economic role; (2) contourites acting as reservoirs and seals.

Major implications of contourite studies

The recognition of contourite deposits implies that bottom currents were active and responsible for the accumulation of sediments. The coarser the sediments involved in the deposit, the stronger should be the currents; the thicker the deposit, the longer the current activity. Thus, strong and long-lasting bottom currents ($>10^2$ years) are fundamental requirements for the development of such deposits, as much as the availability of coarse-grained sediments that could be subjected to the impact of such currents. Their occurrence is linked to particular conditions of ocean circulation, which are directly related to climate characteristics, and their interaction with local margin physiography and sediment availability (Faugères & Stow 1993; Hollister 1993; Stow *et al.* 1998, 2002; Viana *et al.* 1998).

Coarse- to fine-grained sediments, along with sea-floor erosion, are common features in contourite accumulations, independently of water depth. Deep-water coarse-grained deposits have long been considered as important hydrocarbon reservoirs, and are generally considered to be the result of various types of gravity flows. Occasionally, coarse-grained contourites can also present the required characteristics for a potential oil-bearing reservoir, such as extent, porosity and permeability. To simplify the contourite concept application, it is herein proposed that the qualifying terms 'shallow-', 'mid-' and 'deep-water' contourites formerly proposed by Viana *et al.* (1998) should be applied only when an unequivocal bathymetric setting is identified and when such a setting is fundamental in characterizing the deposit. In our understanding, contourites are sedimentary deposits resulting from the action of oceanic bottom currents or mostly influenced by them. The qualifying term 'shallow-water' contourite implies that they occur in water settings where the influence of currents derived from storms, tides and trade winds can be recognized in a minor proportion related to the dominant geostrophic surface slope boundary currents. Shallow-water contourites should be considered as part of a large spectrum of rocks that accumulated from the shelf edge to the upper slope setting under the predominant action of surface slope boundary currents. Nevertheless, situations where the downwelling of dense (saline or cold) flows transport and deposit sediments in cross-isobath trends, such as the Cadiz sandy contourite channels (Habgood *et al.* 2003; Akhmetzhanov *et al.* 2007) defy the idea of contour flowing currents and make much more difficult the proper characterization of contourites as being of shallow-, mid- or deep-water origin.

Fine-grained deposits are important constituents of a petroleum system as well. They can develop both sealing facies or permeability barriers and source rock accumulation. This last alternative is more commonly associated with gas hydrate deposits. Large potential gas hydrate accumulations and associated bottom-simulating reflector (BSR) zones are found in contourite deposits all along the Atlantic margin (Blake Outer Ridge (BOR), Dillon & Paull 1983; Kraemer *et al.* 2000; Rio Grande Cone, Silveira & Machado 2004). Sediment permeability is a significant factor in gas hydrate development, and variations in permeability influence zones of hydrate accumulation. Heterogeneities observed in gas hydrate distribution on the BOR (a large drift of clay-rich sediment in the western Atlantic Ocean that contains 30–40 Gt of carbon stored as methane hydrate and underlying free methane gas; Paull *et al.* 2000) are related to modifications in the thermohaline circulation pattern, which induced different styles of drift development, as accumulating terrigenous or

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biogenic components responded to climatic-induced variations in oceanic circulation (Kraemer *et al.* 2000).

Vigorous slope boundary bottom currents can locally erode the sea floor, causing sediment instability and triggering major mass-flow events, such as those involved in the escape of methane gas from gas hydrate accumulation (Holbrook *et al.* 2002). Identifying relative periods of activity and the factors that induce both local and global-scale current variation through the transport of heat and salt by thermohaline circulation is fundamental in understanding climate changes.

Global climate disequilibria induced by or through the perturbation of ocean circulation can also be evaluated through the study of contourites. Sedimentary current-controlled deposits are directly related to environmental oscillations. Seafloor erosion can also be responsible for the opening of permeable pathways to gas-free zones in gas hydrate accumulations. Such a mechanism might be associated with sustained, ocean-wide release of methane (Holbrook *et al.* 2002), which could cause large-scale continental slope erosion and also induce major changes in thermohaline circulation, such as during the Palaeocene–Eocene thermal maximum and two intervals in the early Toarcian that were apparently characterized by massive methane release (Dickens *et al.* 1995, 1997; Hesselbo *et al.* 2000; Holbrook *et al.* 2002).

The direct relationship between ocean circulation and climate was recently reassessed by Clark *et al.* (2002) and Rahmstorf (2002). Those workers discussed large-scale ocean circulation as a combination of currents driven directly by winds, currents driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt (the thermohaline circulation), and tidal action. These driving mechanisms interact in nonlinear ways (as all currents change the distribution of heat and salt) so that no unique relationship exists. Nevertheless, the distinction is useful, particularly when changes in wind or in surface heat and freshwater fluxes are considered in their effects on circulation (Rahmstorf 2002). Clark *et al.* (2002) pointed out that a number of simulations with general circulation models of the coupled ocean–atmosphere system demonstrate the possibility of a reduced Atlantic thermohaline circulation in response to increased greenhouse gas emissions. Both the data and the models suggest that abrupt climate change during the last glaciation originated through changes in the Atlantic thermohaline circulation in response to small changes in the hydrological cycle. Atmospheric and oceanic responses to these changes were then transmitted globally through a number of feedbacks. The palaeoclimate data and the model results indicate that the stability of thermohaline circulation depends also on the mean climate state. Thus, sedimentary proxies such as primary sedimentary structures and bedforms can be used as direct indicators of current regime changes and consequently link them to palaeoclimate oscillations.

Consequently, three main applied aspects must be considered when studying contourites: (1) energy resources; (2) slope stability; (3) palaeoceanographic–palaeoclimatic evolution and mid- to long-term global climate forecasting.

In this paper we focus on the understanding of the direct economic importance of contourites, and on the energy resources aspect, which has major application in petroleum exploration. Recent papers by Llave *et al.* (2001), Reeder *et al.* (2002), Viana *et al.* (2002*b*), Carter *et al.* (2004) and Lu & Fulthorpe (2004), and others presented in this volume (Carter 2007; Duarte & Viana 2007) have dealt with palaeoceanographic aspects of contourites. Despite the occurrence of gas hydrates in some contourite systems around the world (e.g. Bermuda, Southern Brazil) and their direct association in the accumulation of organic-rich sediments and their erosion and release of methane, the incipient exploration of these energy resources leads us to concentrate on wells drilled in hydrocarbon-rich accumulations and their potential analogues.

Petroleum exploration

The presence and the intensity of contour currents may have an impact on several aspects of petroleum systems. Reservoir, sealing and source rock deposition can be directly or indirectly influenced by ocean current activity, allowing or preventing the accumulation of sediments of different types and textures. Also, the modification of sea-floor topography by erosional and depositional processes controlled by bottom currents may be responsible for a readjustment of accommodation space, resulting in the creation of local sub-basins, sediment ponding, or passageways for sediment transfer. Large-scale margin configuration, related to tectonic or depositional features, can cause shelf–slope projections or re-entrants. Such configurations affect the intensity of bottom currents (Fig. 1) with a direct response in the depositional style (Viana & Faugères 1998).

Contourite reservoirs

To be considered as a potential hydrocarbon reservoir, contourite deposits must present some particular characteristics. Coarse-grained sediments, preserving good petrophysical characteristics, such as porosity, permeability, and lateral and vertical

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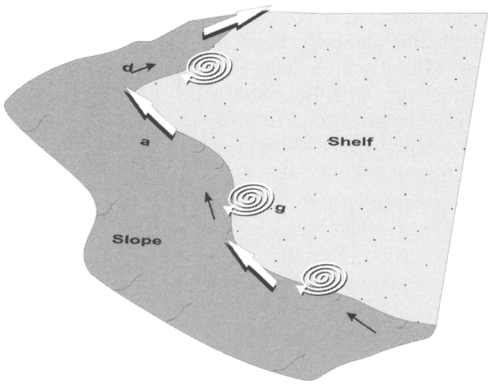

Fig. 1. Schematic representation of current behaviour with respect to margin configuration. Zones of current acceleration (a) are related to seaward margin projections and topographic obstacles that confine the flow; zones of deceleration (d) corresponding to margin re-entrants and flow expansion can induce formation of gyres or eddies (g). Size of arrows indicates current intensity.

transmissibility of fluids, must form part of the deposit. Some reliable criteria for recognizing this, both in seismic profiles and lithology, need to be identified to predict their occurrence.

The main factors controlling geometry and facies characteristics of contourite systems are: (1) intensity and duration of bottom-current regime; (2) the grain-size population available to the current action; (3) sea-floor physiography; (4) margin configuration. These factors regulate where, when and how contourites are deposited into a sedimentary basin.

The persistence and efficiency of a hydrodynamic regime capable of eroding, transporting and redepositing a large volume of sand is fundamental. Strong, semi-permanent bottom currents flowing at $>30 \pm 10$ cm s^{-1} are required for developing sand waves, such as the abyssal dunes of foraminiferal sands on the Carnegie Ridge (Lonsdale & Malfait 1974), and the siliciclastic sand dunes of the Campos Basin upper slope (Viana 1998), the lower Mississippi Fan (Kenyon *et al.* 2002), the Gulf of Cadiz (Habgood *et al.* 2003) and the Faeroe–Shetland Channel (Wynn *et al.* 2002; Masson *et al.* 2004; Akhmetzhanov *et al.* 2007). Two main situations are considered as favourable to the supply of coarse-grained sediments and the action of contour current. The first is a pre-existing sand-rich accumulation whose content is partially transferred to the areas subjected to current action by mechanisms such as shelf currents (currents induced by storms, tides, trade winds, eddies) inducing sand overspill (Viana & Faugères 1998); sediment density flows related to catastrophic floods in a low-gradient, ramp-like margin (hyperpycnal flows in the sense of Mulder *et al.* 2002); and the downwelling of dense saline waters developing sand-rich channels such as in the Gulf of Cadiz (Habgood *et al.* 2003; Mulder *et al.* 2003). The second is a zone subject to isostatic movements (elastic rebound, thermal deformation or halokinesis, intra-plate stresses, etc.) where pre-deposited sand layers are exposed at the sea-floor to sweeping bottom currents (Faugères *et al.* 1999; Davies *et al.* 2004). In both cases, there is no restriction to the water depth.

The largest sand storages in the oceanic realm are on the continental shelves and, to a lesser extent, deep-water sand deposits formerly transferred to the deep sea via any kind of gravity flow, commonly interpreted as turbidites.

Continental margin physiography is extremely important in accelerating or decelerating contour currents. Prominent seaward projections, or regions of relief disturbed by tectonic or adiastrophic structures act as current restrictions enhancing the near-bottom current velocity, whereas re-entrants and canyons reduce current velocity and induce sediment settling (Fig. 1).

The presence of coarse-grained contourites is independent of water depth, although the great majority of sandy contourites have been described from mid-water depth zones (300–2000 m, Viana *et al.* 1998). Studies from different geographical and stratigraphic settings (Mutti *et al.* 1980; Barros *et al.* 1982; Belonin *et al.* 1983; Nelson *et al.* 1993; Shanmugam *et al.* 1993; Famakinwa *et al.* 1997; Castro *et al.* 1998; Parize *et al.* 1998; Viana 1998; Viana & Faugères 1998; Viana *et al.* 1998; Garcia-Moronero & Olmo 2001; Kenyon *et al.* 2002; Cakebread-Brown *et al.* 2003; Isern *et al.* 2004; Rodriguez & Anderson 2004; Akhmetzhanov *et al.* 2007), complemented by a large set of high-resolution 2D and 3D seismic, core, and well log data from the Equatorial and Southwestern Brazilian Atlantic margins, indicate that the occurrence of potentially economic sandy contourites is mostly dependent on the vicinity of a sand-rich area prone to be swept by contour currents.

Processes and main depositional elements. Sands deposited in an outer shelf setting are frequently subjected to hydrographic regimes involving strong storm fronts, tidal currents, and onshelf penetration of superficial slope boundary currents, in the form of meanders and eddies. These can induce an offshelf transport of sand by the development of migrating sand waves. These sands arrive on the upper slope and are there entrained into the slope circulation system. They are redistributed parallel to the isobaths, forming elongated sand-rich deposits (Viana & Faugères 1998; Viana *et al.*

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2002*b*). Systems with similar geometry and bathymetric context have been recognized in the Aptian–Albian series of the Vocontian Basin, SE France, by Parize *et al.* (1998; see Viana 1998) and in the modern western Antarctica outer shelf–upper slope by Rodriguez & Anderson (2004), and are now being recognized in the Miocene sequences of the Campos Basin (see below). Several other systems described in the scientific literature with somewhat different interpretation could be reinterpreted as shallow-water contourites (e.g. the upper slope setting of the Brushy Canyon as presented by Mutti 1992; the western Grand Banks of Newfoundland studied by Dalrymple *et al.* 1992; MacNaughton *et al.* 2000).

The upper slope sand deposits of the Campos Basin described by Viana & Faugères (1998), which are indeed contourites deposited in a relatively shallow-water context, involve sediments deposited by both the surface slope boundary current and its underflowing countercurrent. The former are frequently associated with large bedforms comprising coarse-grained sediments, varying from conglomerates to medium- to fine-grained sand, with rare to frequent primary sedimentary structures indicating strong sea-floor currents. The sands deposited in a deeper setting are predominantly fine-grained, with very fine-grained sands and silts deposited after the entrainment of the sediments into the countercurrent by a downslope component of the surface slope boundary current. Rarely, these sands preserve primary sedimentary structures and are moderately to highly bioturbated.

Contourites deposited in relatively shallow water (upper slope setting, controlled by the action of a surface slope boundary current regime) present similar characteristics and are useful as distinguishable architectural elements. The most frequent elements comprise: (1) an adjacent sand-rich shelf with large unidirectional sand waves; (2) an erosional terrace on the top of the slope; (3) overspilled sand from the shelf, induced by slopeward migration of bedforms (grain-by-grain supply) and/or by short-living or short-distance gravity flows (shelf edge instability or distal reach of flood-related flows from neighbouring rivers); (4) mid- to high-amplitude upper slope sand waves (usually, but not always, trending in an opposite direction to the shelf sand waves trend); (5) canyon heads breaching the upper slope terrace and laterally fed by the upper slope sand waves; (6) preceding upper slope fine-grained sedimentation. These elements can be observed from sidescan sonar records and high-resolution seismic data, and sedimentologically calibrated in piston cores (Viana *et al.* 2002).

Slope indentation by submarine canyons creates an alternative path for the migrating sands on the upper slope. These can feed canyon heads with the accumulation of relative unstable sand wedges (e.g. the migrating sand dunes in the SE African continental margin under the action of the Agulhas Current penetrating onto the shelf described by Flemming 1978, 1980; Ramsay 1994; and on the upper slope of the Campos Basin, SE Brazil, described by Viana & Faugères 1998; and Viana *et al.* 2002*a*, *b*), which are easily transferred downslope along the canyon axis. Transferring mechanisms include the progressive increase of the lee-side gradient of the drift-related prograding wedges (Viana 1998), the continuous action of internal waves and tides (Cacchione & Drake 1986; Bogucki *et al.* 1997; Cacchione *et al.* 2002; Lima *et al.* 2007), sediment resuspension by the action of storm currents (Fukushima *et al.* 1985; Baltzer *et al.* 1994), low-amplitude seismic activity, and the connection of the canyon head to a fluvial system during relative sea-level falls.

In deeper waters, thermohaline currents contouring the isobaths or downwelling slopes interact with pre-existing coarse-grained deposits in several ways, such as sweeping the fine-grained population, partially or totally eroding previous deposits, modifying the original depositional geometry, or transferring sediments to a new depocentre, where coarse-grained contourites can be accumulated and preserved. The NE Atlantic is rich in examples, such as those of the Faeroe–Shetland Channel, the Faeroe Bank and the northern Rockall Trough area, where barchan dunes, furrows, contourite sand sheets and channels were identified and analysed by Kenyon (1986), Cochonat *et al.* (1989), Damuth & Olson (2001), Masson (2001), Masson *et al.* (2002, 2004), Wynn *et al.* (2002) and Akhmetzhanov *et al.* (2007). They reported the presence of such deposits as the result of the action of the southward flow of cold deep water from the Norwegian Sea funnelled through narrow topographic passages that extend from Greenland to Scotland, and the incorporation into the flow of coarse-grained sediments derived from gravity processes transferring sediments from shallower settings. In the eastern Gulf of Mexico sand dunes develop after the reworking of the sand deposits of the Mississipi deep-sea fan by bottom currents (Kenyon *et al.* 2002). In the western Gulf of Mexico, Niedoroda *et al.* (2003) and Bryant & Slowey (2004) observed vigorous bottom flow of the westward branch of the Loop Current reaching speeds of the order of 100 cm s^{-1}. Such strong velocities probably result from constriction of the Loop Current against the Sigsbee Escarpment by the Coriolis effect, resulting in a giant field of mega-furrows, and the sweeping and erosion of flanks and summits of salt knolls as illustrated in Figure 2, modified from Bryant & Slowey (2004). The incorporation of dissolved

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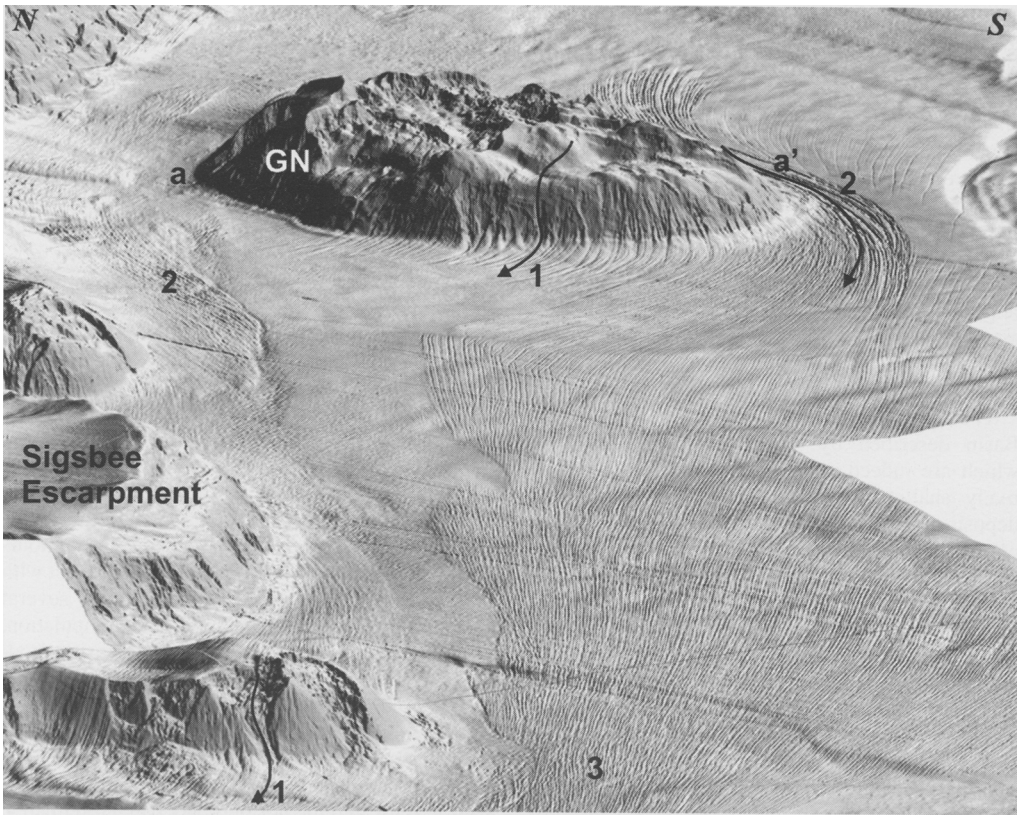

Fig. 2. A 3D rendered surface showing the action of the deep westward branch of the Loop Current at the foot of the Sigsbee Escarpment, northwestern Gulf of Mexico. The presence of a large field of mega-furrows should be noted. The depth and alignment of the furrows indicate the intensity of the currents. The currents pass over and erode the summit of the Green Knoll (GN, *c.* 15.5 km of its NW–SE-trending long axis a–a′). The incorporation of salt from the knoll affects the density and the current velocity (1). Current intensity is also augmented at the foot of the topographic obstacles (2) such as knolls and escarpments. Equally, lateral restrictions of flows can concentrate currents towards the converging axis (3), where currents accelerate. Figure modified from Bryant & Slowey (2004).

salt locally increases the flow density, and this effect is accompanied by an increase in the current's erosion and transport capacity. Density-enhanced bottom currents are expected to occur in other salt-deformed basins where evaporitic structures crop out at the sea floor, such as those occurring on both sides of the South Atlantic, or in areas with a high exchange of heat or salt, as exemplified by the Mediterranean Outflow Water penetrating into the Gulf of Cadiz (Mulder *et al.* 2002; Habgood *et al.* 2003; Llave *et al.* 2007).

In all studied cases, the presence of coarse-grained contourites in deep water is commonly associated with a set of medium- to large-scale bedforms. An order of increasing current velocity as proposed by Masson *et al.* (2004) includes fine-grained sediment waves and mounded contourite deposits, contourite sand sheets, coarse-grained sediment waves, barchan-like dunes, sand ribbons, channels, comet or obstacle marks, furrows and erosional scours.

Deep-sea unconformities. Diachronous, regional unconformities found at the base of contourite systems (the basal erosional surface of Faugères *et al.* 1999) are overlaid by onlapping upslope-migrating layers. These erosional features can be easily misinterpreted as sequence boundary unconformities, in the sense of Vail *et al.* (1977) and Posamentier & Vail (1988). However, their regional extent and abrasive aspect, with along-slope trending rather than downslope scouring characteristics, suggest a contour current-related erosion. The South Atlantic Brazilian margin is prone to such unconformities, such as the examples described by Viana (2001), Gomes & Viana (2002), Lima

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(2003) and Duarte & Viana (2007). The physical coincidence between some of these unconformities and sequence boundaries is also probable, and has been demonstrated for the Santos Drift example (Duarte & Viana 2007), where deep-water drift boundaries were correlated to regional sequence boundaries tied with exploratory wells. The upslope-migrating package, a frequent feature on separated or plastered drifts (Faugères *et al.* 1999), is occasionally misinterpreted as lowstand prograding wedges in the sense of their sequence stratigraphic position. These two different interpretations lead to differing interpretations of sedimentary facies and either penalize or favour any exploratory prospects. The stratigraphic–palaeoceanographic reconstruction of drift evolution along the SE Brazil margin, from shallow to deep water, based on isotopic and biostratigraphic data, some corroborated by ^{14}C dating (Viana 1998; Viana & Faugères 1998), permits us to propose the profile presented in Figure 3, where we identify the period from the latest lowstand to the early transgressive phase (20–12 ka BP) as that of greater bottom-current activity, inducing effective sea-floor erosion and accumulation of coarse-grained deposits. In such a scheme, sands are preferentially accumulated in the upper slope setting and at the foot of topographic obstacles, where pre-existing sand is available for resedimentation under the action of currents. This scenario, conceived for the Brazilian margin, must be checked for other margins, where timing of sediment delivery to the slope and contour current acceleration may diverge.

The impact of sea-floor topography. The continental slopes and rises often present complex sea-floor topography such as salt walls, fault planes, knolls, mud or salt diapirs, submarine volcanoes and escarpments, among other features. The size of the relief and its trend in relation to the current flow, associated with the Coriolis effect, play an important role in the interaction of accelerated currents with unconfined, exposed sand supply. In a strong bottom-current regime coarse-grained material present on the sea floor may be incorporated into flows as bed-load supply, developing different bedforms and depositional geometries as a function of the intensity and duration of the flow regime, and accommodation space.

The intensity, width and position of the current core change with time. Flow regime modifications, responding to high- or low-frequency climatic oscillations or to margin physiographic modifications caused by local tectonic or erosional activity, affect the width and locus of the current core. Dynamic changes in the sea-floor topography related to such processes may also constrain (and accelerate) or relax (and decelerate) the flow, influencing the related depositional style.

Along-slope current re-accelerations are geographically frequent, and often related to physiographic changes such as margin projections (Figs 1 and 3), topographic restrictions (straits, passages, sills), and changes in gradient (which, along with their coincidence with water masses boundaries, were advocated by Habgood *et al.* (2003) to explain the abrupt termination of the sand deposits in the Gil Eanes contourite channel in the Gulf of Cadiz). Margin projections may induce the formation of meanders and gyres, which locally play an important role as sedimentary agents by sweeping the sea bottom, and resuspending and incorporating sediments along their path ('the sea-floor polishing effect', Viana *et al.* 1998; Viana & Stow 2000). The gyres can develop independently of the water masses involved (Fig. 4) and at any water depth, as demonstrated by the results of the HEBBLE project (McCave 1976; Nowell *et al.* 1982, 1985; McCave *et al.* 2002), and also recently exemplified by the break-up of both the Atlantic Deep Western Boundary Current and the North Brazil Current into several eddies along their path in the eastern and equatorial South America margins (Dengler *et al.* 2004). Thus, alternation between current acceleration and deceleration along its path is expected, as well as short-term reversals in its sense of flow. These modifications result in different types of sediment record.

Some examples from the SE Brazilian margin are presented here to illustrate the importance of the sea floor in controlling the flow and development of sedimentary accumulations involving coarse-grained sediments. One case, in a lower slope–continental rise setting, shows the presence of Cenozoic sand layers exposed at the sea floor as a result of salt diapir uplift. The seismic lines of Figure 5a–c show high-amplitude, hummocky packages corresponding to upper Oligocene–lower Miocene turbiditic sands exposed at the sea floor along the flank of an escarpment developed by salt halokinesis. A broad channel has been carved as a result of the restriction of the current flow imposed by the escarpment; the sand layers have been eroded and the sediments redistributed downstream. A map of the sea-floor seismic amplitudes obtained in that area was calibrated with the sediment facies using several piston cores (Viana 2001; Viana *et al.* 2001). A wide regional sand sheet, of more than 500 km^2, laterally passing into a sand ribbon zone, was observed downstream of the zone of current erosion of the Oligo-Miocene sands (Fig. 5b). Seismic horizon slices at different depths indicate that the sand sheet passes downslope into a contourite mud-rich drift, in an unconfined setting, with the development of a sediment wave field and a furrow

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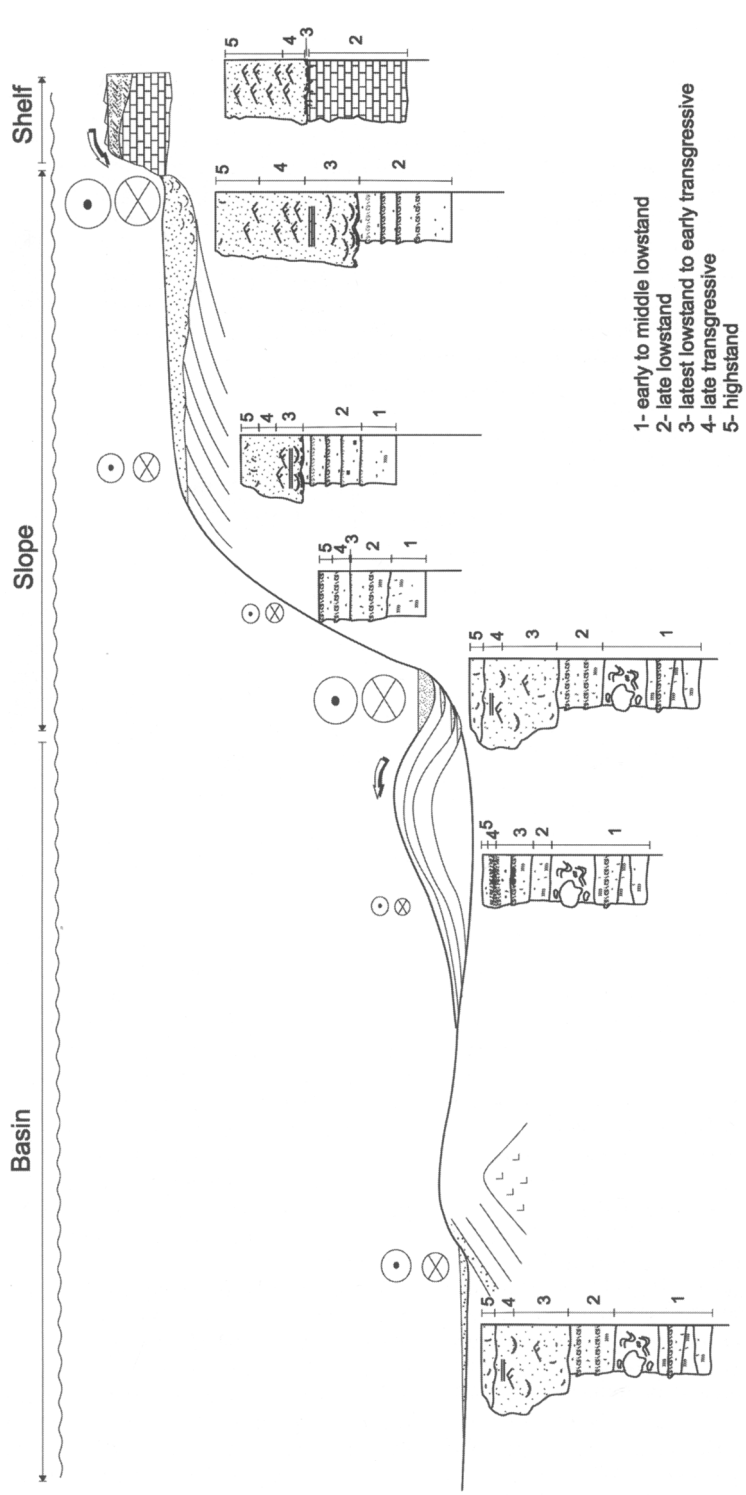

Fig. 3. Schematic profile suggesting the location of preferred sites for coarse-grained contourite deposits, and their relationship with relative sea level. From this graph, based on Viana & Faugères (1998) and Viana *et al.* (2002*b*), the period from the maximum lowstand to the late transgressive phase corresponds to the period of stronger currents and to the deposition of coarser-grained material.

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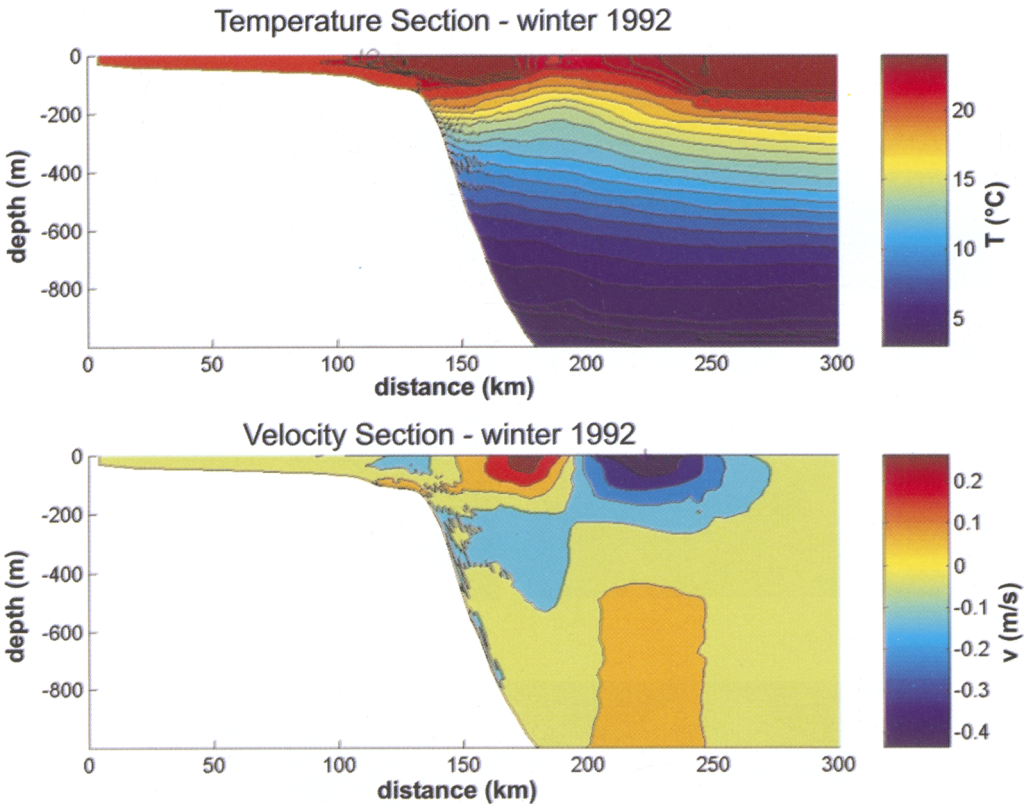

Fig. 4. Temperature and velocity sections through the Campos Basin, SE Brazil margin, showing the presence of a meso-scale eddy and its impact in a deep-water setting where a water column of >400 m depth is affected.

system (Fig. 6). Cores retrieved in the sand ribbon zone confirm this depositional transition, and show an alternating deposition of decimetre-thick fine- to very fine-grained sands and mud layers (Fig. 6).

The impact on sedimentation of a vigorous current, flowing above a large region of a margin strongly marked by topographic modifications, is illustrated in a lower Eocene section from the Santos Basin on the SE margin of Brazil, imaged by 3D seismic data (Fig. 7). The general trend of the slope in this section is east–west and salt withdrawal resulted in the development of elongated mini-basins with a NNE–SSW trend. The mini-basins acted as current corridors in which the intensity of the bottom flow is increased because of the lateral topographic constriction. In a deep-water setting, a large field of current-carved furrows was identified in amplitude coherence maps. The furrows are aligned parallel to the axis of the salt mini-basins (Fig. 7). Some of the mini-basins are depocentres for sands transferred from shallower settings by gravity currents. Independently of the sediment conduit (mini-basin axis, fill and spill, or salt crestal troughs; Fig. 7), the sands emplaced by gravity currents are exposed to current action and, consequently, their original depositional geometry is greatly modified. In this example, the sands are delivered to the core of the mini-basin via avulsion from a salt crestal trough used as sediment fairway, developing an elongated lobe. This geometry was subsequently modified by the currents, and by the sands incorporated into the furrows (Fig. 7).

These currents, following the NNE trend of the mini-basin's axis, encountered the east–west-trending continental slope obliquely. The Eocene slope in that area possesses a narrow and steep upper slope escarpment (Moreira *et al.* 2001) and a wide terrace at its base, where shallow water-derived coarse- and fine-grained sediments accumulated, producing a chaotic seismic pattern. In our analysis the terrace was the initial depocentre of sands exported from the shelf by various mechanisms

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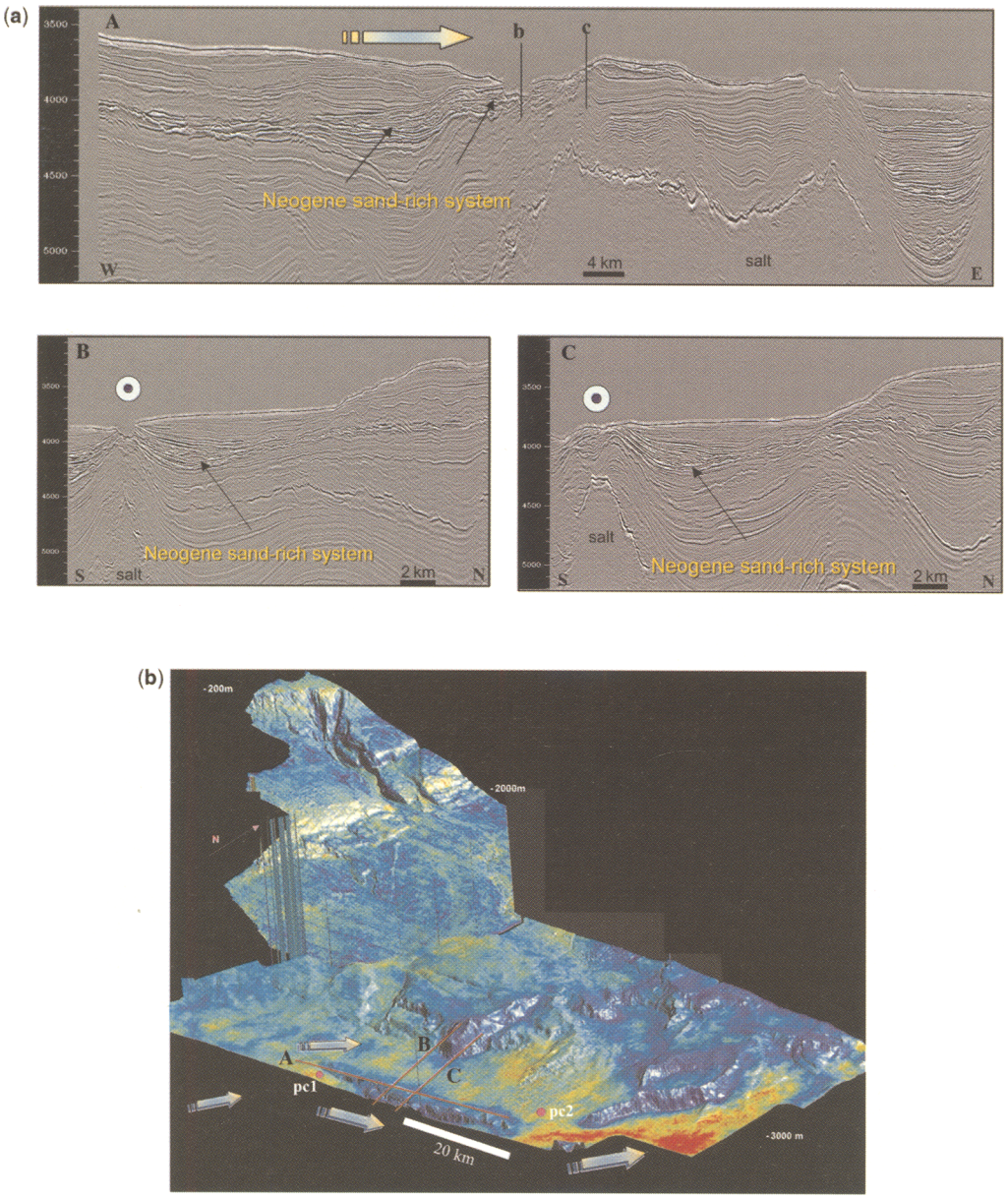

Fig. 5. (**a**) Seismic lines indicating a high-amplitude sand-rich package truncated at the sea floor by bottom currents, after uplift by salt ascent. (**b**) Oblique 3D view of the sea floor indicating the position of the seismic lines of (**a**). The topographic obstacle created by the salt wall is fundamental in accelerating bottom currents. Pink dots indicate the position of piston cores that retrieved the Neogene sands cropping out at the sea floor (pc1) and the sands redeposited as a contourite sheet (pc2).

such as delta front flows and/or erosion of the shelf edge by oceanic processes inducing water sapping at the face of the slope setting, resulting in shelf break–upper slope instability. The impingement of the strong NE-flowing bottom currents against the east–west slope escarpment reworked the shelf-derived sediments at the escarpment base and started development of ENE-migrating barchan sand dunes above the terrace, as seen in the seismic amplitude map of Figure 8. Extensive fields of

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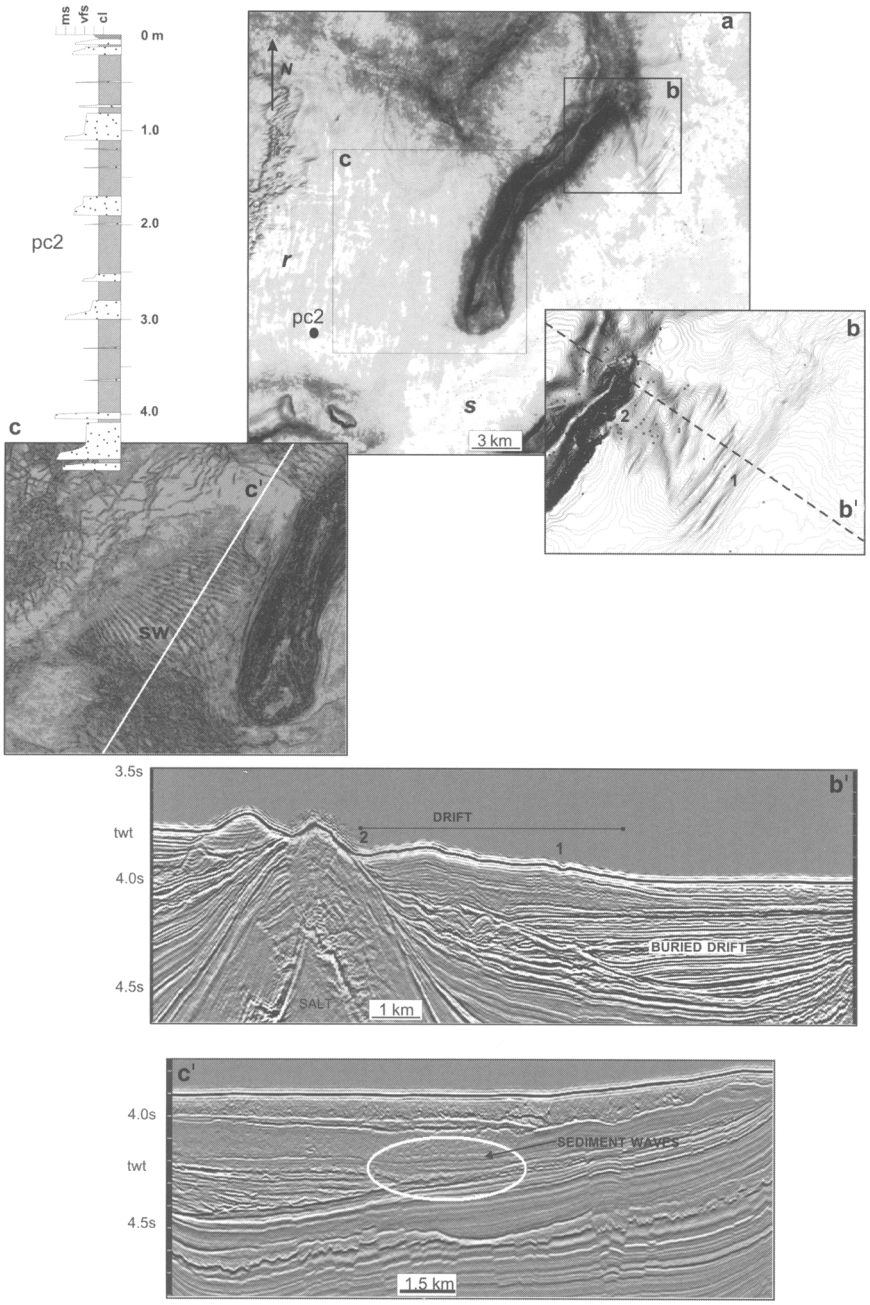

Fig. 6. (**a**) Amplitude map of sea bottom of the area adjacent to that shown in Figure 5, where the sand-rich Neogene section is eroded. Amplitude anomalies are presented as ribbon-like features (*r*) and as sheets (*s*). Piston cores retrieved from these anomalies (pc2) indicated the presence of contourite sands. (**b**) Detail of a moat-drift system and furrows influenced by the presence of the salt wall. *B′* is a seismic line indicating the construction of moat-drift deposits related to the topographic obstacle caused by the salt wall. (**c**) Horizon slice from a seismic reflector with a crenulated pattern identified below and beyond a huge mass-flow deposit. The seismic image of this reflector, obtained from a coherence map, suggests a field of sediment waves migrating northeastward, following the flow pattern of the ribbon-like features and the furrows observed on the modern sea floor, and in agreement with the suggested current direction based on the construction of moat-drift deposits in the area. The seismic line c′ indicates the position of the horizon slice and seismic pattern associated with the sediment waves. twt, two-way travel time.

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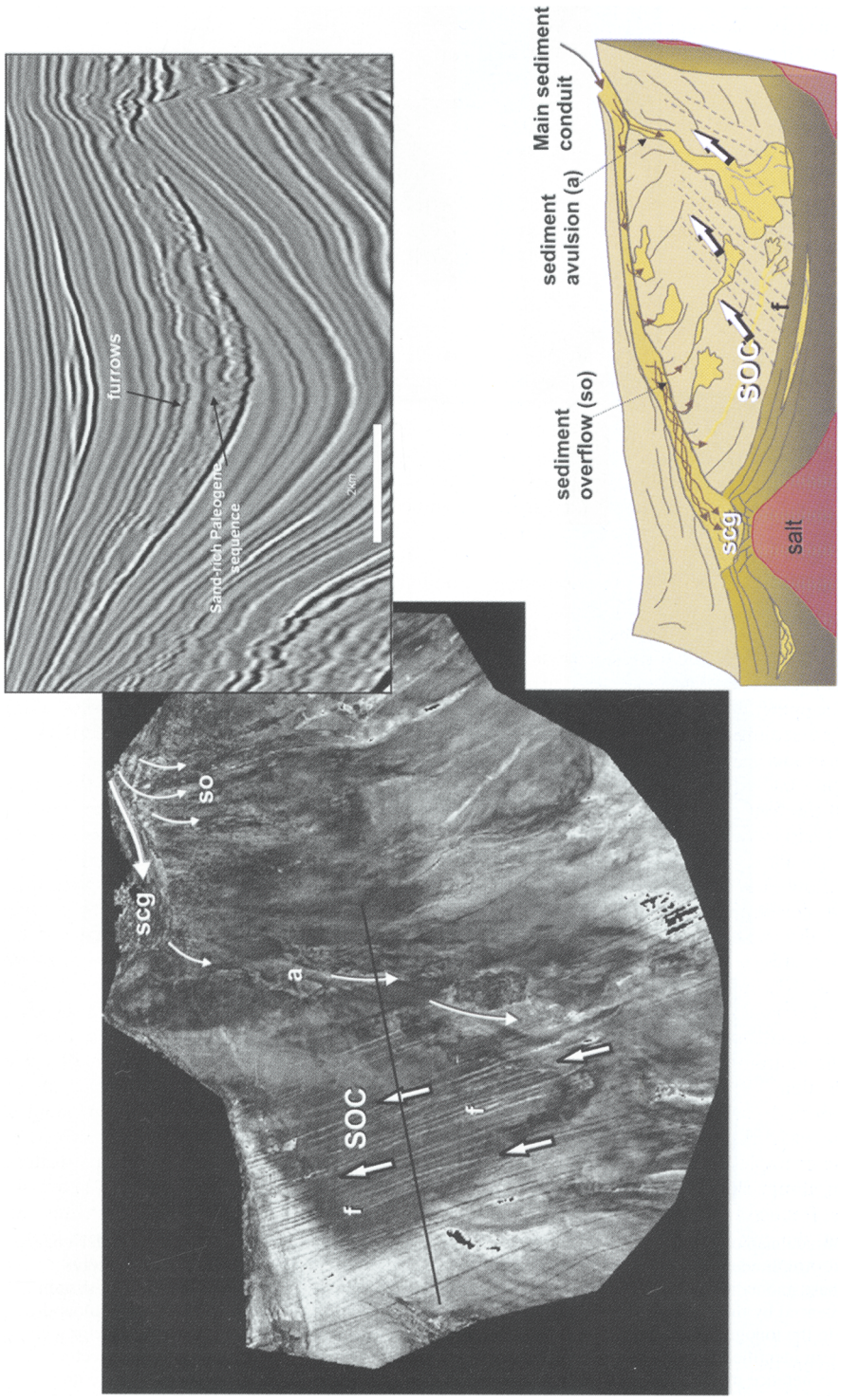

Fig. 7. Linear features (furrows; f) scouring the latest Palaeocene–earliest Eocene sea floor of the Santos Basin deep-water area. Horizon slice of the furrow surface, indicating the seismic line, shows the furrows interacting with the high-amplitude patches (sands?) delivered to the core of the mini-basin by avulsion or spillover from the channel developed within a salt crestal graben (scg). A schematic representation of these coupled processes is shown. SOC, Southern Ocean Current.

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barchan dunes, sand waves and mega-furrows have developed on the modern sea floor of the Gulf of Mexico, in water depths ranging from 2000 to 3000 m, as a result of bottom currents flowing at about 100 cm s^{-1} (Bryant *et al.* 2000; Kenyon *et al.* 2002; Niedoroda *et al.* 2003; Bryant & Slowey 2004). Similar strong bottom currents probably caused the formation of the barchan dunes identified in the uppermost Palaeocene–lower Eocene section of the Santos Basin, indicating bottom-current activity in a period when coarse-grained sediments were delivered to the basin to form potential reservoirs.

Large-scale analysis of 3D seismic data for the Santos Basin suggests that slope instability could be related to the action of strong slope currents. In such a case, vigorous SW-flowing slope surface currents, in a pattern similar to that of the present-day Brazil Current (see discussion by Duarte & Viana 2007), would erode and induce instability at the tip of the shelf edge clinoforms prograding from the shelf edge, where the gradient increases. Such erosion induces the introduction of sediments into the basin via successive mass flows, whose heads are aligned for several tens of kilometres along the isobaths. Figure 9 presents seismic imaging of this kind of erosive feature, more than 50 km long, which is highly linear and conspicuous. We consider that such erosion exposed aquifers and induced water sapping, a continuous low-rate flow of water-charged sediments. Such flows are probably the explanation for the sinuous channels crossing the slope and the mass-flow deposits accumulated at the foot of the upper slope escarpment. They developed a series of short, narrow and parallel slope aprons that evolved to a chaotic relief of mass-flow deposits of intermingled sand and mud that developed above the mid-slope terrace where the barchan dunes were found (Fig. 8). Above this terrace dominated by the chaotic deposits, NE-flowing deep-water currents are accelerated because of the constriction of the upper slope escarpment and the complex local relief. Here the bottom currents have eroded a sinuous, more than 30 km long, slope-parallel channel, with drifted contouritic sediments developing an asymmetric channel–levee system (Figs 8 and 9). These examples illustrate the close interaction between abrupt slope gradient changes and strong currents, frequently inducing destabilization of the adjacent slope in any bathymetric setting, with the development of small- to mid-scale mass movement deposits.

Seismic and well log characteristics of sandy contourites. Given the credible evidence for the existence of coarse-grained deposits associated with contour currents, the recognition and characterization of their depositional elements from seismic and well log data is an essential element. The diagnostic criteria for recognition of contourites in seismic lines were presented by Faugères *et al.* (1999), who focused on the distinction of contourites from turbidites, as well as on the identification of seismic features that correspond to coarse-grained contourites, to provide predictive tools for reservoir identification. Linear, and largely continuous strong seismic amplitudes were observed in the lower Pliocene contourite gas-bearing sands with more than 30% porosity in the Spanish Gulf of Cadiz (Cakebread-Brown *et al.* 2003). These biogenic gas accumulations exhibit seismic amplitude anomalies (amplitude v. offset), and their presence in the Gulf of Cadiz region, the characterization of their seismic geomorphology and the regional occurrence of a potential source rock open the possibility of a new giant play in the Algarve basin. Also in the Gulf of Cadiz, Garcia-Mojonero & Olmo (2001), on the basis of seismic lines and one exploratory well, identified upper Pliocene–Quaternary contourite deposits consisting of more than 800 m thick sand–shale intercalations, with an average net-to-gross (total sand content) of 75%, with the sand beds reaching 40 m thickness with good lateral continuity and porosities >30%. Below are some examples of contourites deposited both in shallow and deep water based on industrial 3D seismic data, shot along the Brazilian SE margin, coupled with exploratory and appraisal well data and piston cores.

In the first example, concerning upper slope contourites, a seismic amplitude map close to the Serravallian unconformity (middle Miocene) was obtained from the shelf edge down to the basin (Fig. 10). Strong negative amplitudes, calibrated by well data, correspond to coarse-grained deposits. They occur at the top of the slope as a >10 km long and 3–5 km wide field of linear ridges that are parallel to the slope. The ridges grade downslope and downstream to weak positive amplitude reflections, corresponding to finer-grained sediments. The seismic lines of Figure 10 suggest the presence of a small upper slope escarpment with an adjacent terrace above, bearing high-amplitude reflectors corresponding to the location of the ridges. Locally, these reflections develop a hummocky clinoform seismic pattern, suggesting a migration of the bedforms above the terrace. Recurrent, stacked similar features are observed, suggesting that the depositional system was maintained during a relatively long period (>1 Ma), alternating with continuous low-amplitude, high-frequency reflectors, interpreted as periods of fine-grained deposition, related to the weakening of the current regime.

Linear seismic amplitude anomalies are also observed on the modern deep sea floor, as discussed

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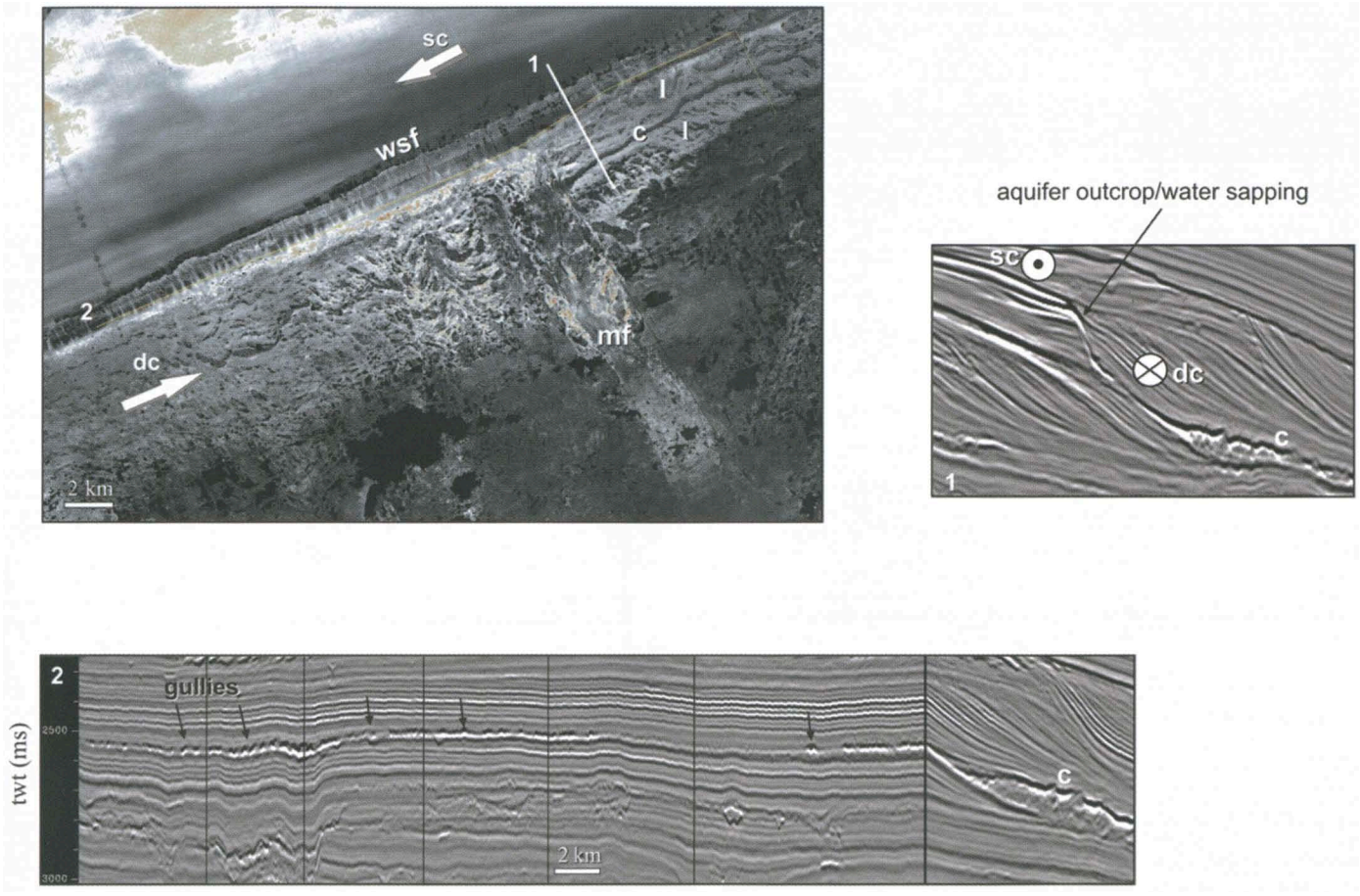

Fig. 9. Seismic amplitude image showing detail of slope erosion by boundary currents inducing a conspicuous, linear water-sapping front (wsf) and related slope apron deposits, evolving downslope to chaotic features carved by a sinuous, parallel-to-the-slope channel (c). The drifted material from the channel path develops an asymmetric levee system (l). The white bar indicates the position of the seismic line 1, showing a narrow extension of the upper slope escarpment where porous, water-saturated beds (strong white reflections truncated against the escarpment face indicated by the arrow) cropped out against the lower–middle Eocene sea floor. Composite yellow seismic line 2 crosses the several gullies and sediment aprons formed by the water sapping (small black arrows) and its termination indicates their genetic relationship with the chaotic, sand-rich mound carved by the channel. A huge mass-flow feature (mf) is observed, indicating local unsteadiness of the chaotic deposits, probably because of movement of adjacent salt walls. White arrows indicate the sense of flow of surface currents (sc) and deep currents (dc).

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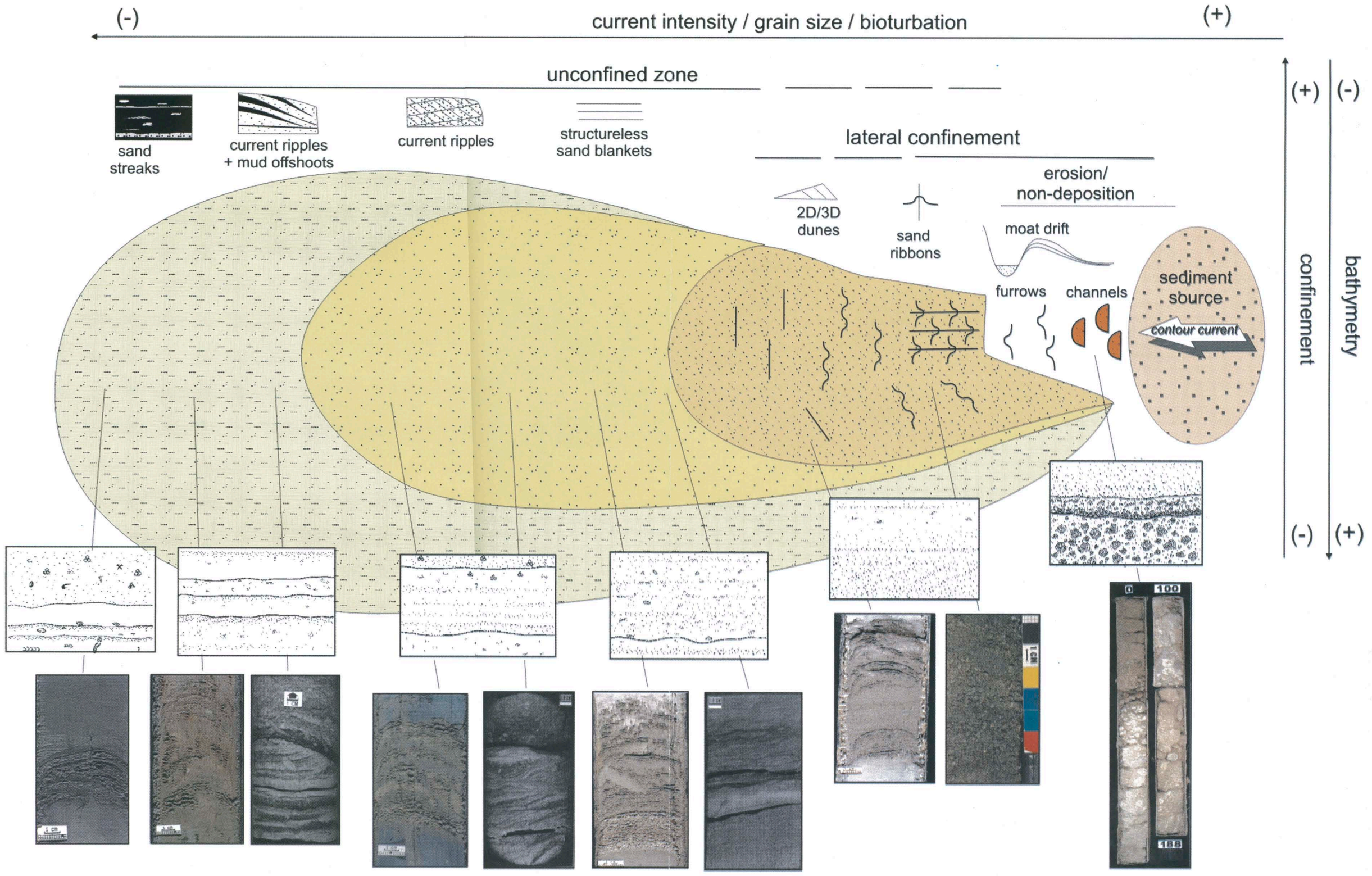

Fig. 12. Schematic representation of sedimentary facies and bedforms distribution along a contourite system. The system grades from a predominantly coarse-grained zone upstream to a fine-grained zone downstream. A lateral confinement in the proximal area and a pre-existing coarse-grained source are considered. Facies distribution shows a longitudinal and transverse decrease in current intensity.

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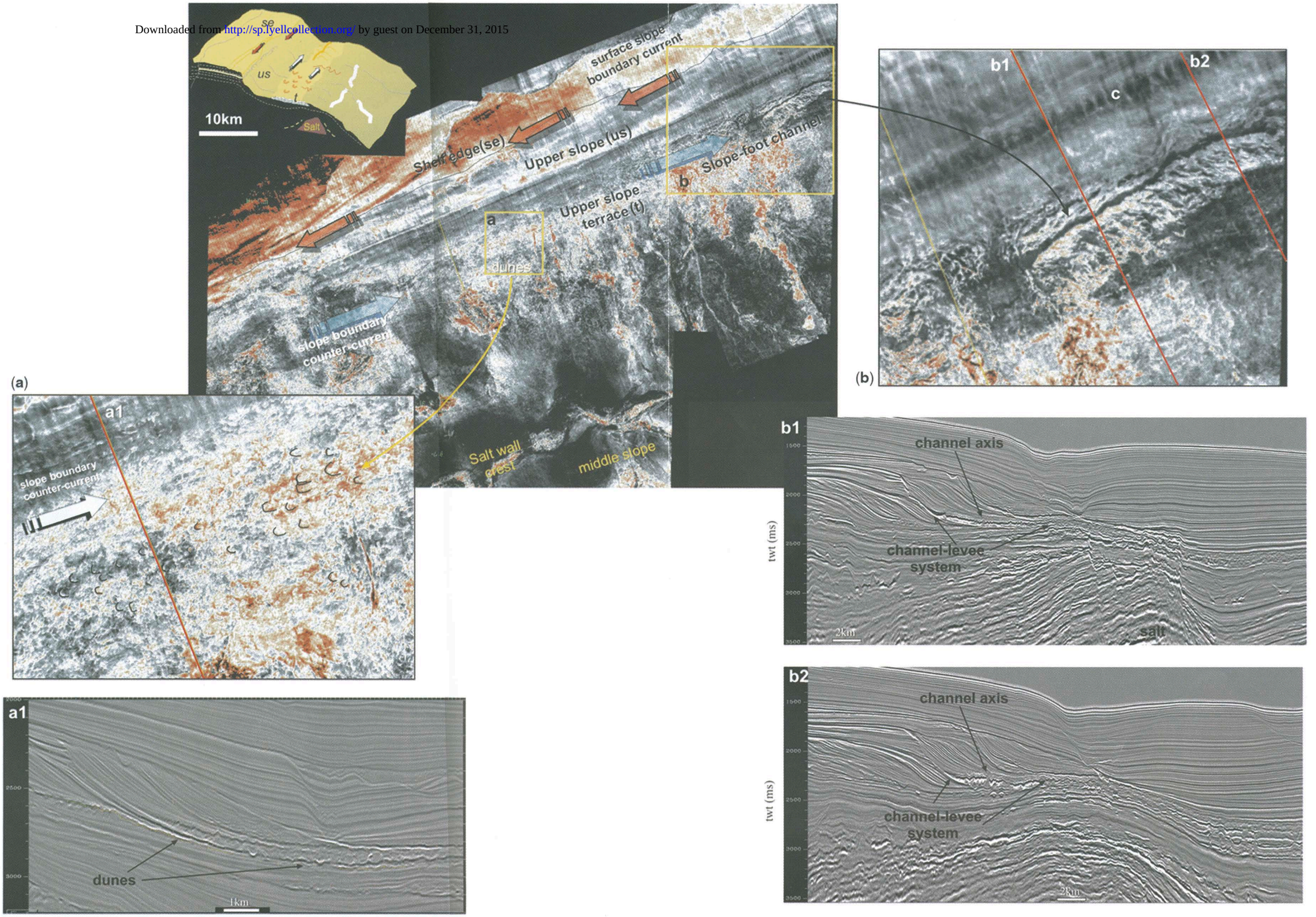

Fig. 8. RMS seismic amplitude map representing the passage of the margin configuration form a ramp style (late Palaeocene–early Eocene) to a shelf–slope environment with a narrowand steep upper slope escarpment (middle–late Eocene). Above the slope terrace the sands develop different types of deposits such as chaotic accumulations, a barchan dune field with a NE migration trend (a), a striking parallel-to-the-slope channel (b), developed in continuity with the barchan dune field probably as a result of a lateral flow restriction induced by topographic confinement related to the underlying mass-flow deposits, and a series of linear upper slope–outer shelf water-sapping features, associated with the sea-floor erosion by surface slope boundary currents and the cropping out of sand-rich aquifers (c, and Fig. 9). Inset a and seismic line a1 illustrate the sand dune field; the discontinuous yellow line represents a discontinuity of the lower Eocene above which the sand dunes formed. Inset b and seismic lines b1 and b2 illustrate the foot-of-slope channel and its levee system, indicating the topographic control of the underlying deformation by the subjacent salt movement. The schematic block diagram synthesizes the main physiographic–depositional features and the trend of bottom currents.

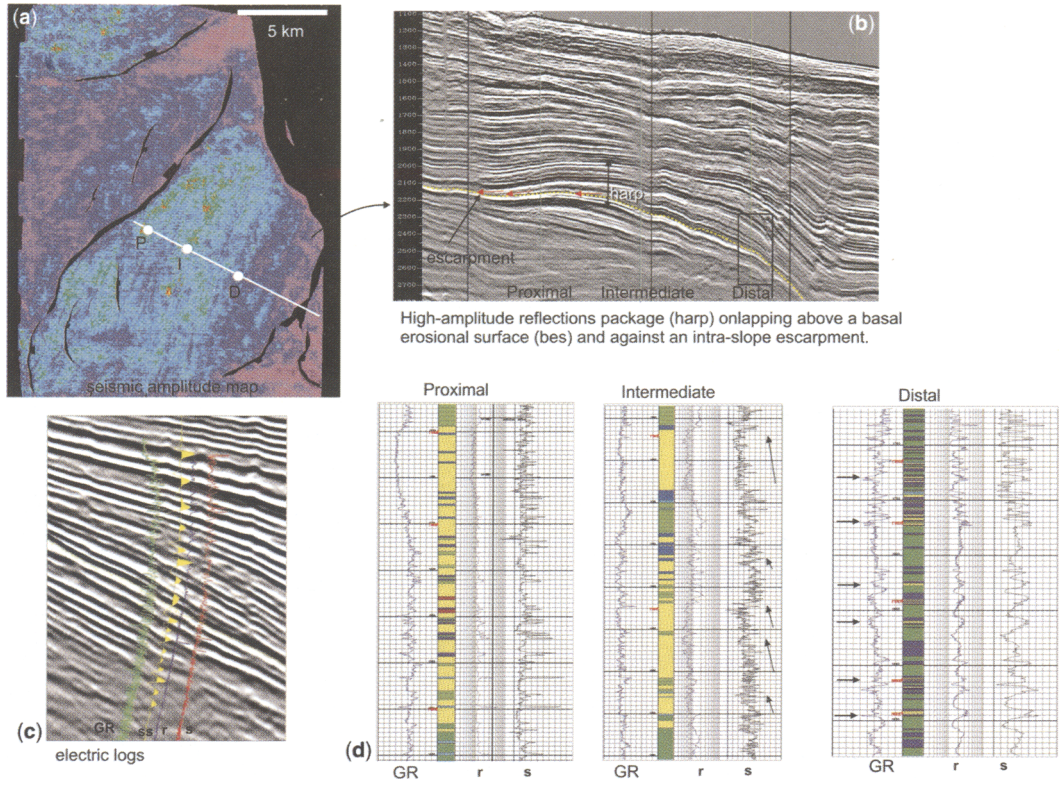

Fig. 10. (**a**) Seismic map of maximum negative amplitudes of a lower to middle Miocene interval showing linear seismic anomalies, elongated parallel to the slope, corresponding to sandy contourites deposited in a palaeo upper slope setting. Locations of seismic line and pseudo wells are indicated. (**b**) Seismic line crossing the area of higher seismic anomalies and the location of the wells. An intra-slope terrace adjacent to an escarpment is the site of occurrence of strong negative amplitudes, with onlaps (red arrows) against an erosional surface (bes; yellow dashed line) marking the base of the contourite wedge. (**c**) Detail of the distal portion of the contourite wedge with high-frequency reflections of large acoustic impedance contrast and corresponding log profiles (GR, gamma-ray; r, resistivity; s, sonic) and synthetic seismogram (ss). Lower values of the electric logs are toward the left. (**d**) Log profiles of proximal, intermediate and distal wells located above the contourite wedge. In the proximal well, thick (several metres to tens of metres thick) sand packages with constant sonic and resistivity characteristics occur, suggesting homogeneous permiability–porosity behaviour. Decreasing gamma-ray and resistivity values towards the top suggest a cleaning or coarsening upward tendency. In the intermediate well, a sharper separation of the sand packages is observed, with lower velocity towards the top of each (a few to several metres thick) package (suggesting better porosity). In the distal well, the sand packages are a metre thick, and are widely separated by finer-grained layers. In this example, they are oil-bearing metre-scale sand beds.

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above (Fig. 4), such as linear ribbon-like features and sheet-like amplitude anomalies observed in the Campos Basin. Piston cores retrieved sand beds a few tens of centimetres thick intercalated with mud intervals.

The stacked pattern of intercalated sand-rich and mud-rich intervals in upper slope contourite deposits is also recorded in well log profiles (Figs 10 and 11). The integrated interpretation of several data types (e.g. gamma-ray, resistivity and sonic logs, biostratigraphic data, and seismic stratigraphic pattern) suggests a fourth- or fifth-order frequency (<100 ka) (Vail *et al.* 1991) of alternating sand–mud intervals, associated with a climatic control of current regime. The closer to the escarpment, the stronger the current velocity and the higher the sand content of the deposit.

The log profiles from different wells drilled in the upper slope and crossing seismic features like those described above allow us to identify some features related to coarse-grained contourites. The gamma-ray signature corresponds to two transitional styles: an upward grading well-sorted sand, 'cleaning trend' (gamma-ray decrease towards the top), and a blocky pattern of clean sands. The most common association is of the cleaning trend at the base and a blockier pattern at the top (Fig. 10). These styles occur both on a bed scale (0.1–1 m) and on a sequence scale (1–100 m). The resistivity and sonic logs have a similar signal, suggesting a frequent improvement in reservoir quality towards the top, mostly marked in medium to distal areas. Such quality improvement occurs both on a bed scale and on a sequence scale. Isopach maps corroborated by aquifer and oil reservoir pressures indicate that the reservoirs are apparently continuous for several hundred metres both downstream and downslope (Fig. 11).

The deeper-water prospects have not yet been drilled, so that evidence of physical properties based on well logs is still missing. A similar physical, sedimentological and physiographic condition for shallow- and deep-water contourites implies a probable similar pattern of an upward improvement in reservoir quality. The transition from poor to good quality reservoir depends on sediment availability and, mostly, on the bottom-current regime. In the wells illustrated in Figure 10, the transition from an average reservoir to a higher-quality one, in the sequence scale, corresponds to a long-term current action transferring and accumulating progressively coarse-grained, well-sorted sediments. High-frequency oscillations, mostly observed in sonic logs, are assumed to correspond to the current oscillations, resulting in small-scale variations in grain size with a minimum impact on porosity characteristics at a proximal location although they result in distinguishable and high-performing permeability discontinuities in distal areas (Figs 10 and 11). The common presence of escarpments bordering the internal flank or both flanks of sand-rich contourites is an important factor for stacking sands and defining their geometry (Fig. 11). Structural closure and a frequent association with localized deep-seated faults are important elements in trapping and oil migration (Fig. 11).

Fine-grained contourites: sealing rocks

Strong bottom currents are described as local and short-lived phenomena. The model is of slope and basin settings with low- to medium-intensity currents, capable of transporting fine-grained sediment population. Such sediments are introduced into the basins by hypopycnal flows associated with river discharge, sea-floor erosion, sediment gravity currents and primary productivity close to upwelling zones, and then incorporated into the oceanic circulation regime. Thick and widespread fine-grained drifts are recognized throughout the oceanic basins (for references, see Faugères & Stow 1993; Stow & Faugères 1998; Stow *et al.* 2002). In the northern Santos Basin, the >600 m thick Neogene-age Santos Drift acts locally as an excellent sealing rock for Palaeogene oil-bearing sandstones (Duarte & Viana 2007). Souza Cruz (1995, 1998) suggested a bottom-current origin for the thick mid- to upper Miocene wedge developed in the central Campos Basin, overlying the sand-rich Palaeogene–lower Neogene section where several giant oilfields have been discovered (e.g. Marlim, Albacora and Barracuda oilfields). The wedge, composed of shale–marl cyclic intercalations, works as an excellent seal. Less frequently documented, but also important in appraisal projects, are the internal heterogeneities in oil-bearing reservoirs that can be related to the action of bottom currents. Moraes *et al.* (2007) have presented an example of a giant oilfield in the Campos Basin where thick packages of oil-rich sandstones deposited in structural troughs are separated by an extremely bioturbated anisotropic silt facies, interpreted as being the product of bottom-current reworking along the trough (see Moraes *et al.* 2007, Fig. 5). This fine-grained facies acts as an important permeability barrier and the understanding of its distribution and thickness is fundamental in water injection and recovery projects.

Sedimentary facies assemblage

The sedimentary facies present in contourite systems are directly related to the type of sediments available and to the current regime. A bi-directional fining tendency is typically observed: one, along the flow, accompanying downstream current intensity

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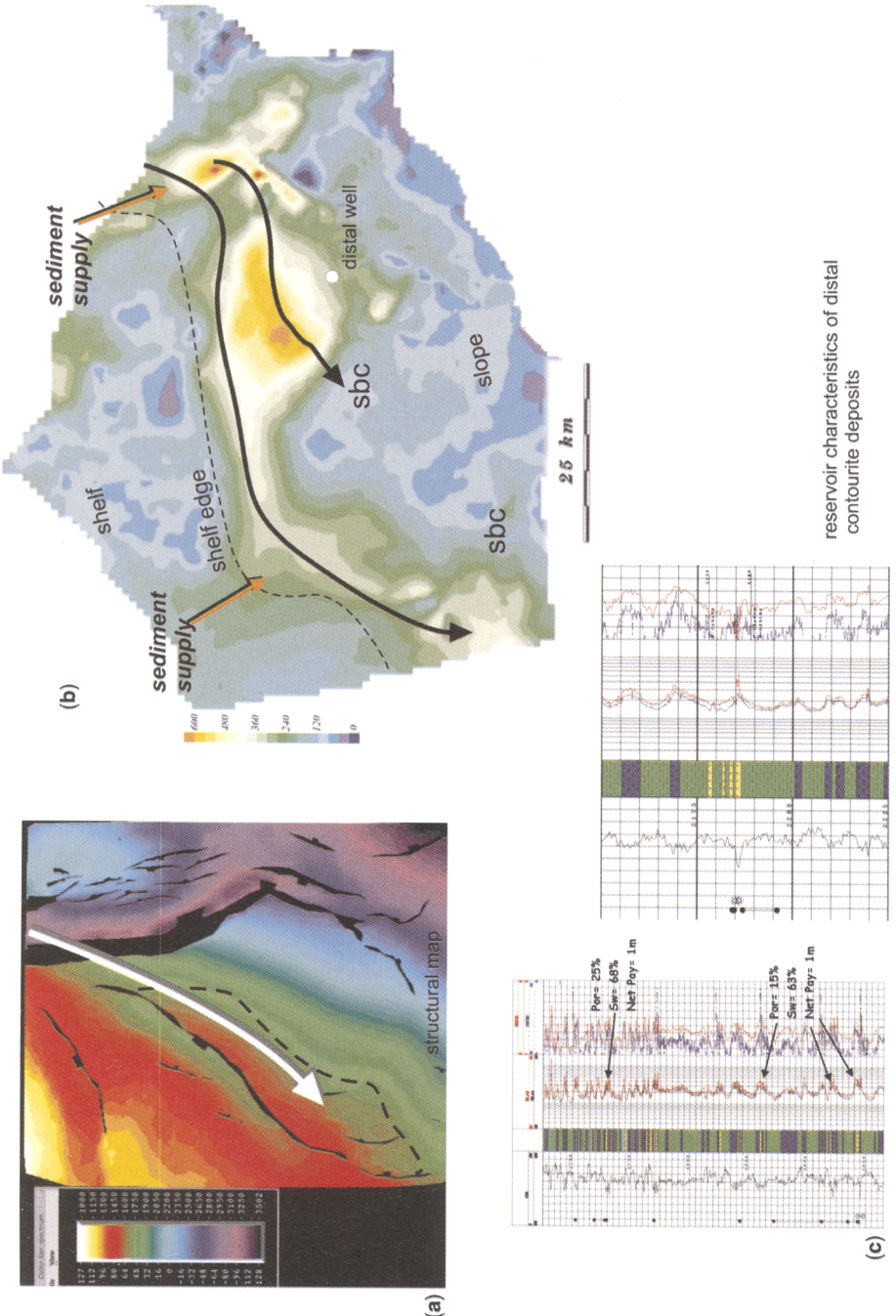

Fig. 11. (**a**) Structural map of middle Miocene interval where contourite sands predominate. The closure against the fault (dashed line) provides an interesting structural trap with higher sand content close to the fault, which may also have served as migration pathway. (**b**) Isopach map of the lower to middle Miocene sand-rich interval indicating thicker accumulation on a trend parallel to the isobaths; the sediments were introduced to the slope via point sources (incised valleys?) and distributed by the slope boundary current (sbc). (**c**) Gamma-ray, resistivity and density logs of a distal well with measured porosity, water saturation and average net pay in oil-bearing sand beds.

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changes, and another, downslope trending, related to the width of the current core and to the spacing from that core, both marked by a general decrease in current speed and thus, in the transported or accumulated grain size.

The pattern and distribution of bedforms are indicative of the bottom-current intensity. The examples from the Faeroe–Shetland Channel and the Gulf of Cadiz channels (Habgood *et al.* 2003; Masson *et al.* 2004; Akhmetzhanov *et al.* 2007) and Campos Basin upper slope terrace (Viana & Faugères 1998; Viana *et al.* 2002*b*) are good illustrations of such flow oscillations and their related erosional–depositional features. The erosional pavements, gravel patches, furrows–grooves–striations, sand ribbons, sand dunes, current ripples and fine-grained sediment waves are subsequently deposited with a decrease in the current intensity.

A large spectrum of sedimentary facies is attributed to contourites. Most of these are similar, being deposited under other current regimes where bed-load and suspended-load transport can coexist with different intensities as a function of the basin morphology and environmental constraints. Structureless or faintly to well-defined cross-stratified, very fine-grained to coarse-grained siliciclastic or bioclastic sands develop individual sets a few millimetres to several decimetres thick. The high-frequency alternation between coarser and finer sediments is indicative of high-frequency current changes and is marked by truncations, abrupt changes in grain-size stacking or in millimetre to centimetre thick passages from normal to inverse grading. Slope intraclasts are frequently preserved at the location of major current acceleration and, because traction prevails in a coarse-grained contourite system, they probably do not travel very far from the point of their plucking. Traction structures are dominant, even in very thin sand streaks where millimetre thick layers of very fine to fine-grained sand occur, probably accumulated by rolling or saltation under the action of bottom currents transporting sediments delivered to the basin by different mechanisms or from the reworking of previously deposited sands. Nevertheless, suspension may occur where current velocity surpasses the threshold of bed-load transport or when the suspended sediments of gravity flows or in benthic storms are entrained by any kind of contour currents (Adams & Weatherly 1981; Nowell *et al.* 1982; Nowell & Hollister 1985; McCave 1986). Bioturbation is common, occurring in several degrees of intensity and suggesting oxygenation of the bottom water. Sharp erosive contacts are also a frequent feature. They indicate an abrupt increase of bottom current intensity and separate any textural class susceptible to current action.

The 'normal' behaviour of an oceanic flow is marked by current intensity changes along its path as well as over time. Bottom-current reversals, tidal imprints and extreme high- to low-frequency oscillations in the current intensity are commonly observed (McCave 1976; Nowell & Hollister 1985; De Madron & Weatherly 1994; Huthnance 1995; Habgood *et al.* 2003), and induce the development of sedimentary structures similar to tidal or flood-related hyperpycnal flow-derived deposits (in the sense of Mulder *et al.* 2003). The distinction of contourites from sediments deposited under such conditions requires good sampling, palaeogeographical reconstructions, and vertical and lateral facies association analysis. The activity of bedforms and bioturbation respond also to current variability. A schematic representation of the sedimentary facies distributed along a coarse-grained contourite system is proposed in Figure 12. Sedimentary facies from various sites on the SE Brazil margin were chosen to illustrate this conceptual representation. The general model is a representation of the facies changes along the path of a slope contour current, which crosses a sand-rich area (sediment source) and distributes the sediment load downstream. The lateral confinement of the flow is provided by any topographic feature, either pre-existing or constructed by the current itself. The current intensity decreases downstream, inducing a diversity of sedimentary facies and bedforms as shown in Figure 12. A longitudinal trend of coarser-grained sediments accompanies the current core. If the current is strong enough to erode the substrate to form channels, the development of levees and oblique sediment waves is also expected, as shown in Figure 7, where the funnelling of the currents against the foot of the upper slope escarpment has resulted in a channel–levee-like system.

Final remarks

The recognition of deep-water coarse-grained deposits as contourites still remains controversial. A gravity-flow culture prevails upon the idea of contour-current action mostly as a result of: (1) the early establishment of conceptual models proposing facies characterization and the geometry of the gravity-flow accumulations; (2) gravity-flow deposits of sand are volumetrically predominant at least in the modern ocean; (3) most sandy contourites involve sediment transport on the upper slope, a zone that was poorly investigated in the 1960s to 1980s. The continuous scientific and industrial research in deep-water realms is providing new data that have been used in some attempts to characterize the coarse-grained contourites and indicate their economic potential. Controversy is

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an important triggering mechanism to stimulate further efforts in identifying and describing contourites. We hope that this paper will be useful in providing impetus to propose further ideas concerning the characterization and the economic importance of contourites as well as the continuity of the effort in determining the role of palaeoceanographic changes in bottom-current regimes and their geological record, and thus provide a basis for a better understanding of the wide spectrum of depositional systems in the marine environment.

A large number of Petrobras colleagues were fundamental in development of the ideas presented in this paper. Their contribution occurred in several ways, through discussions, seismic mapping, and mostly following their criticisms and enthusiasm in pushing forward the efforts to broaden the understanding of the role of bottom currents in shaping and building sedimentary deposits of economic interest along the Brazilian margin. Among them, R. Kowsmann was involved in the 'industrial marine geology' approach to contourites. Discussions with M. Carminatti and C. E. Souza Cruz provided extremely fruitful intellectual exchange. J.-C. Faugères was involved since the start of the evolution of these thoughts, and motivated the pursuit of the contourite task. The briefer than desired moments of conversation with E. Mutti and his geological wisdom greatly influenced how the ideas were adjusted and helped to point out the doubts that remain unsolved after this overview. We sincerely thank J. Howe and D. Piper for their precise scientific suggestions and help in adjusting the manuscript into a readable format. M. Rebesco, in the double role of first author's friend and co-editor of this volume, was fundamental in pushing forward during the periods when the production of this paper was menaced by the endless and absorbing tasks of petroleum exploration.

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