Upper slope sands: late Quaternary shallow-water sandy contourites of Campos Basin, SW Atlantic Margin

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Abstract: Upper slope sand deposits comprise a widespread but thin elongate accumulation of coarse to very fine-grained sand resulting from the action of slope boundary currents upon shelf-derived sediments. Sediment distribution on the Campos Basin upper slope responds to the action of the southward-flowing western boundary Brazil Current (BC). Linear, multi-source sediment supply to the slope is provided by shelf overspill due to the action of different forcing mechanisms: tides, storm fronts, and BC current onshelf penetration as gyres and meanders. On the slope, the sediment is pirated and redistributed by the BC. Coarse-grained sediments (pebbles to very coarse sand) are found below the zone of maximum acceleration of the BC. Downstream, fining is observed as a consequence of the morphologically controlled BC deceleration. The resultant accumulation is an elongate (*c.* 70 km long) and thin (< 50 m) wedge-shaped deposit. This depositional model is based on hydrographic, physiographic and sedimentologic characteristics of the modern Campos Basin margin, SE Brazil and characterizes a shallow water contouritic deposit.

The Campos Basin is located on the southeastern Brazilian continental margin, between 21°S and 24.5°S. A marked similarity between the modern coastline and the shelf break is observed, characterized by the seaward projection of the margin at the Cape São Tomé region (Fig. 1). The continental shelf widens and deepens to the south of this cape, ranging from 50 km wide in the north, with a NW–SE trend, to 100 km wide in the south, with a NE–SW trend. The continental slope extends 45 km from the shelfbreak (~120 m) down to the 2000 m isobath. Large submarine canyons are developed perpendicular to the shelfbreak: the Almirante Camara and Itapemirim to the north, and São Tomé to the south (Fig. 1).The shelfbreak is marked by a conspicuous scarp between the 120 and 220 m isobaths, in places with a slope angle of up to 10°, and a series of gullies that locally incise the shelf edge. Mass-movement scars and buried canyon heads smooth the scarp in the southernmost part of the study area.

The northern upper slope is separated from the southern slope by the Sao Tomé submarine canyon (STC) and presents a 10 km wide, flat erosional terrace, the Albacora Terrace, that extends from the base of the shelf break scarp to the 450 m-isobath. In its inner portion the terrace is marked by bottom current related erosional ridges elongated parallel or slightly oblique to the isobaths, and trending south towards the São Tomé canyon head. These ridges are tens of metres high, a few kilometres long and hundreds of metres wide. Furrows are also evident parallel to the isobaths in this region, passing in to a region of sinuous-crested sand waves to the south (Fig. 2). The southern upper slope is marked by a narrow terrace developed at the foot of the shelf edge scarp, at about the 200 m isobath. The upper slope shows a generally concave profile from 250 m to 550 m water depth, on the upper/middle slope boundary. To the far south of the study area, the headwalls of slide scars cut into the shelf edge.

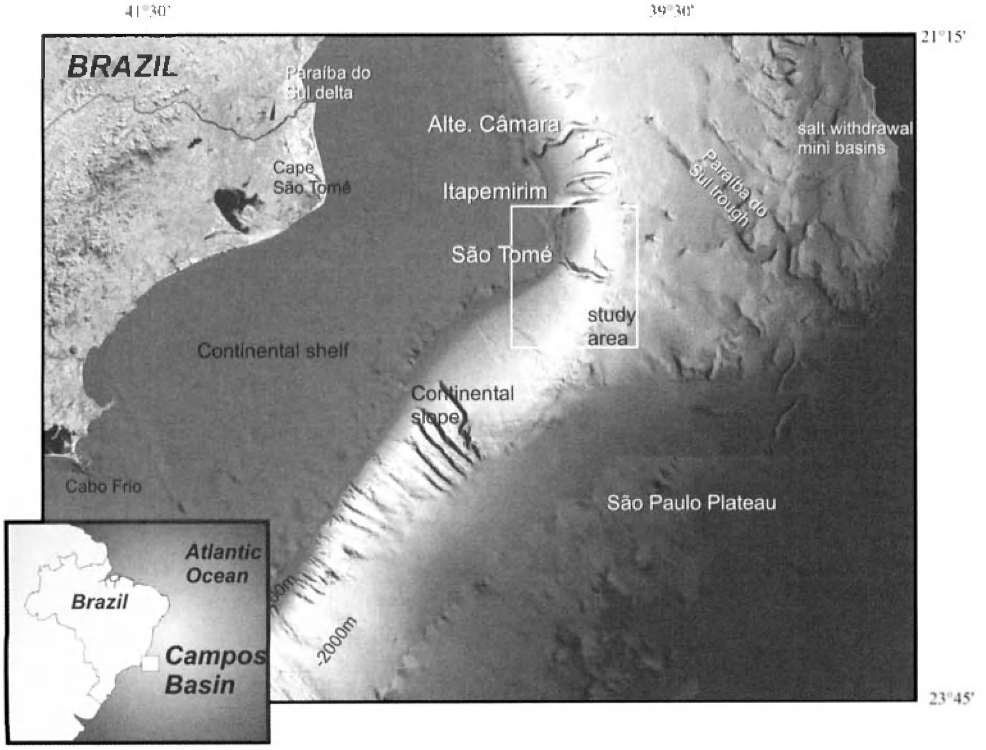

Fig. 1. Shaded bathymetric map presenting the main physiographic features mentioned in the text. White rectangle outlines the study area. Camara, Itapemirim and São Tomé are submarine canyons cited in the text. Note the similarity in shape between the coastline and the shelf edge. Deepest areas to the right reach up to 3000 m deep. Lighter areas correspond to continental slope (depths ranging from 400 m to 2000 m. Detailed bathymetry is presented in Figure 5.

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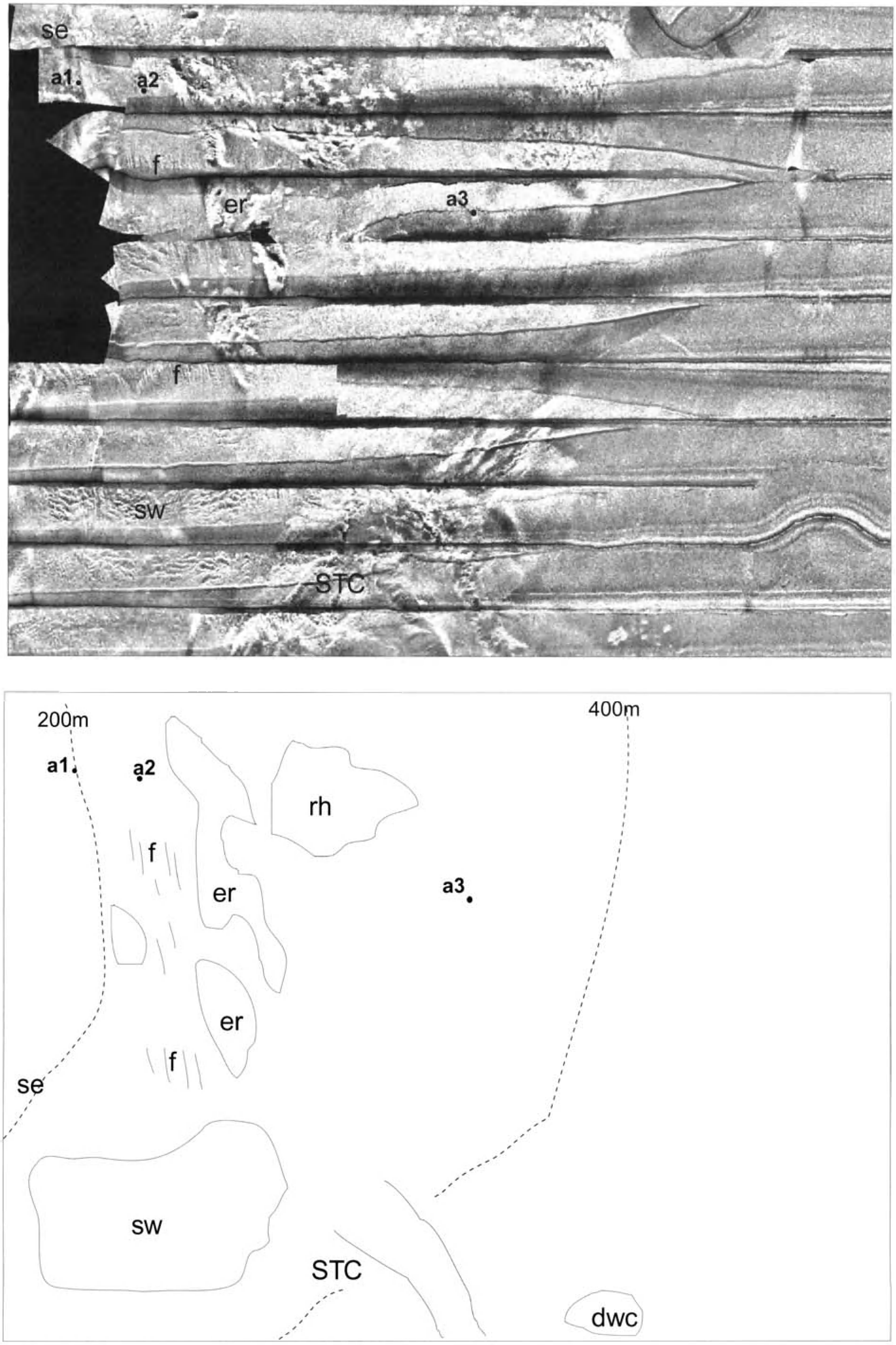

Fig. 2. Mosaic of side scan sonar images illustrating the funnelling zone of the southward flowing Brazil Current (BC). The impact of bottom currents and their southward intensity decrease are expressed as furrows (f) to the north where bottom currents are topographically confined between the shelf edge escarpment (se) and an upper slope erosional ridge (er), passing to 3D sandwaves (sw) to the south, in the expansion zone. Sand migration trend is towards the São Tomé canyon head (STC). a1, a2 and a3 are cores from the funnelling zone presented in Figure 7. dwc, deep water carbonates; rh, rhodolites.

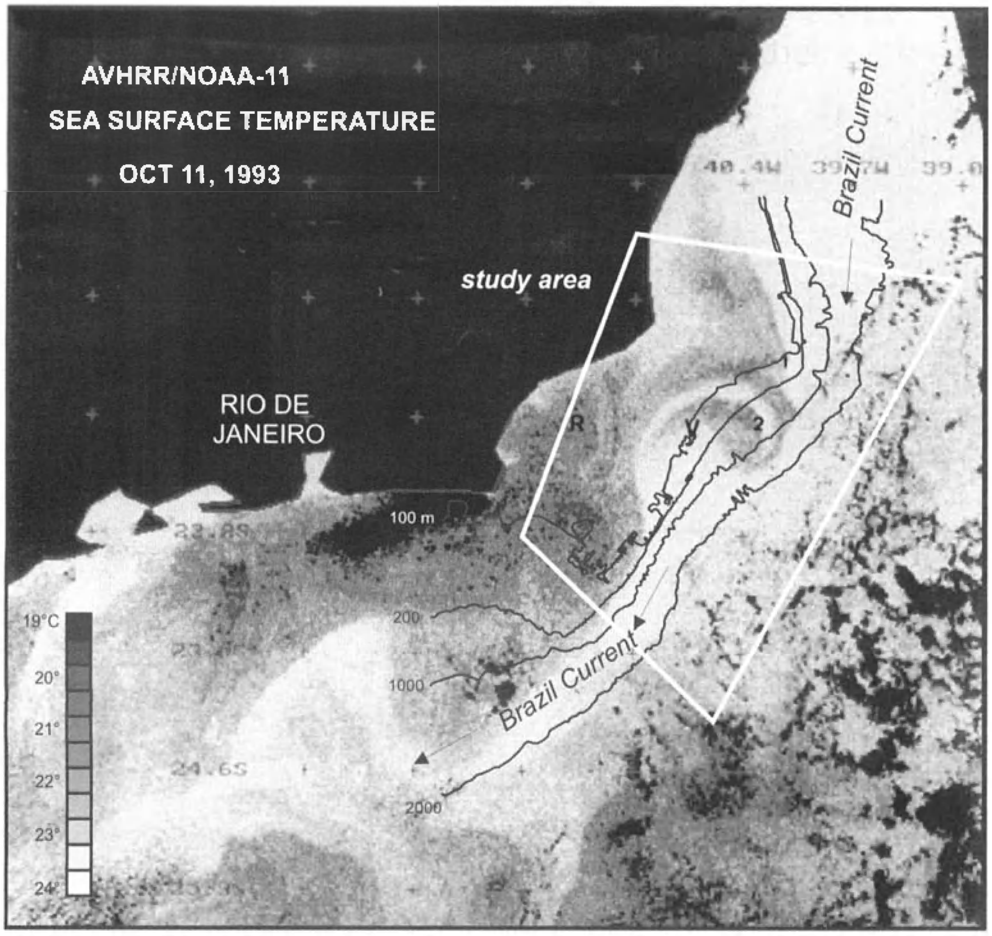

Fig. 3. Sea surface Temperature satellite image illustrating the general surface circulation of the SE Brazilian margin. V – Zone of Brazil Current (BC) eddy generation; 1, Exit of the BC funnelling zone (maximum lateral current narrowing and speed increase); 2, Re-entering of a BC filament in the BC expansion zone (current deceleration and flow perturbation – meanders and eddies).

Oceanographic setting

The hydrographic characteristics of the south-eastern Brazilian margin have been studied by many authors and are listed in Viana (1998) and Viana & Faugères (1998). The surface circulation (Fig. 3) can be separated into shelf currents and the Brazil Current (BC). Shelf currents are the result of combined meteorological and tidal forcing upon the shelf waters. The observations made by Campos & Miller (1995) suggest a northeastward propagation of shelf waters between the shelf break and the coast. The BC is a warm (> 20°C) saline (> 36‰) southward flowing western boundary current driven by the atmospheric circulation of the South Atlantic Gyre. The inner edge of the BC roughly coincides with the shelf break. Below the BC (400–1500 m), the Brazil Intermediate Counter-Current (BICC; Lima 1998) drives to the north both the South Atlantic Central Water (SACW) and the Antarctic Intermediate Water (AAIW). Over the lower slope, the sluggish southward flowing North Atlantic Deep Water is sometimes disturbed by benthic storms, that result in an increased flow velocity and, in some cases, a reversal in the flow direction.

The passage of the cyclonic gyres over the shelf imposes a 'sea-floor polishing' effect (Viana *et al.* 1995) provoking re-suspension and transport of sediments (Fig. 4). Eddies, storm- and tide-driven currents induce the shelf sand to spill over onto the slope, mainly as low concentration gravity flows and secondarily as high concentration fluid and plastic gravity flows. Once on the slope, sediments are subject to the BC and transported along the isobaths (Fig. 5).

Sediment characteristics

Superficial sediments on the outer shelf are composed of siliciclastic sands, carbonate debris and mixed composition material (Fig. 6). Siliciclastic sands extend throughout the outer shelf area developing large fields of sand waves, dunes and megaripples, tens of kilometres long and kilometres to tens of kilometres wide, being developed from the outer shelf to the shelf break. Between the 85 m and 130 m isobaths, sand waves have rectilinear crests (2D geometry in the sense of Harms *et al.* 1982) and show a north-eastern transport direction towards the shelf break. This direction corresponds to the resultant trend of the bottom shelf currents. On the upper slope terrace, sets of curvilinear-crested sand waves (3D geometry) are observed migrating towards the southwest, controlled by the Brazil Current passage.

The vertical succession of the latest Pleistocene–Recent upper slope sediments (Fig. 7) comprise from base to top: Facies 1 – a more than 50 m thick interval of closely interbedded sand and mud (S/M ratio < 0.2), resembling the muddy-silty contourites described from the Faro Drift (Gonthier *et al.* 1984), and deposited during the late Pleistocene: 85 – *c.* 25 ka BP (biozone Y2/lower Y1; Ericson and Wollin 1968); Facies 2 – a few metres- to several decimetres-thick interval of pebble to fine-grained sand, erosive into the muddy-silty contourite interval, and deposited during the Last Glacial Maximum (*c.* 18 ka BP) up to the onset of sea-level rise (Latest Pleistocene/early Holocene *c.* 12 ka BP); Facies 3 – at the very top of the sequence, extending downslope to the 700 m isobath, a fining upward few metres to several decimetres thick interval of coarse- to very fine-grained sand, deposited during the Holocene. Maximum thickness of the coarse-grained deposits (Facies 2 and 3) is about 30 m (Fig. 8).

Discussion

Upper slope sand deposits were developed on the modern Campos Basin margin due to particular characteristics of margin morphology and superficial hydrodynamics. The main conditions

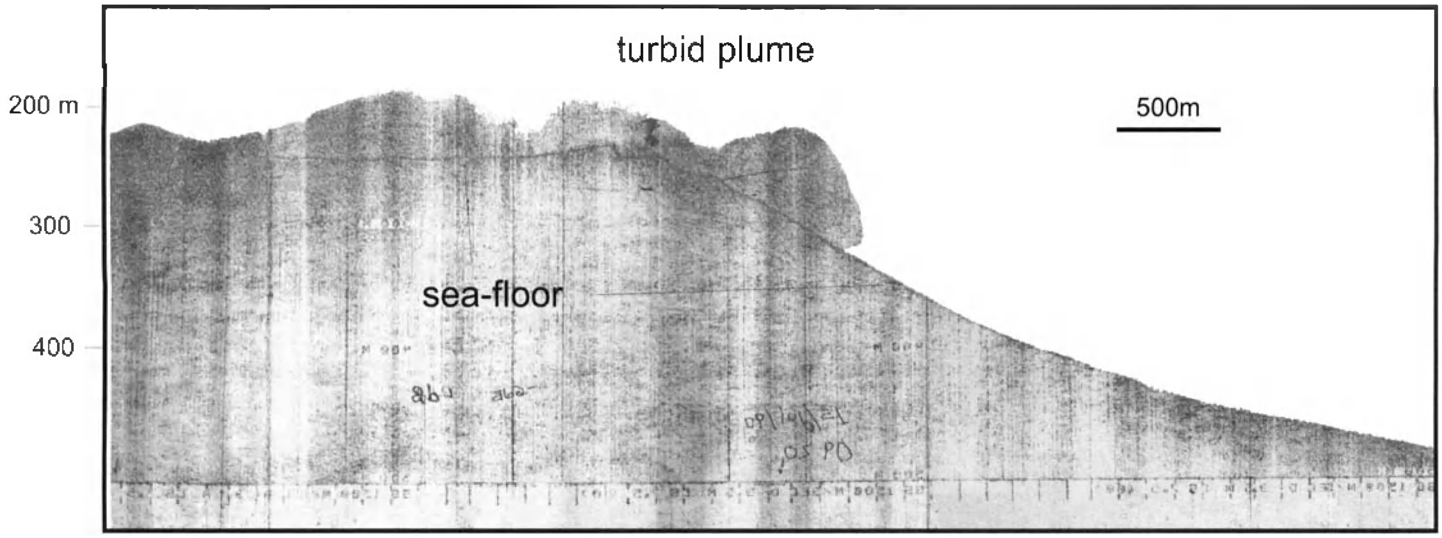

Fig. 4. 12 kHz echo-sounder record showing a turbid plume being detached from the shelf edge in the zone of the Brazil Current eddy activity (point 2 in the satellite image).

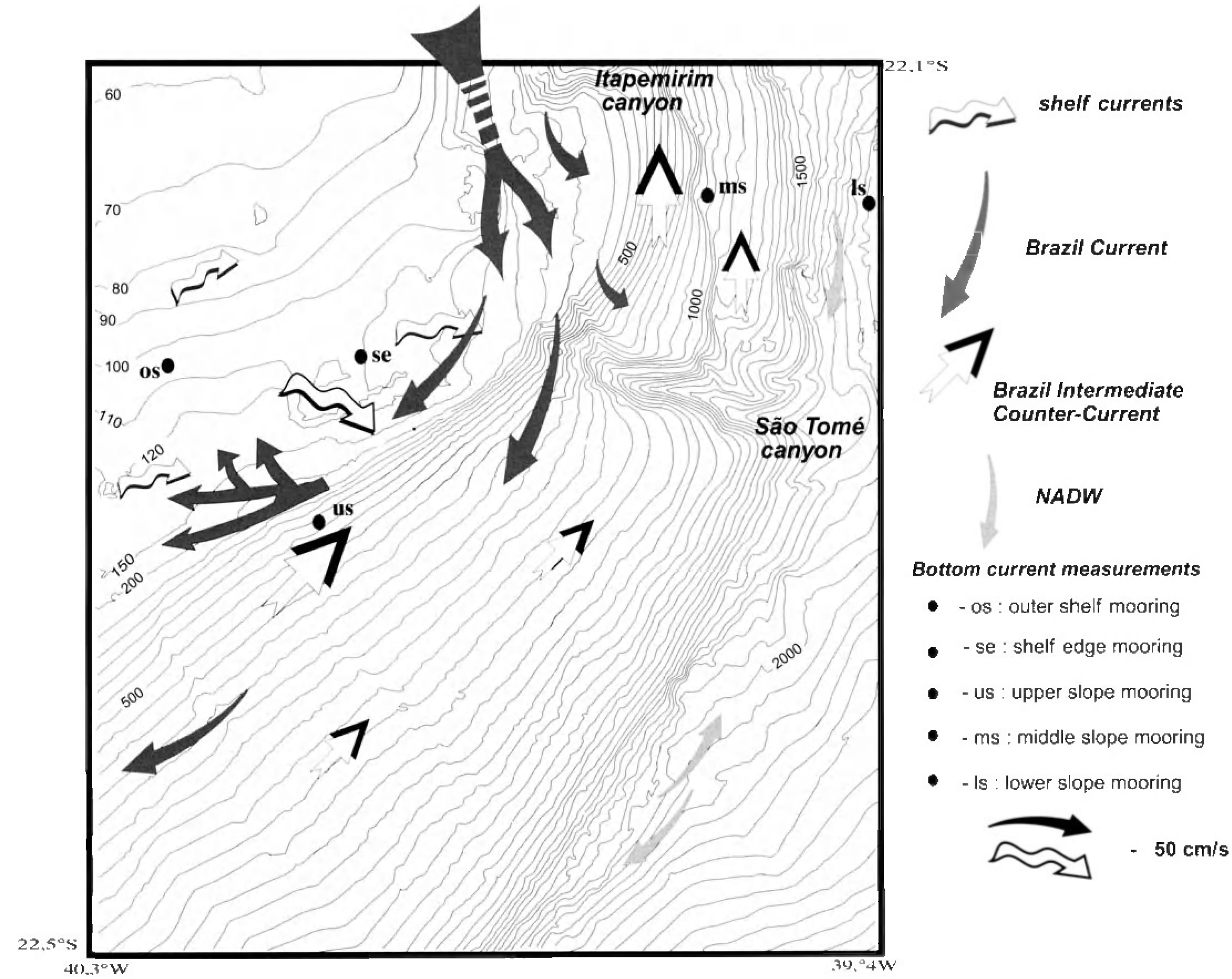

Fig. 5. Sea-floor projection of the main bottom currents: shelf currents are meteorologically controlled (southerly storm fronts and NE trade winds); the Brazil Current is a locally vigourous western boundary surface current with meanders and eddies; the Brazil Intermediate Counter-Current and the North Atlantic Deep Water Current are geostrophic currents locally controlled by topographically-induced long-term oscillations.

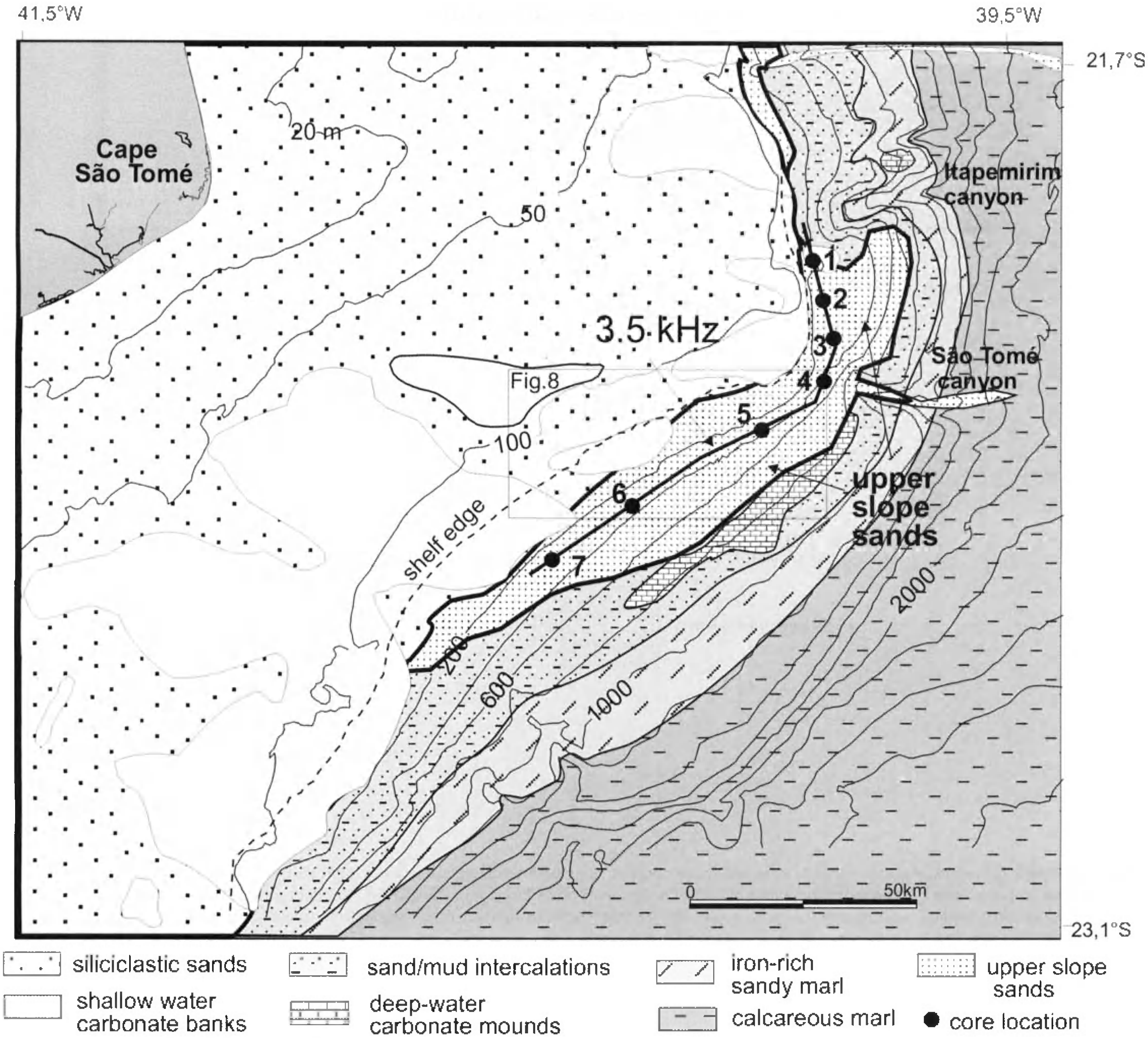

Fig. 6. Surface sediment distribution map highlighting the upper slope sand distribution, and location of the cores and 3.5 kHz record presented in Figure 9.

for development of upper slope sand accumulations are: (1) a convex outer shelf/slope morphology; (2) sandy sediment available at the shelf edge; (3) net offshelf transport of shelf sands induced by shelf edge bottom currents; and (4) the presence of a relatively strong slope boundary current. The interaction between the shelf/slope morphology and the hydrological factors is very important in leading to the deposition of upper slope sands. Two key physiographic sectors are involved: (1) The seaward projection of the shelf edge and the region immediately to the north. The morphology of this zone induces a funnelling effect on the southward circulation of the superficial BC. In this 'funnelling zone' the BC is accelerated to very high speeds and sweeps the shelf edge and the uppermost slope. (2) South of the seaward projection of the shelf, the BC expands and decelerates in response to the change in shelf/slope morphology, which shows a landward inflexion. In this 'expansion zone', the BC meanders and generates eddies whose activity interferes with the shelf currents.

In the 'funnelling zone', the modern sedimentation reflects very high energy environments (Figs 9 and 10a). As a consequence, the shelf edge is swept clean of sediment and the BC introduces coarse sediments onto the upper slope. Gravelly-to-coarse-grained sand deposits, and erosional features are common. Downslope, the sediments become fine-grained (very-fine sand at the transition between upper and middle slope, around 600 m water depth).

In the expansion zone (Figs 9 and 10b), outer shelf environments are dominated by shelf currents which induce the ENE migration of sand waves towards the shelf edge. Oceanic eddies constitute an important mechanism in the sand transport across the outer shelf. Downwelling of shelf waters seems to increase the downslope transfer of shelf sands, which are prolonged in the form of gravity-driven sand fluxes. Sand fluxes behave as successive and continuous grain flows, and, more locally, as high-density turbidity currents. Sandy sediments flow downslope, mainly through canyons and gullies, and also as direct spillover. In contrast to the northern area, where erosive features predominate, the uppermost

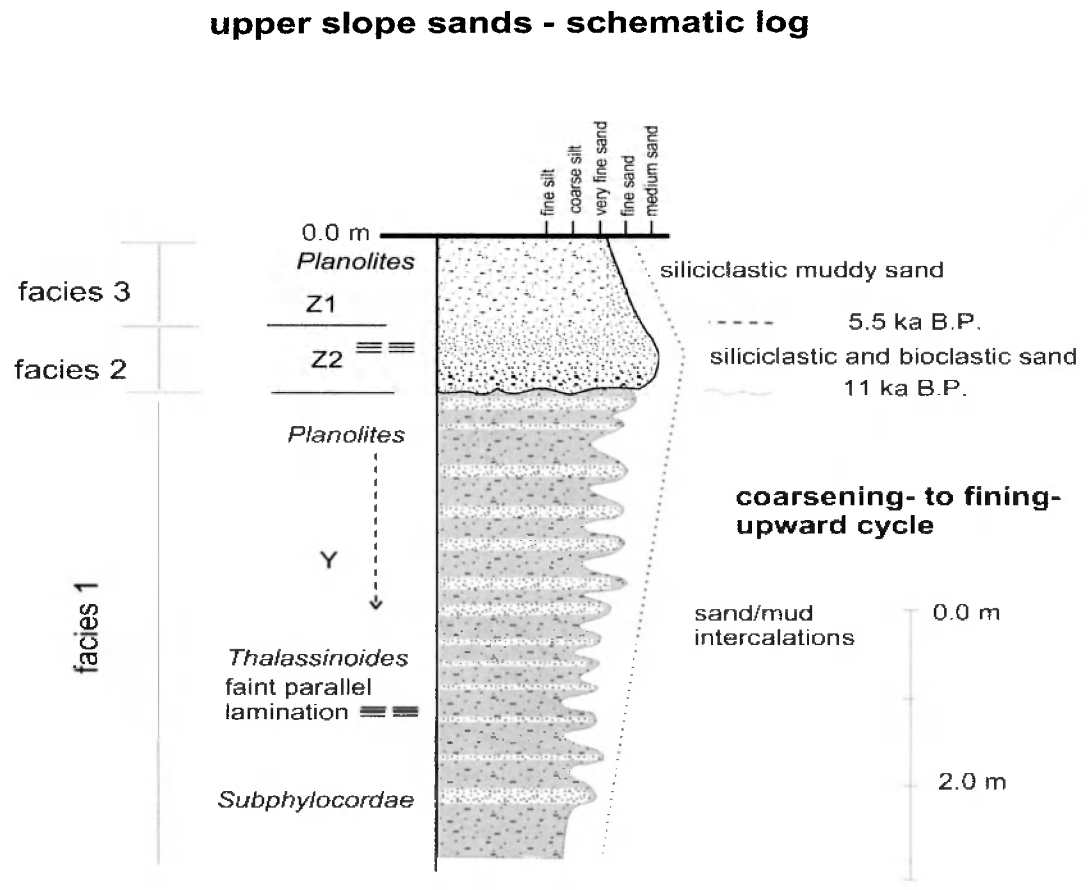

Fig. 7. Schematic log representing the vertical facies succession of upper slope sand accumulation at water depths around 400 m. X, Y, and Z are foraminiferal biozones from Ericson & Wollin (1966). Sediment is extremely bioturbated with ichnofossils also reported. The general characteristics of these deposits are coarsening- to fining-upward cycles, separated one from the other by sharp erosional contacts. Coarse-grained sediments were mainly deposited during the Holocene.

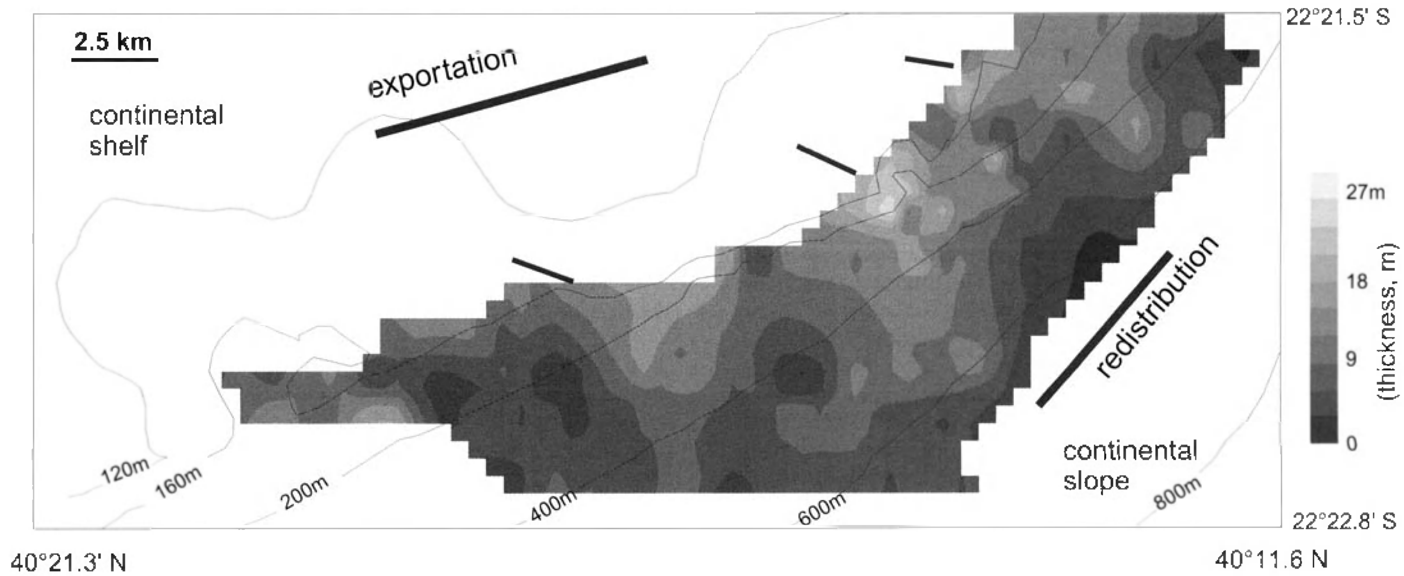

Fig. 8. Isopach map of upper slope sands in the expansion zone, elaborated from 3.5 kHz data. Thicker deposits are found spread along the foot of the shelf edge escarpment. Arrows indicate main trends of sand transport.

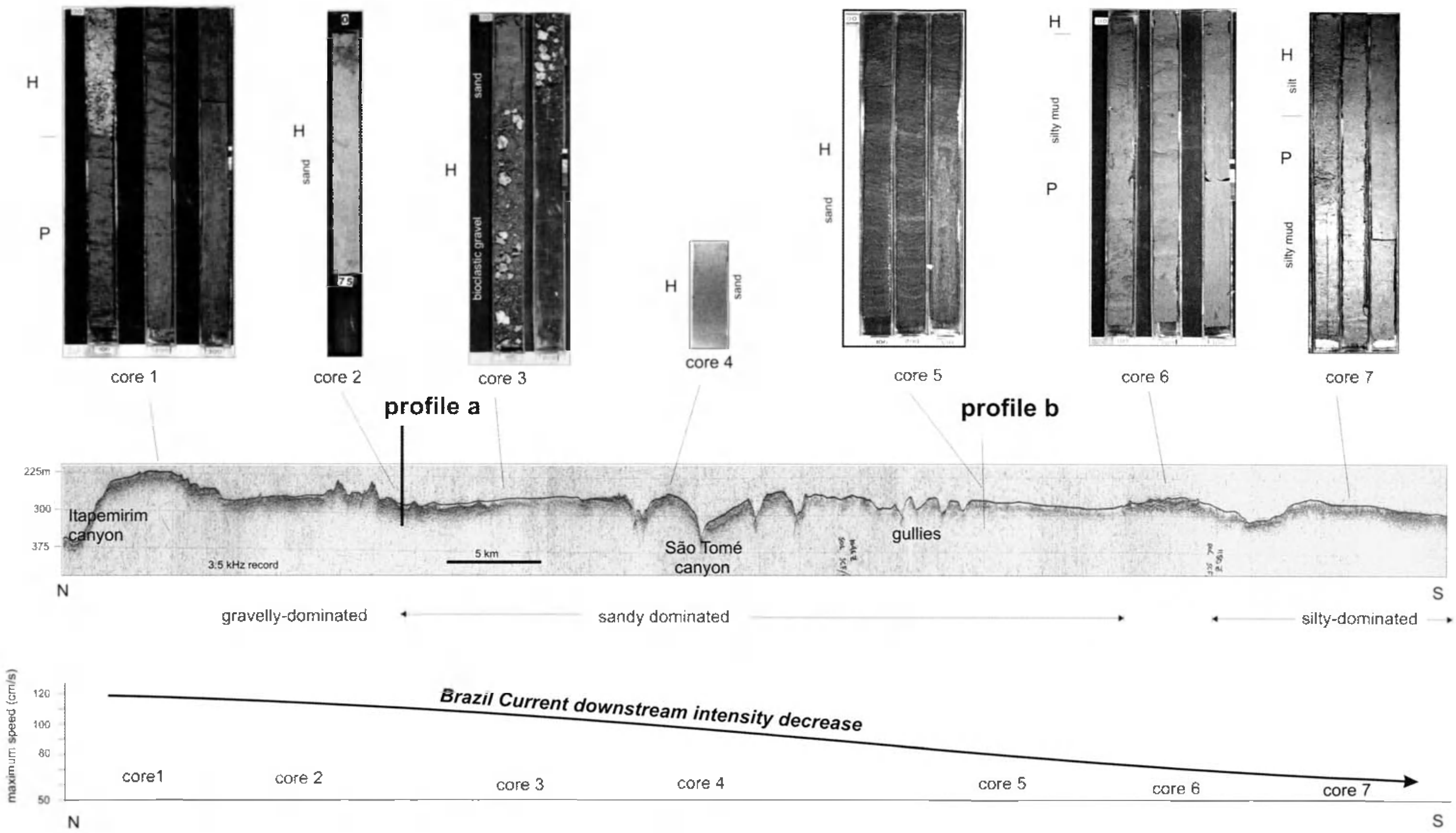

Fig. 9. Integration of core, shallow seismic (3.5kHz) and hydrographic data in an alongslope trend (~350 m water depth) corroborates the influence of the Brazil Current (BC) on sediment distribution over the slope. The shallow transparent zone on 3.5 kHz profile (see location on Fig. 6) represents areas of sand accumulation. A decrease in grain size is observed (cores 1 to 7) related to a decrease in intensity of the BC. In the current funnelling/acceleration zone, coarse-grained sediments are deposited (cores 1 to 3) and the Pleistocene (P)/Holocene (H) boundary is often marked by a sharp/erosional contact (core 1). The São Tomé canyon head is filled by BC-transported sands (core 4, see also side scan sonar image, Fig. 2). Coarse to medium sand was retrieved in the entrance of the expansion zone (core 5), showing planar and cross lamination. Sea-floor erosion (core 6) is related to sediment-starved topographic highs. Fine-grained sediments retrieved in core 7 represent the distal portion of the upper slope sand deposit, related to the absence of shelf sediment input and to a decrease in bottom current activity.

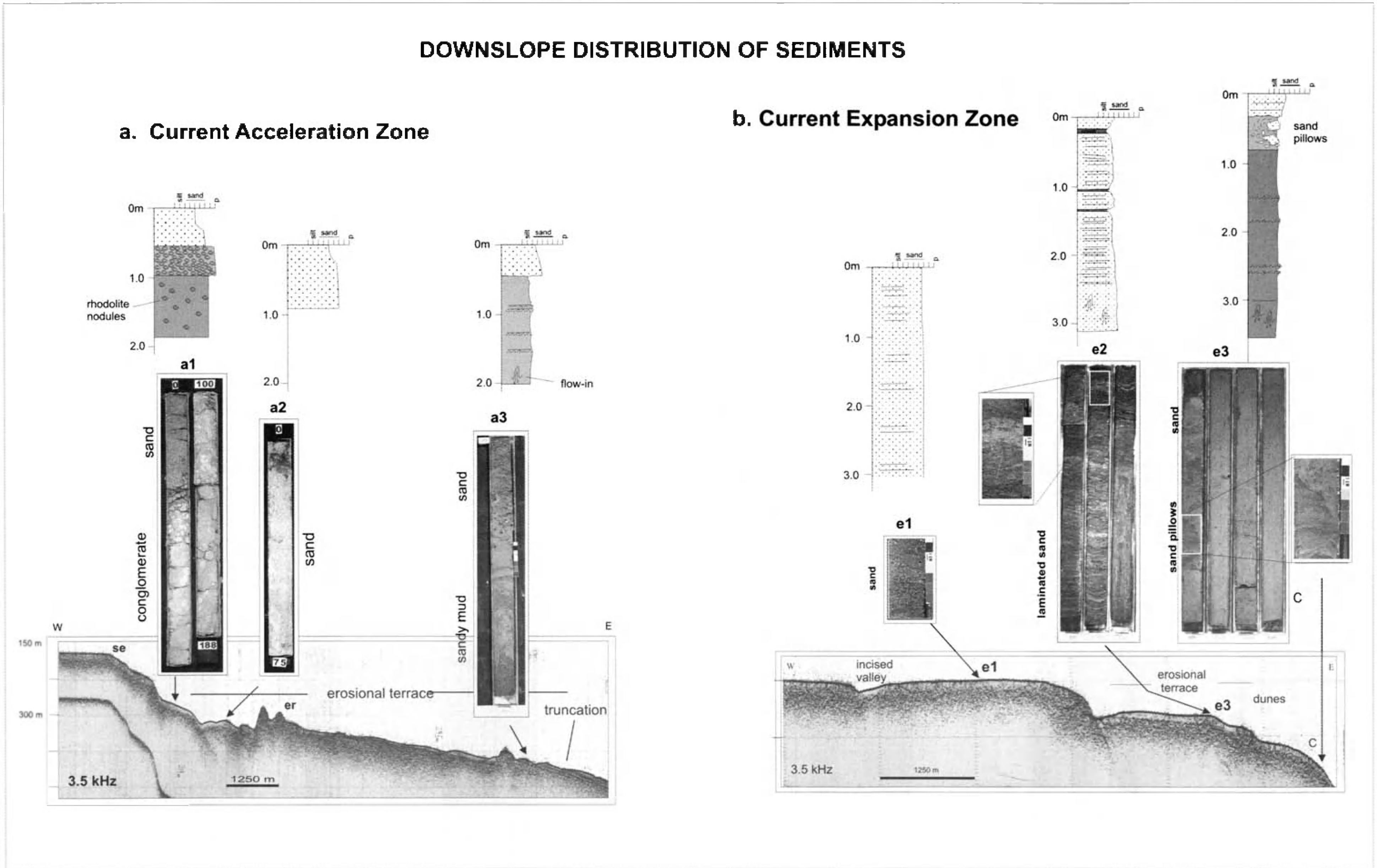

Fig. 10. Downslope 3.5 kHz profiles in the current funnelling zone (**a**) and in the current expansion zone (**b**). The downslope fining is well characterized in both cross sections. In section (**a**), very coarse-grained sediments are related to the export of the adjacent shelf edge carbonates (se). The channelled area between the shelf edge and the erosional ridges (er). The erosional terrace results from the activity of the BC. Truncation is observed in the distal portion of this section. Location of cores a1, a2 and a3 are presented in Fig. 2. Section (**b**) shows incised valleys at the outermost shelf and a narrow erosional terrace at the uppermost slope where large bedforms are developed. Core e2 presents planar and cross lamination indicating the high energy of the environment. Core e3 presents sandy contourites intermingled with gravity flow deposits, characterised by the medium-grained sand in a finer matrix (silty sand).

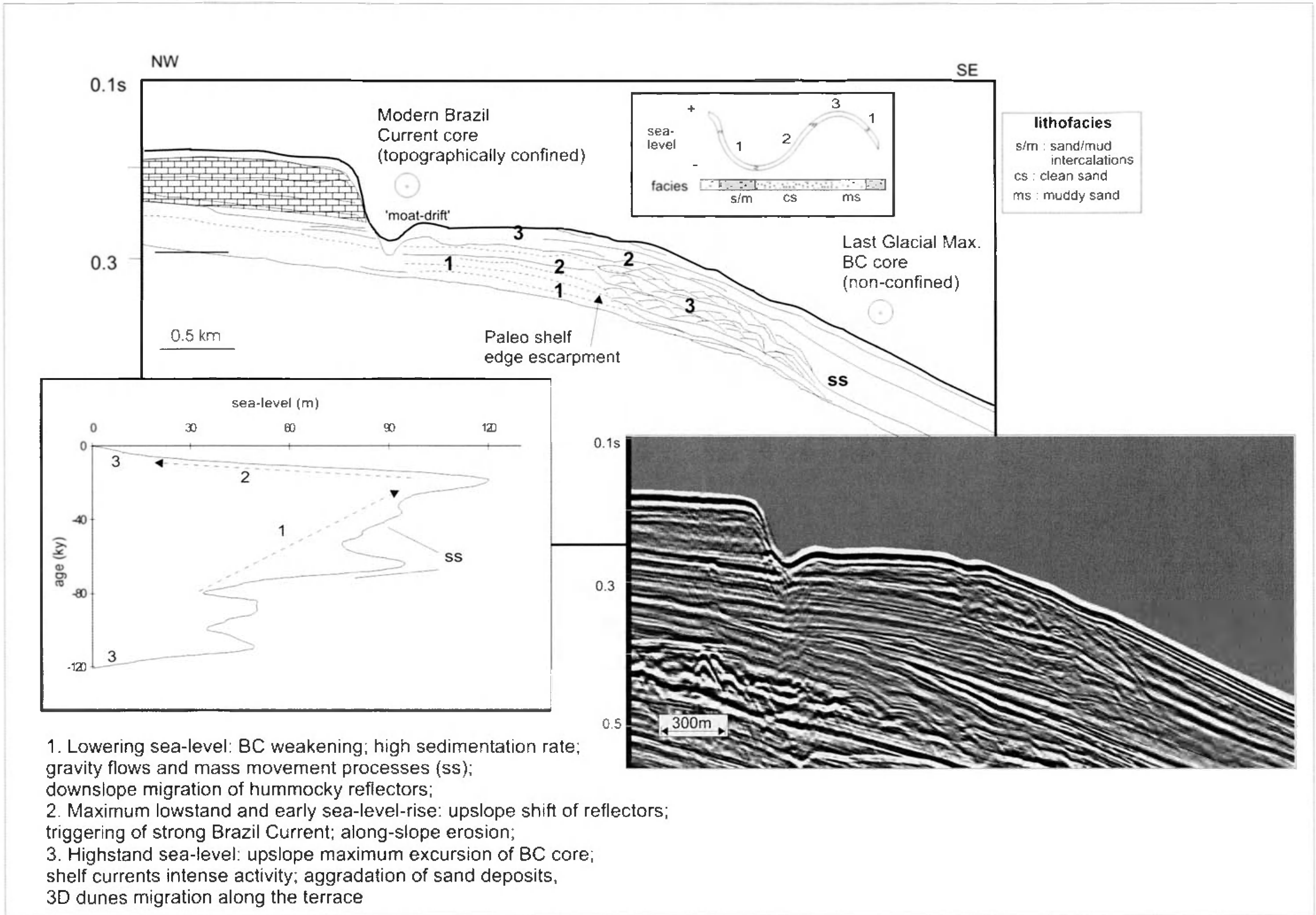

Fig. 11. Seismic-stratigraphic scheme of upper slope sand deposition. Clean sands were deposited during the early sea-level rise, when the BC achieved its maximum intensity. The relative deceleration of the BC during the modern highstand resulted in the deposition of muddy sands. Sand/mud intercalations correspond to sea-level lowering deposits. Major periods of sand accumulation are found from the early sea-level rise to the present highstand.

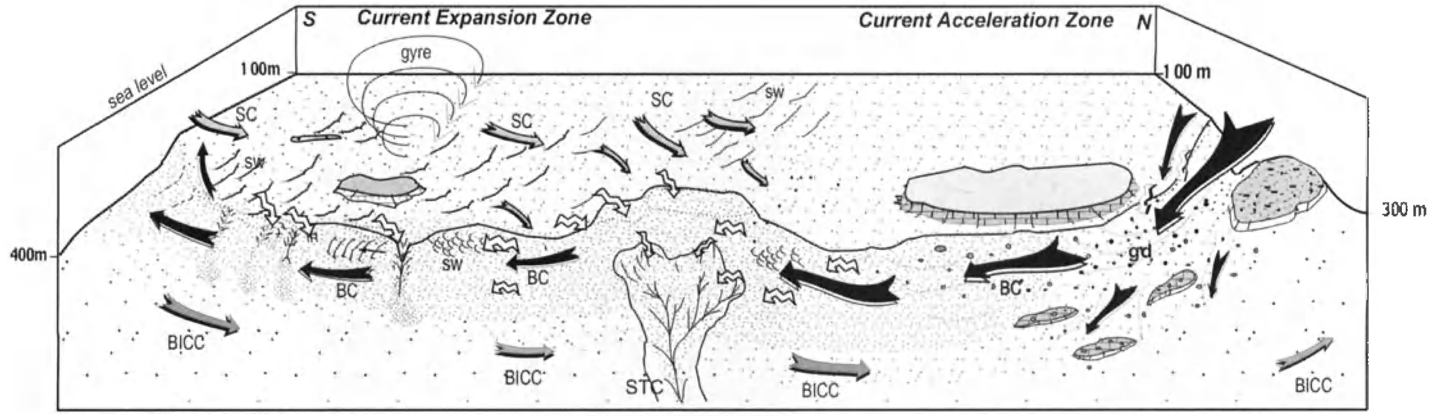

Fig. 12. Schematic representation of the main sedimentary processes related to the passage of bottom currents over the shelf edge and upper slope. BC, Brazil Current; BICC, Brazil Intermediate Counter-Current; SC, Shelf Currents; STC, São Tomé Canyon; sw, sand waves; gd, gravel deposit. Wavy arrows indicate bed-load transfer. From Viana & Faugères (1998).

slope is characterized by bedforms migrating along the trend of the southward flowing BC. They develop curvilinear-crested (3D) sand waves in the head of the gullies and rectilinear-crested (2D) sand waves in the intergully areas. Downslope, the sand is redistributed as sand sheets by the BICC.

The vertical transition to underlying fine-grained sediments is erosive in the funnelling zone, whereas in the expansion zone, it is sharp or gradual. The general vertical facies succession observed in both zones defines a coarsening-fining upward sequence. The general geometry of the upper slope sand deposits is a thin wedge-shaped accumulation, tens of metres thick in the proximal zone, thinning downslope. The wedge is five to ten km wide downslope and extends tens of kilometres alongslope.

The internal seismic pattern of the coarse-grained sandy layers is transparent to discontinuous and hummocky. The fine-grained sand to sand/mud facies shows a hummocky clinoform seismic pattern grading to wavy and then parallel reflections in the steepest southern zone, and a parallel pattern in the flattened northern zone (Fig. 11).

The model here proposed is summarised in Figure 12. It suggests that important sand accumulations occur at the upper slope during highstands of sea-level (Fig. 11). The highstand activity is due to the presence of shelf currents that sweep off the shelf large volumes of sand, and to strong superficial slope-boundary currents, that rework the sand along the slope. These currents were inhibited during sea-level fall, and the shelf currents no longer existed at the maximum lowstand, when the shelf areas were subaerially exposed.

Coarse-grained, well-sorted sand deposits covering relatively large areas make the upper slope sand deposits an attractive play to be investigated for potential hydrocarbon reservoirs. The main difficulty in the application of this model to hydrocarbon reservoir analogues seems to be the vertical and lateral development of sealing facies. The Campos Basin example suggests that the hydrodynamic changes which accompany the climatic/sea-level fluctuations may be severe enough to induce the needed facies alternation. A more systematic study of modern environments must be coupled with research on ancient rock outcrops in order to evaluate the geological record of different expressions of the controlling mechanisms of our model.

The analysis of facies distribution, depositional geometry and physiographic and hydrographic features indicates that the development of upper slope sand bodies results mainly from the alongslope sediment reworking and redistribution by slope boundary currents. Factors important in generating such sedimentation are: (i) relatively strong offshelf-trending bottom currents, (ii) a linear multiple source supply, with direct shelf sediment spillover, (iii) short downslope gravity transport, and (iv) vigorous slope boundary currents. The presence of coarser facies and large erosional features on the northern slope indicates the higher energy of that area corroborating the hydrographic observations. The grain size fining trend along the upper slope sand deposits coincides with Brazil Current downstream intensity decrease demonstrating the direct relationship between the deposit and the Brazil current activity. The fundamental elements of such a model are: a sand-rich shelf; an erosional terrace at the top of the slope; offshelf sand spillover by gravity flows and dune migration; sand rich deposits on the upper slope, and; lateral filling of canyon heads.

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