The Columbia Channel–levee system: a fan drift in the southern Brazil Basin

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Abstract: The Columbia Channel is a turbiditic channel elongated W–E on the rise of the south Brazilian basin (4200 to 5000 m water depth). The whole area is swept by the northward flowing Antarctic Bottom Water. As a consequence, depositional processes have built a fan drift system. This system displays a levee along the northern flank of the channel while no levee occurs on its southern flank due to the Coriolis effect. The levee (400 km in length and 100 to 200 km in width) is bounded to the north by the Vitoria–Trindade Seamounts. It shows, first, a W–E trend parallel to the channel axis and predominantly turbiditic pattern, and then a S–N trend parallel to the rise contours with a predominant contouritic pattern. Its thickness is up to 1000 m. The distribution of sedimentary processes and associated deposits were investigated on the basis of water gun seismic and 3.5 kHz echosounding profiles, and core lithology. On the lower S–N part of the levee, the deposits consist of muddy contourites. On the shallowest part, turbidites that originate from the upper continental margin in the channel and on the southern part of the levee close to the channel, and from the Vitoria–Trindade Seamounts on the northern part of the levee, are interbedded with contouritic muds, and top-truncated silty turbidites. Areas subjected to turbidity current processes show chaotic to well-stratified, high amplitude reflections, in the subsurface, and more or less prolonged echofacies with or without sub-bottom reflectors, at the seabed. Areas subjected to contour currents show, in the subsurface, transparent seismofacies with some discontinuous low amplitude wavy reflections, and, in the surficial deposits, predominant wavy echofacies with sub-bottom relectors, frequently associated with tangential hyperbolae.

The Columbia fan-drift system in the northern part of the southern Brazil Basin is an example of a mixed drift body formed as a consequence of the interaction of turbidity and contour current depositional processes (Fig. 1, Table 1). This is similar to the Hikurangi fan-drift system off New Zealand (Carter & McCave 1994; Lewis 1994; McCave & Carter 1997). In this paper we summarize and develop earlier work on the Columbia fan-drift (Massé *et al.* 1998; Faugères *et al.* 1999), based on data acquired during the BYBLOS cruise (Faugères 1988) including 3.5 kHz and water-gun seismic lines, and six Kullenberg cores. The cores were collected along two 3.5 kHz profiles crossing the system. The shallower western profile runs S–N, normal to the axis of the channel. Cores KS 8820 and KS 8821 are located on the northern levee, core KS 8822 in the axis of the channel, and cores KS 8823 and KS 8824 on the southern edge of the channel. The deeper eastern transect is oriented SW–NE, with core KS 8826 collected on top of the levee.

Table 1. *Principal characteristics*

Location:	the continental rise and abyssal plain of the south Brazilian basin
Setting:	major channel-levee system along a volcanic seamount chain (4200–4700 m water depth)
Age:	end Oligocene ? to Recent
Drift type:	fan-drift system with a turbiditic levee merging into a contouritic levee downslope
Dimensions:	length 400 km; width 100 to 200 km; thickness about 1000 m
Seismic facies:	transparent reflections and a very thick undulating echofacies with numerous subbottom reflectors as contourite signature
Sediment facies:	turbidites, muddy contourites, top-truncated turbidites

Geological and oceanographic setting

The Southern Brazil Basin first developed during the Cretaceous and is marked by active transform faults and volcanic lineaments directed E–W (Schobbenhaus *et al.* 1984). The Columbia Channel is more or less parallel to two of these major lineaments, the Rio de Janeiro lineament in the south and the Vitoria Trindade lineament in the north, and its course seems to be under a strong structural control. The channel is a major feature that displays an overall WNW–ESE orientation and can be traced to 5000 m water depth across the abyssal plain. The shallow-water sediments passing through the channel accumulate on its northern edge, where a smooth levee occurs. In contrast, a gently northward sloping accumulation is observed on the southern flank of the channel.

In the Southern Brazil Basin, Antarctic Bottom Water (AABW) is found at depths greater than 4000 m, and flows northwards (Reid *et al.* 1977; Reid 1996). It is responsible for the construction of contouritic accumulations on the lower rise and the abyssal plain (Massé 1993; Mézerais *et al.* 1993; Massé *et al.* 1994; Faugères *et al.* 2002). In the vicinity of the Columbia Channel, AABW is deflected eastwards along the northern levee and the Vitoria–Trindade Chain (Fig. 15), developing eastward trending rise swells, and enters the northern part of the Brazil Basin through the deep passages crossing the Chain (Mello 1988; Castro 1992).

Two major sources of sediments may provide material to the study area (Massé 1993; Massé *et al.* 1996): (1) the Brazilian continental slope and rise north of Rio de Janeiro (downslope supply with high kaolinite contents) and (2) the deep Argentine and South Brazil Basin swept by the northward moving AABW current (alongslope supply with very low kaolinite and predominant chlorite and smectite contents). In addition, some sediments may come from the surrounding volcanic seamounts.

Bathymetry

The Columbia Channel (Figs 1 to 7) is a deep valley elongated downslope from 4200 to 5200 m, with a downslope decreasing channel depth (from about 400 to 250 m), a width of about 20 km at the top of the valley flanks, and 4 to 5 km on the very flat valley floor. It is firstly directed WNW–ESE and then moves slightly

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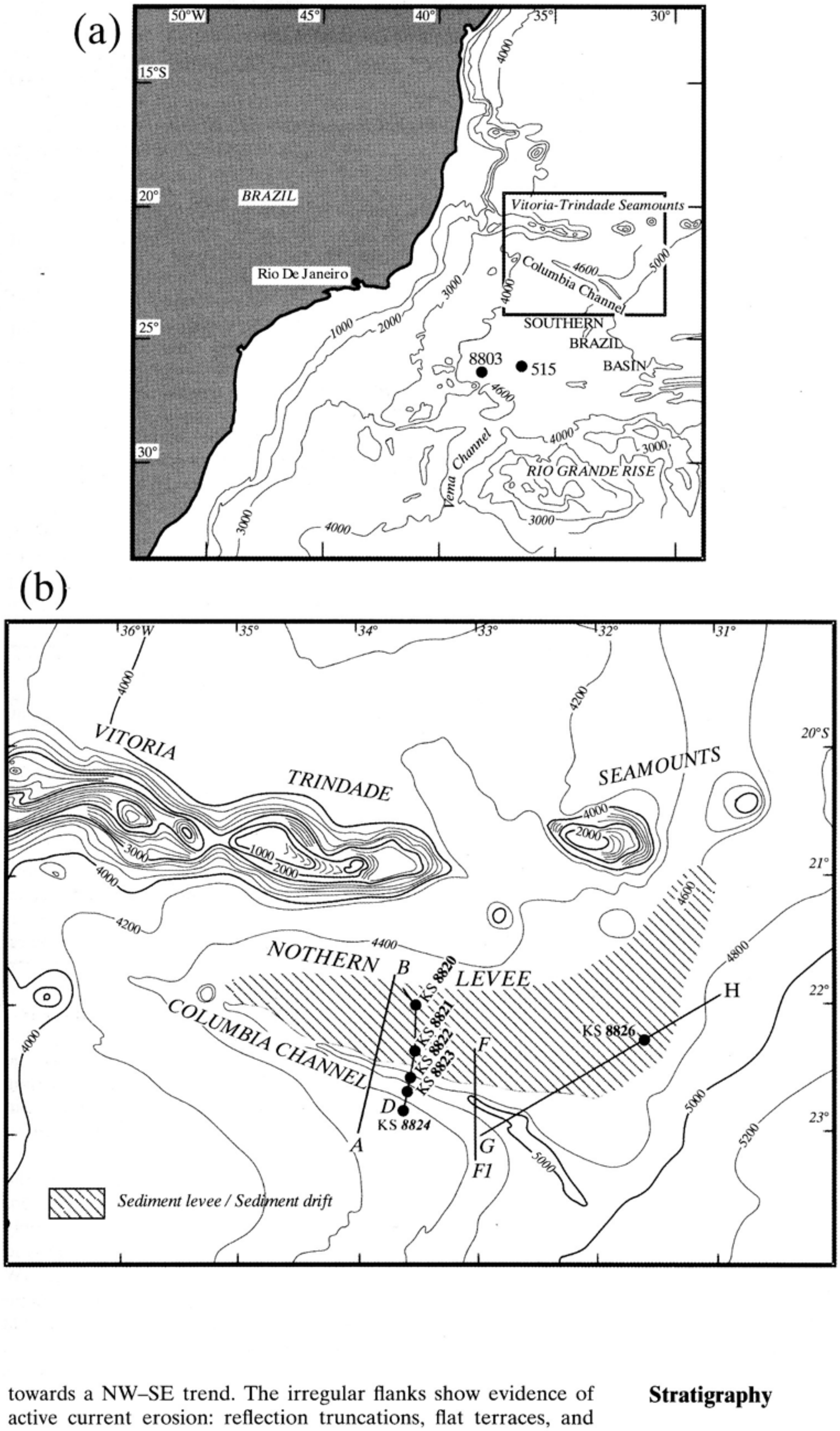

Fig. 1. (**a**) Location map of the study area, with DSDP site 515 and Byblos core KS8803; (**b**) bathymetric map of the Columbia Channel–Levee System (depths are in metres), and location of the cores and seismic and 3.5 kHz echosounding profiles (AB, FF1, GH).

towards a NW–SE trend. The irregular flanks show evidence of active current erosion: reflection truncations, flat terraces, and erosive scars linked to sliding processes.

The northern levee developed along the channel is about 400 km long and 100 to 200 km wide and is bounded to the north by the Vitoria–Trindade volcanic seamounts. It has a gentle relief with a fairly flat and regular surface without any secondary channels. At greater depths, the levee shifts towards a SSW–NNE orientation, parallel to the rise contour, and has a more mounded shape with wavy bedforms. There is no levee south of the channel where the rise sea-floor slopes down gently and regularly northwards and eastwards.

Stratigraphy

Due to a lack of carbonate in the sediments deposited below the CCD, and the occurrence of frequent hiatuses and sediment reworking linked to the turbidity currents, in the cores, there is no good control of the core and seismic stratigraphy. A fairly reliable stratigraphy has been established only for core KS 8826. It is supported by nannofossil biostratigraphy, excess 230^{Th} activity analyses, carbonate curves and comparison with cores collected in the Vema contourite fan area (Massé 1993; Faugères *et al.* 2002). In addition, there is no deep-sea drilling site in the vicinity of the study area to support seismic interpretation.

Seismic characteristics: reflection profile

Seismic reflection profiles

Two water-gun profiles that cross the system (Figs 2 and 3) are presented here. The proposed stratigraphical interpretation is hypothetical as it is only supported by data from DSDP site 515 (Gamboa & Rabinowitz, 1981, 1984; Gamboa *et al.* 1983; Fig. 1a) located far away to the south. Profile AB oriented NNE–SSW (Fig. 2) crosses the shallow part of the system. It shows a striking contrast in seismic pattern between the area south of the channel and the northern levee.

South of the channel, two seismic units can be distinguished above the acoustic substratum:

(a) A lower South Unit 1 (SU1, 600 m in the south to 400 m close to the channel) is subdivided into 2 subunits. SU1a, at the base, is characterized by predominant high amplitude chaotic reflections that merge upwards into high amplitude reflectors showing a progressively better stratification. The SU1b-SU1a boundary is marked by a locally erosional discontinuity (R1) and by a reflection change. SU1b displays well-stratified high amplitude fairly continuous reflections. However the reflectors become locally irregular, with onlap or truncated geometry often associated with thin lenses of chaotic reflections (erosive shallow mini-channels). SU1b is truncated at the top by an erosional, flat and horizontal surface (R2).

(b) An upper South Unit 2 (SU2) increases in thickness southward (400 to 800m) and displays very transparent reflections with small-scale wavy reflections, the amplitude of which may increase towards the South or at the top.

Below the Columbia Channel, the acoustic substratum is not well marked. Basal transparent to chaotic reflections are overlain by irregular reflectors. A shallow channel (ch.2, Fig. 2) appears at approximately the same horizon as the R1 discontinuity. It then migrates northwards still as a shallow feature, and deepens due to sediment accumulation on both flanks and/or erosion and transport on the valley bottom. Both flanks show high amplitude chaotic reflections.

North of the channel, 2 major units can be distinguished:

(a) A basal North Unit (NU1, 350–400 m) covers the acoustic substratum. It is characterized by predominant high amplitude chaotic reflections that merge upwards into high amplitude reflectors progressively showing better stratification. The most prominent reflectors present a gentle southward dip and suggest a N–S progradation of the deposits. This unit is bounded at the top by a discontinuity underlined by a rapid change in the seismic reflections, and local erosive patterns. In the southern part of this unit, the reflections display channel-like geometries (ch. 1, Fig. 2). At the north end of the profile where the unit thickens, correlations between other available seismic profiles allow the intrepretation of this discontinuity as equivalent to R1. This implies that NU1 can be correlated with SU1a, and hence the equivalent of SU1b either should have been (partly or totally) eroded before the deposition of the overlying NU2 or corresponds to the lower part of the overlying NU2 Unit.

(b) An Upper North Unit 2 (NU2, 600–800 m) shows, at the base, uniform transparent reflections (SU1b?) that progressively merge upwards into high amplitude chaotic reflections in the south of the unit, and, in the uppermost northern part of the unit, high amplitude irregular and more or less continuous reflectors that, in the north, gently dip southward. Wavy geometries occur at the top, near the channel.

SU2 is characterized by transparent to wavy reflections and interpreted as a contouritic sheet drift. It was most likely deposited since the upper Oligocene on the R2 surface (correlated with the lower-Oligocene AABW erosive event, Gamboa & Rabinowitz 1981, 1984; Gamboa *et al.* 1983; Mézerais 1991; Mézerais *et al.* 1993; Faugères *et al.* 2002). SU1, at the base, could correspond to pelagic hemipelagic sedimentation (SU1a, pre-Eocene deposits?), merging progressively upwards into coarser-grained deposits controlled by turbidity or contour currents (SU1b, lower to middle Eocene ?).

The flat upper North Unit (NU2) compared to the upper south unit (SU2) displays different seismic patterns with predominant chaotic and high amplitude reflections. It is interpreted as a turbiditic sheet. The turbiditic supply seems to originate from either the Columbia Channel or from a more northern source (Vitoria Trindade ?) with turbidity currents responsible for the southward dip of the high amplitude continuous reflectors in the northern upper part of the levee. However, in the lower part of the levee and near the top close to the channel axis, the occurrence of transparent reflections associated with subtle wavy bedding, very similar to the reflections in the SU2 unit, suggest that the contouritic deposits may play a significant role in the building of the levee body. Taking into account the flat surface, it would be more sensible to call this 'northern levee' a 'turbiditic sheet' and even probably a 'mixed turbiditic-contouritic sheet'. The age of the basal R1 discontinuity remains speculative: (?) lower Eocene. Both flanks of the channel display very high amplitude chaotic reflections and a sharp lateral contact with the contouritic deposits to the south and the turbiditic deposits to the north. They are interpreted as coarser-grained turbiditic sediments associated with downslope mass movement.

Profile GH (Fig. 3) crosses the deepest part of the system in a NE–SW direction. It displays a basal SU1' comparable to SU1 unit and bounded at the top by the R2 erosive surface. SU1' runs with similar seismic pattern northeastward, and is called NU1'. However NU1' is bounded at the top by an erosive surface interpreted as equivalent to R1. Above R2, south of the channel, an upper SU2' unit shows seismic reflections identical to those of the SU2 upslope, implying no major change in the contouritic sheet drift down the rise, except for a decrease in thickness. Above R1, north of the channel, a thick mounded unit (NU2', up to 800 m) also presents seismic patterns similar to those of the contouritic SU2 and SU2' (transparent to wavy reflections). It is interpreted as a contouritic levee. This means that the predominantly turbiditic sheet (NU2) observed upslope has merged progressively into a contouritic levee (NU2'). The Columbia Channel first occurrence seems to be synchronous to R1 discontinuity or slightly before. A clear northward migration of the channel axis occurs during the first stages of the channel history, which is opposite to what should be produced by predominant turbidity currents, i.e. the building of a turbiditic levee on the left (north) flank of the channel. This would imply the dominant role of contour currents in building the north basal levee. On the channel flanks, high amplitude continuous reflections associated with more or less discontinuous to chaotic reflections more likely correspond to turbiditic deposits. These deposits extend further away from the channel, and the lateral transition with the contouritic deposits are more gradational than on the previous profile.

Echofacies mapping

The echofacies and the lithology of the deposits from the shallow part of the system are presented on Fig. 4. Various echo types have been distinguished (Figs 4 and 5a) and interpreted according to Damuth (1975) and Damuth & Hayes (1977).

Large irregular hyperbolae with varying vertex elevations (echo-type IIIA) are found in the steeper portions of the channel walls due to a rugged morphology. The axis of the channel is

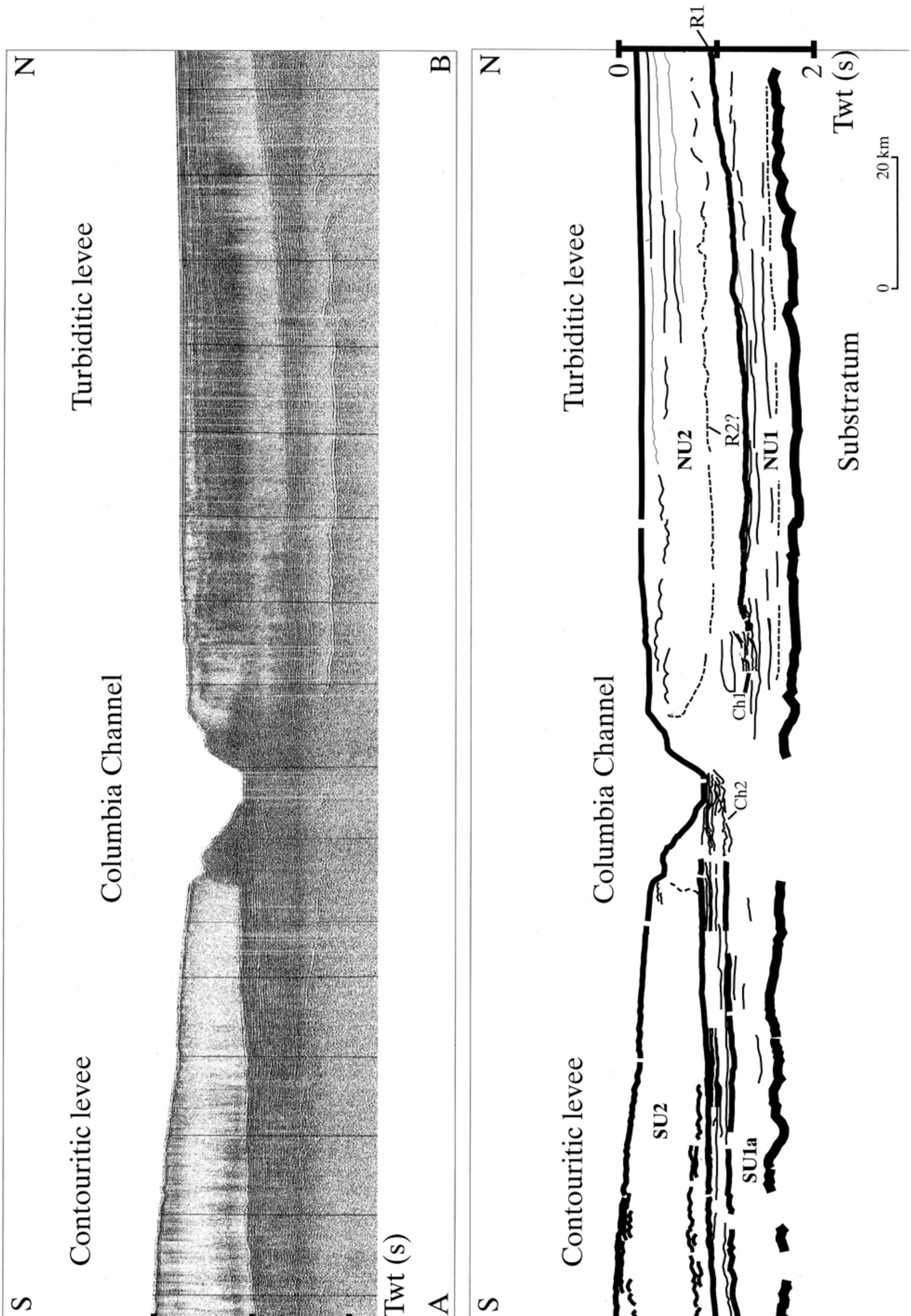

Fig. 2. Seismic line A–B, crossing the shallower part of the channel-levee system.

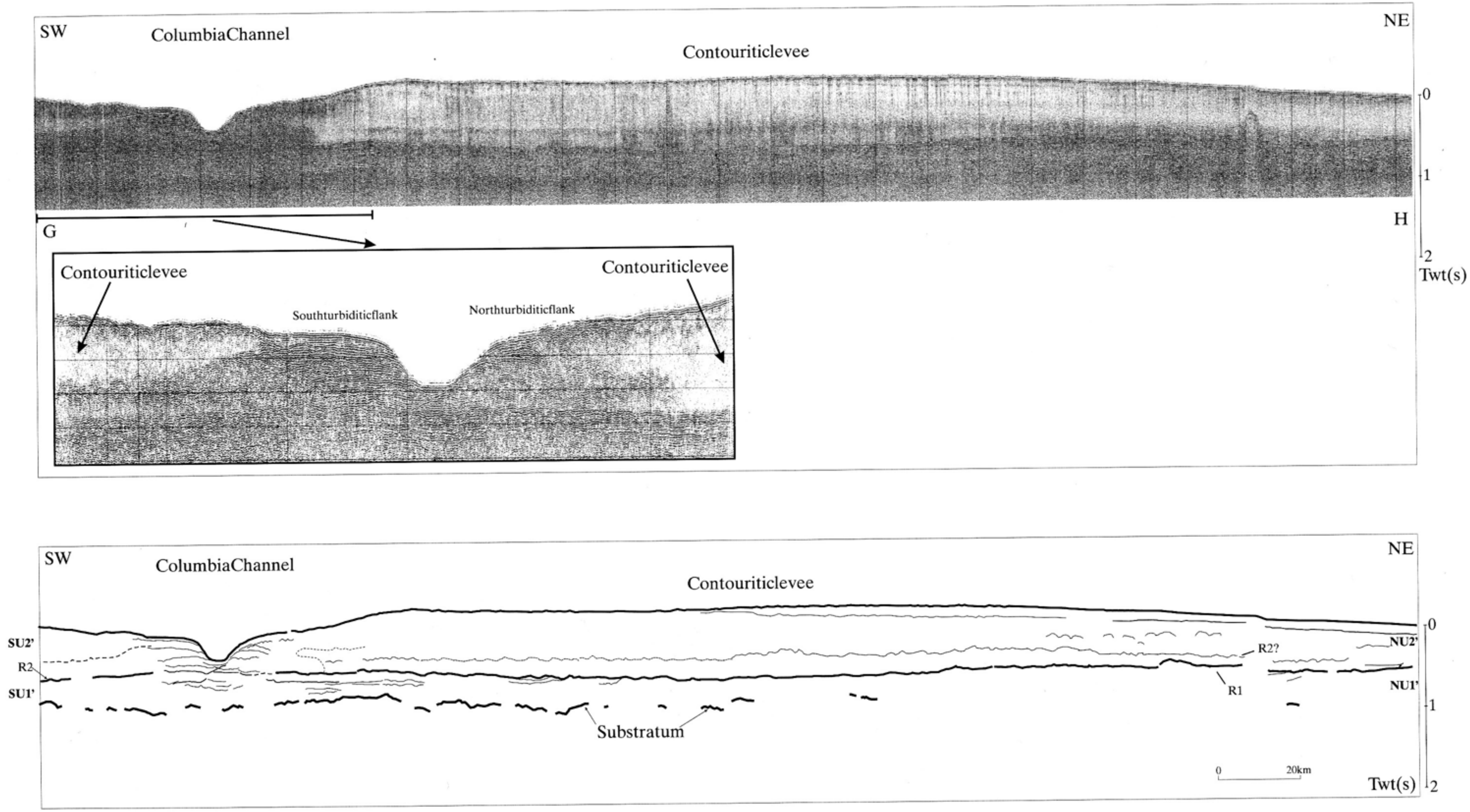

Fig. 3. Seismic line G–H, crossing the deepest part of the channel-levee system.

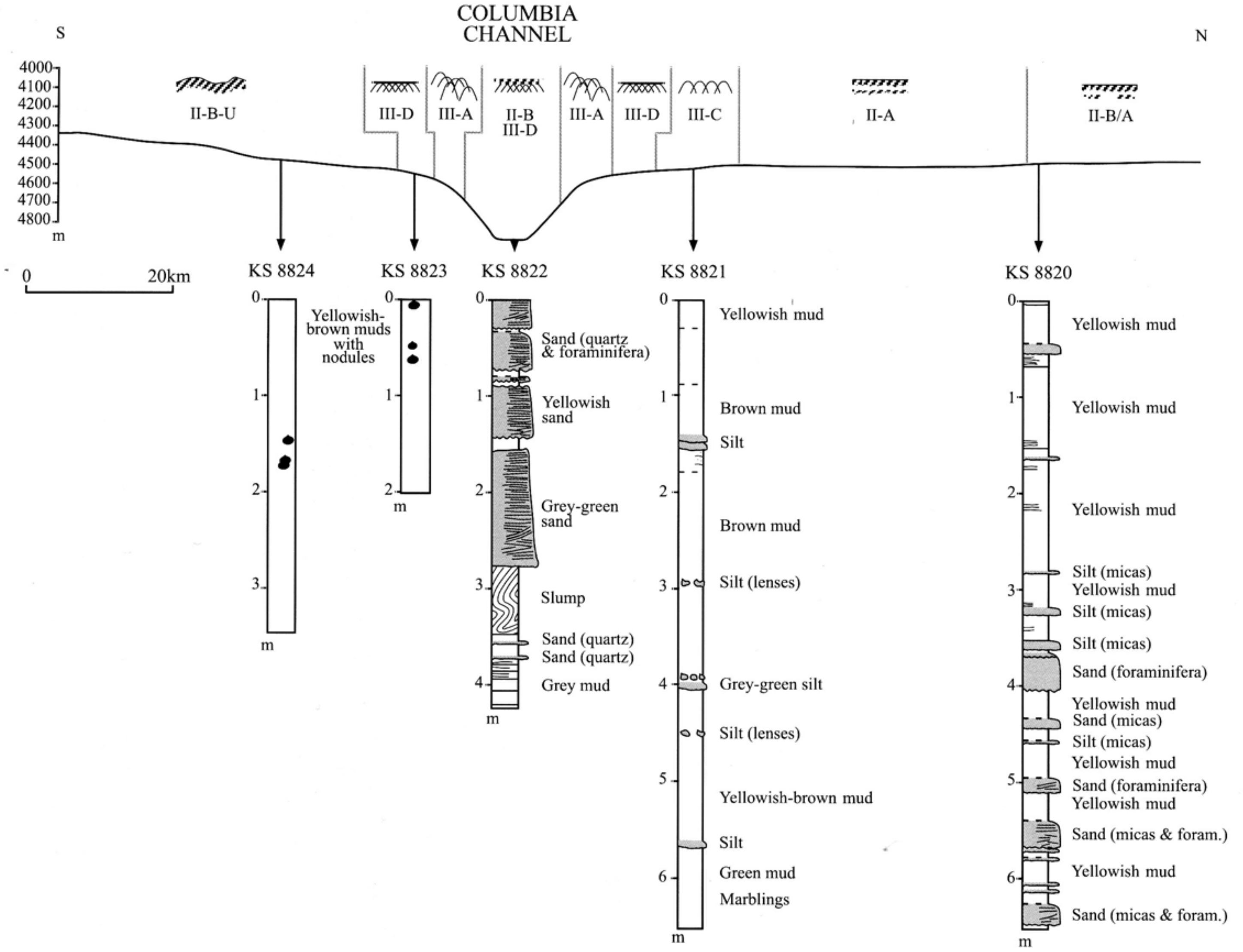

Fig. 4. Echofacies distribution and core lithology along the western transect (DB profile, see Fig. 1a for location).

characterized by the association of a very prolonged bottom echo with no sub-bottom reflectors (echo-type IIB) and hyperbolae tangential to the sea-floor (echo-type IIB-IIID). They indicate abundant sandy deposits (IIB) in an area with active turbidity currents as confirmed by core KS 8822. The upper parts of both flanks display a similar sharp surface echo with hyperbolae tangential to the sea-floor (IIID echo-type). Such echoes on the northern flank may be associated with a decrease in turbidity current energy and sand abundance. On the southern flank, it corresponds to very homogeneous yellowish-brown muds associated with manganese nodules, with neither coarse-grained silt or sand material nor turbiditic deposits (core KS 8823).

A small area further north of the IIID echotype is characterized by regular overlapping hyperbolae with varying vertex elevations above the sea-floor (echo-type IIIC). This may be caused by regularly spaced erosional depositional bed forms and could reflect a combination of overflowing turbidity currents and contour currents, as suggested by core KS 8821 showing muddy deposits with thin and widely spaced silt/sand layers (see Discussion section).

To the north, the major part of the levee is characterized by indistinct prolonged or semi-prolonged echoes. North to south, there is a southward succession of echofacies: firstly IIB/A echo-type, between indistinct prolonged echoes and semi-prolonged echoes with zones of discontinuous parallel sub-bottom reflectors, related to the occurrence of abundant silt/sand layers (KS 8820); then a typical IIA echo-type characterized by semi-prolonged bottom echoes with discontinuous, parallel sub-bottom reflectors that indicate finer-grained deposits; and lastly the IIIC echotype. This succession seems to indicate a decreasing trend in the abundance and/or thickness of sandy layers, and suggests that the Vitoria-Trindade chain is a significant sediment source for the levee.

The distal part of the southern flank of the channel shows an undulating prolonged bottom echo with no sub-bottom reflectors (echo-type IIB-U, Fig. 5a, b). This echo is associated with homogeneous manganiferous yellowish-brown muds (KS 8824), very similar to that of core KS 8823. Consequently, this IIB-U echo could result from regular small erosional to depositional contour-current-generated bedforms (metric to decimetric; Ewing *et al.* 1973; Embley 1975), whereas the wavy pattern indicates larger sediment waves (average wavelength of 1 km).

To conclude, contour current processes seem to be dominant south of the channel. Turbidity currents are dominant in the channel and on the northern levee where deposits originate from supply transported by the channel or delivered from the Vitoria Trindade chain. Evidence of process interaction is present on the levee.

In the deepest part of the system (Figs 1, 5c–g and 6), the morphology of the channel-levee is asymmetrical with a channel

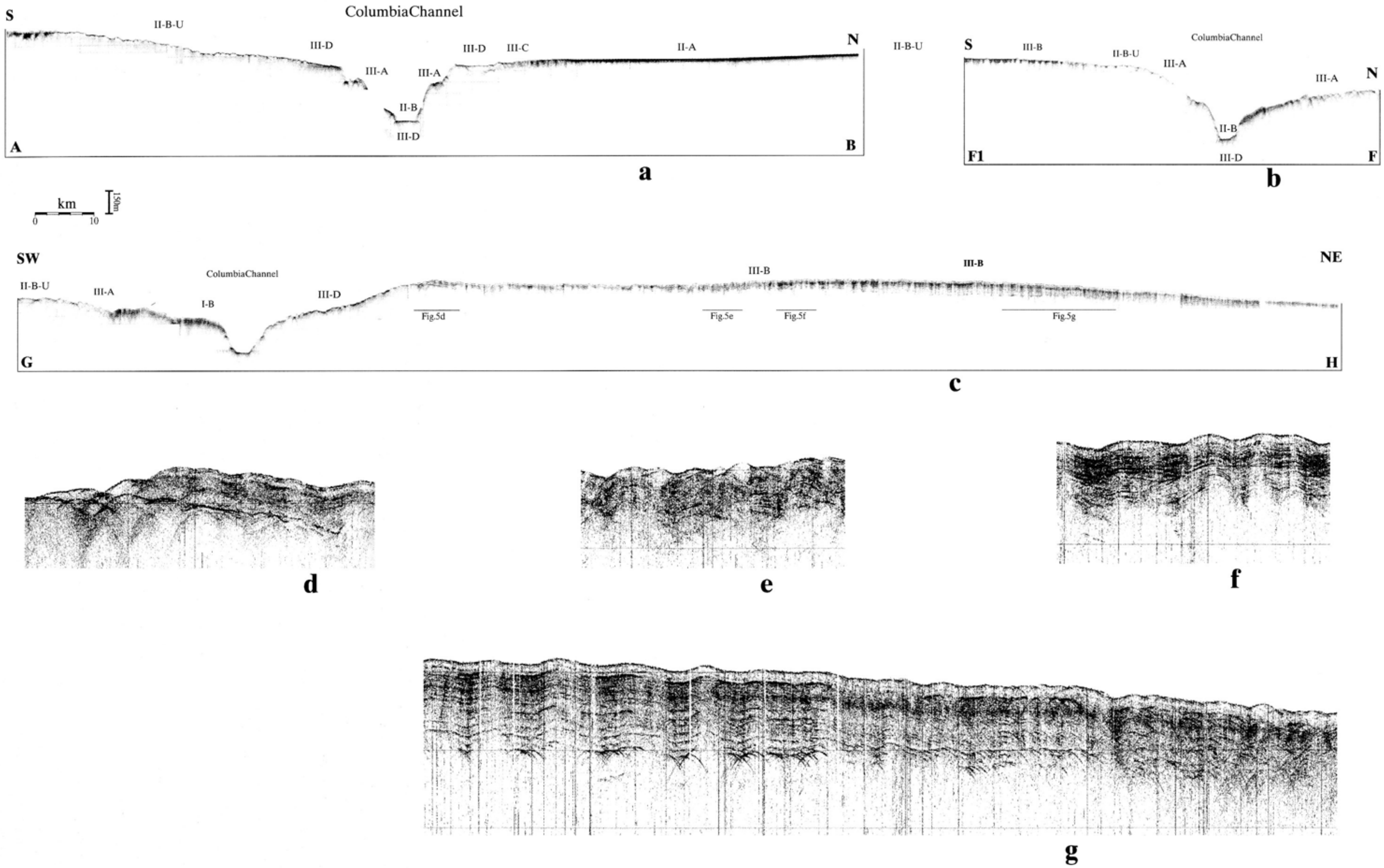

Fig. 5. 3.5kHz profiles (see Fig. 1 for location) and echofacies. (**a**) Profile (AB) crossing the shallower part of the channel-levee system; (**b**) Profile (FF1) crossing the mid part of the channel-levee system; (**b**) Profile (GH) crossing the deeper part of the channel-levee system; (**d**, **e**, **f** & **g**) Detail of contouritic echofacies, showing an erosive discontinuity underlined by a III-D echofacies and overlained by a wavy echofacies with more or less discontinuous subbottom reflectors (**d**), wavy surficial echo associated with chaotic subbottom reflectors probably due to sliding disturbance (**e**),onlaping contact between two generations of sediment waves (**f**), and typical contouritic III-B echofacies: a very thick undulated echo-type with stationary surficial sediment waves and comformable sub-bottom reflectors, some of them associated with tangential hyperbolae (**g**).

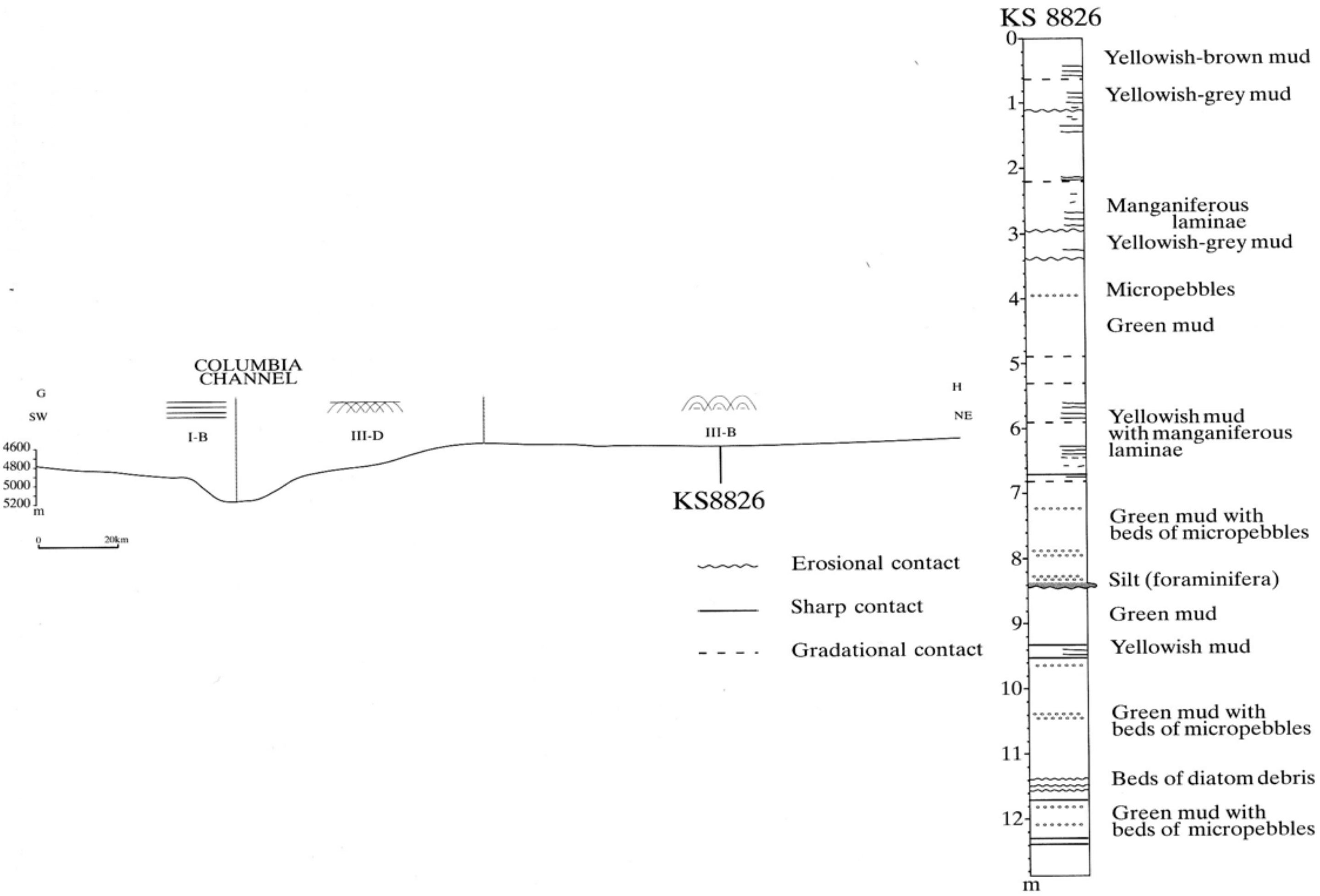

Fig. 6. Echofacies distribution and core lithology (KS 8826) along the eastern transect (GH profile, see Fig. 1a for location).

bottom depth of 5200 m, a prominent northern levee culminating at a depth of 4600 m, and a southern flank with a lower sediment relief (4800 m). The profile shows the predominance of hyperbolic and wavy echoes.

The southern flank of the channel displays a IB echo-type with a sharp bottom echo and continuous, sharp, parallel sub-bottom reflectors, probably associated with mud deposition from very sluggish bottom currents. The II-B indistinct, prolonged echo-type only occurs on the valley bottom (Figs 4, 5 and 6). The northern flank of the channel displays a IIID echo-type similar to that observed along the shallower western profile. It is associated with erosional/depositional bedforms generated by more active geostrophic and/or turbiditic bottom currents. Finally, the major part of the northern levee displays a very thick IIIB undulating echo-type characterized by deep regular single or slightly overlapping hyperbolae with comformable sub-bottom reflectors, some of them associated with tangential hyperbolae (Fig. 5c, g). This may indicate current-generated stationary sediment waves that are typical of the contouritic levee deposits. As shown by core KS 8826 (Fig. 11), these deposits consist of abundant muds with extremely rare and thin silty layers. Very similar lithology and echofacies were described in the southernmost part of the Brazil Basin, where only muddy contourites are deposited along the path of the AABW currents (Faugères *et al.* 2002). Locally the III-B is strongly disturbed, probably by sediment sliding (Fig. 5e) and episodes of more active currents responsible for erosive surfaces are underlined by high amplitude reflectors associated with tangential hyperbolae (Fig. 5d)

Sediments: core description and facies

The facies observed in the five cores collected on the upper part of the system fall into two categories (Figs 4, 8, 9 and 10): (1) silty-clayey muds, and (2) interbedded sandy turbidites.

Cores KS 8824 and KS 8823 (Fig. 4) on the southern flank of the channel, are characterized by very homogeneous yellowish-brown muds with ferro-manganiferous nodules. The carbonate content is very low (less than 5%). The median grain size is 5 μm (fine silt and clay, Fig. 7), and the sand content very low (< 3.5%). There are no silt-sand turbiditic layers. It is likely that turbidites are deflected towards the north as a result of the Coriolis force, and geostrophic bottom currents are the dominant process in this area. Consequently, these muds are interpreted as contouritic muds rather than 'red' pelagic clay. This is confirmed by the wavy IIB-U echofacies nearby and by the strong lithological and grain size similarities between these deposits and contouritic muds described further south (Fig. 7), at the northern exit of the Vema Channel (Massé 1993; Massé *et al.* 1994, Faugères *et al.* 2002).

Core KS 8822, in the axis of the Columbia Channel, displays very thick (up to 120 cm) classical sandy turbidites (Fig. 4). The material shows a medium carbonate content (20 to 40%), a median grain size between 60 and 200 μm and a sand content always exceeding 40%. The sand fraction is composed of quartz and micas (30 and 10% respectively), planktonic foraminifera (50%) and minor quantities of various bioclasts. Interbedded muds are similar to those described south of the channel (Fig. 7) and are then interpreted as muddy contourites. However, the mud

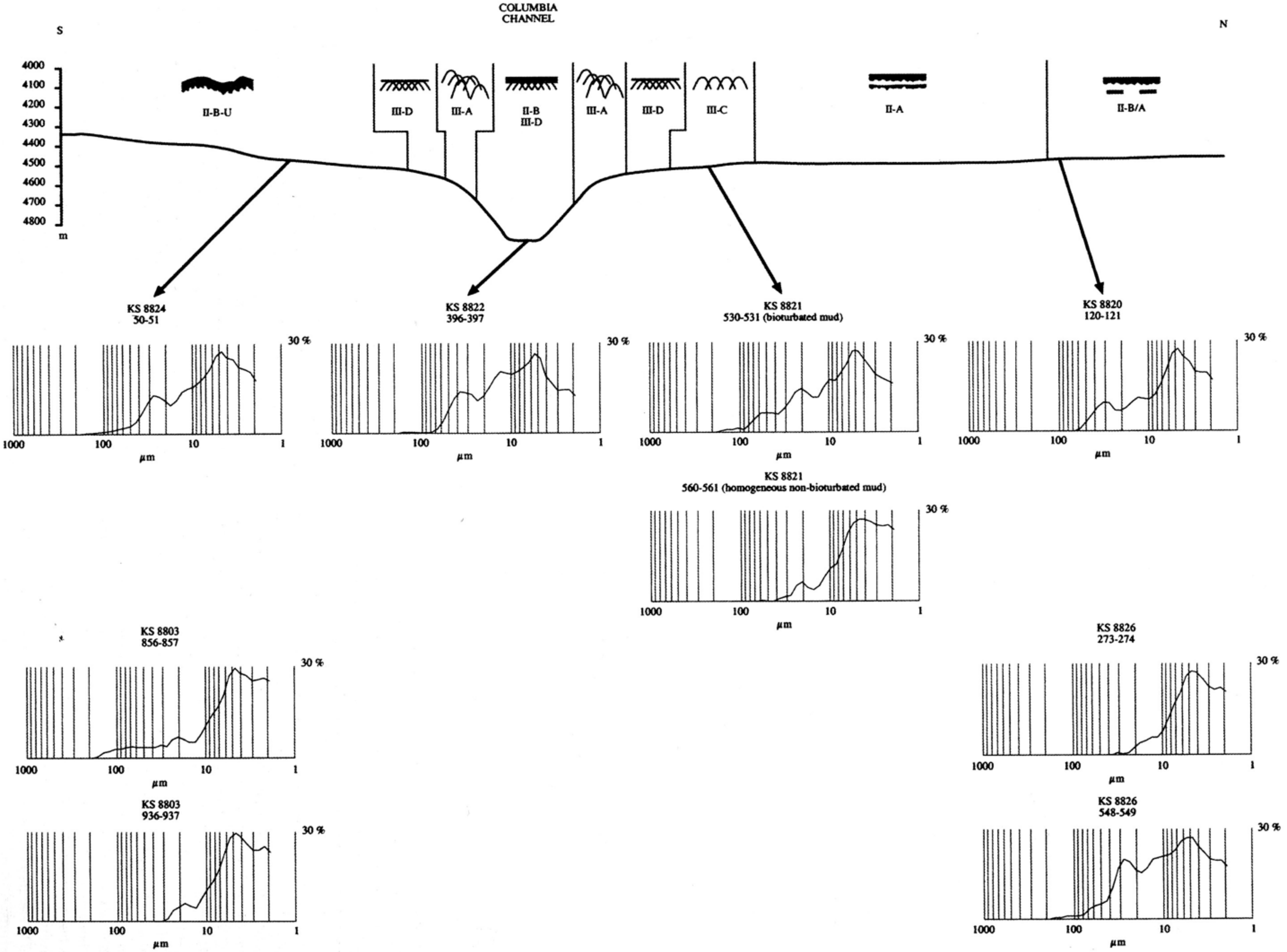

Fig. 7. Grain size frequency curves for the muds. Two samples from core KS 8803 (see Fig. 1a for location) representing the whole range of grain size variability in contouritic muds are included for comparison.

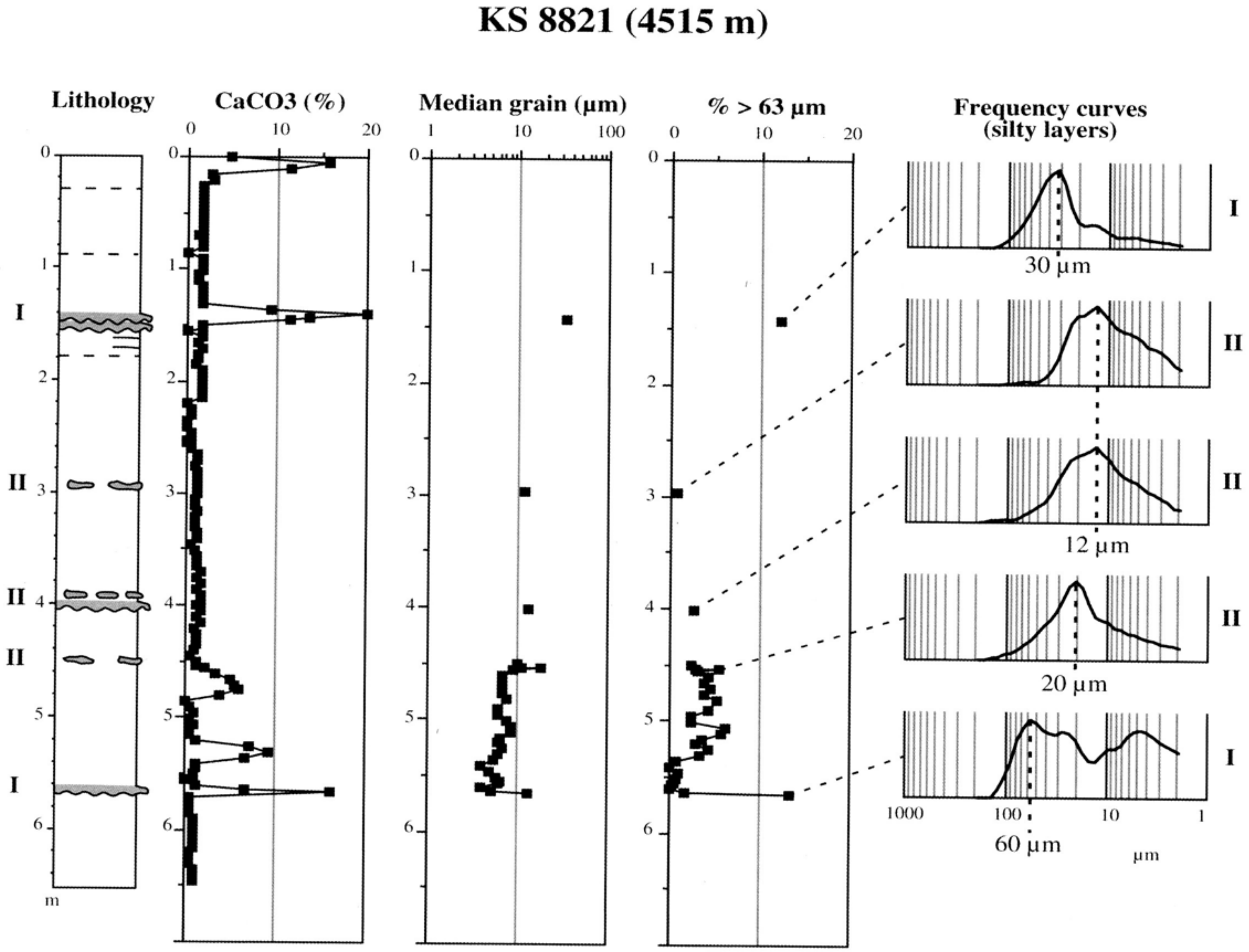

Fig. 8. Lithology of core KS 8821 (northern levee). I and II refer to type I (silty muddy turbidites) and type II (Top truncated silty muddy turbidites) silty layers respectively.

modal peak in KS 8822 is slightly coarser and suggests that a part of the mud material may be derived from turbiditic supply.

Core KS 8821 (Fig. 8), on the northern levee close to the axis of the channel, is characterized by abundant muds similar to those described on the southern flank of the channel (Fig. 7), which could thus be considered as muddy contourites, with a part of the material derived from turbiditic flows. This seems supported by the mineralogical composition (K/I ratio; Massé *et al.* 1998). In addition to these muds, the core displays thin and widely spaced silty layers (Figs 8 and 9) that fall into two types interpreted as type I: silty-muddy turbidites and type II: top-truncated silty-muddy turbidites resulting from contour current reworking.

Type I, silty-muddy turbidites (145 and 565 cm in Figs 8 & 9), show a basal thin layer (3 cm), with an erosive contact at the base, a significant carbonate content (10 to 20%), a median grain up to 30 µm (coarse silts), and a sand content exceeding 10%. This is overlain, with a gradual transition, by a cm- to dm-thick layer of very homogeneous, non-bioturbated mud, with some coarser layers but no evidence of grading. At the top, these muds are progressively overlain by bioturbated muds with fairly similar texture (Fig. 7). The non-bioturbated mud suggests rapid deposition and is interpreted as the upper division of a silty-muddy turbidite. In contrast, bioturbated muds are interpreted as muddy contourites with a much lower deposition rate.

Type II, top-truncated silty-muddy turbidites (155, 295, 395, 403 and 455 cm in Figs 8 and 9), have a cm-thick lenticular basal bed with an erosive contact, zero carbonate content, a median grain-size never exceeding 20 µm, a modal peak corresponding to fine silts (10 to 20 µm), and a sand content lower than 5%. In contrast to type I silty muddy turbidites, they are not overlain by homogeneous muds. Type II silts at 455 cm are topped by a very thin alternation (1 cm thick) of millimetric silty and muddy layers and characterized by a sharp contact at the top. This is overlain by bioturbated muddy contourites. Some burrows truncate the silt layer and the erosional contact at the base. These type II sequences are interpreted as turbiditic deposits truncated by the action of contour currents (see Discussion section).

Core KS 8820, on the northern levee, well away from the axis of the channel, is characterized by abundant graded sandy turbidites (Fig. 10). However, these turbidites are thinner (up to 50 cm) and more frequent than in the axis of the channel (core KS 8822), and the material is characterized by more variable carbonate contents (5 to 85%) and median grain-sizes (20 to 150 µm). The sand content ranges from 5 to 85%, with modal peaks at 30 to 150 µm, (coarse silt/fine to medium sands). The sand composition is different from that described in the channel with a much lower quartz content (never exceeding 10%), more abundant foraminifera (up to 90%), and up to 50% of fine mica. The

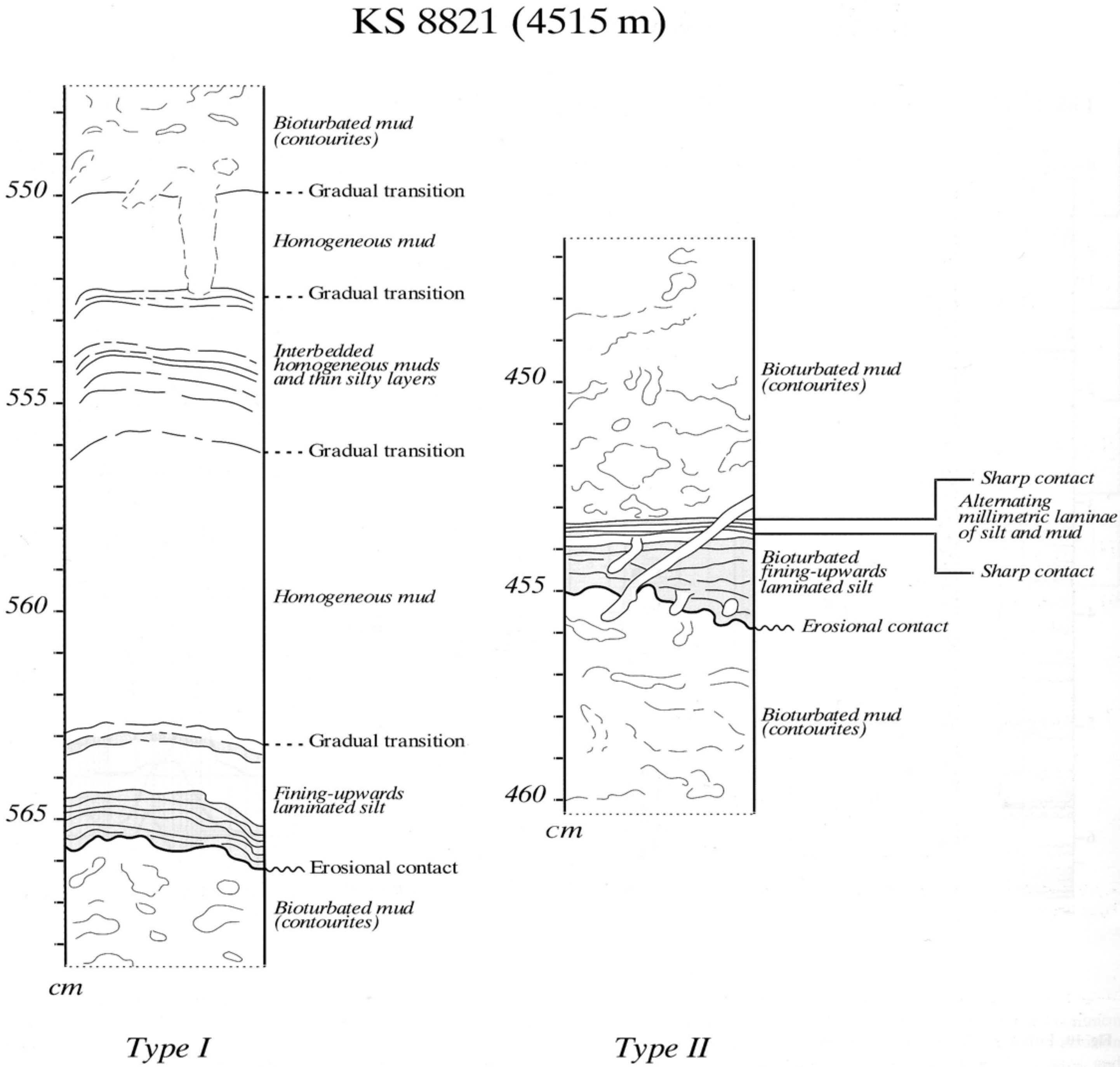

Fig. 9. Interpretative sketches of X-radiographs showing the detailed lithologic characters of type I and type II silt layers (core KS 8821, northern levee).

interbedded muds (Fig. 7) are very similar to those described on the southern flank of the channel, and are assumed to be muddy contourites, although a part of the material may be derived from the turbiditic flows.

The facies observed in core KS 8826 from the top of the deepest part of the levee (Figs 6, 11 and 12) are dominated by silty-clayey muddy contourites. These muds display a grain size mostly ranging between 3 and 7 μm (fine silt and clay-sized material), with a > 10 μm fraction between 10% and 30%, very low carbonate contents (mostly less than 5%, sometimes up to 25 %) and occasional erosional surfaces (Fig. 12). Two major facies can be defined that alternate throughout the core: (1) yellowish-brown muds, bearing bioturbation marks, and frequently displaying manganese enrichments that appear as millimetre-to-centimetre-scale dark grey laminae, ranging from very diffuse mottling, slightly darker than the adjacent muds to well-defined horizons with sharp boundaries; and (2) grey-green homogeneous muds, occasionally displaying millimetric beds of muddy micropebbles (microbrecciated muds) due to short episodes of enhanced bottom currents (Massé 1993). These muds are very similar to the muddy contourites described in the previous cores, and also further south at the northern exit of the Vema Channel where similar facies alternations have been observed (Mézerais 1991; Mézerais *et al.* 1993; Massé 1993; Massé *et al.* 1994; Faugères *et al.* 2002). All these characteristics give evidence of AABW contour current control during deposition. Clay mineralogical data (K/I ratio, Massé *et al.* 1998), suggest that a part of the muddy material in KS 8826 may be derived from the Columbia Channel turbiditic flows. A unique silty-clay calcareous turbidite occurs at 840 cm depth in the core (Fig. 12). It shows a 10 cm thick sequence with a basal erosive foram-rich bed overlain by white muds (50% carbonate) that suggest a Vitoria Trindade chain biogenic sediment source.

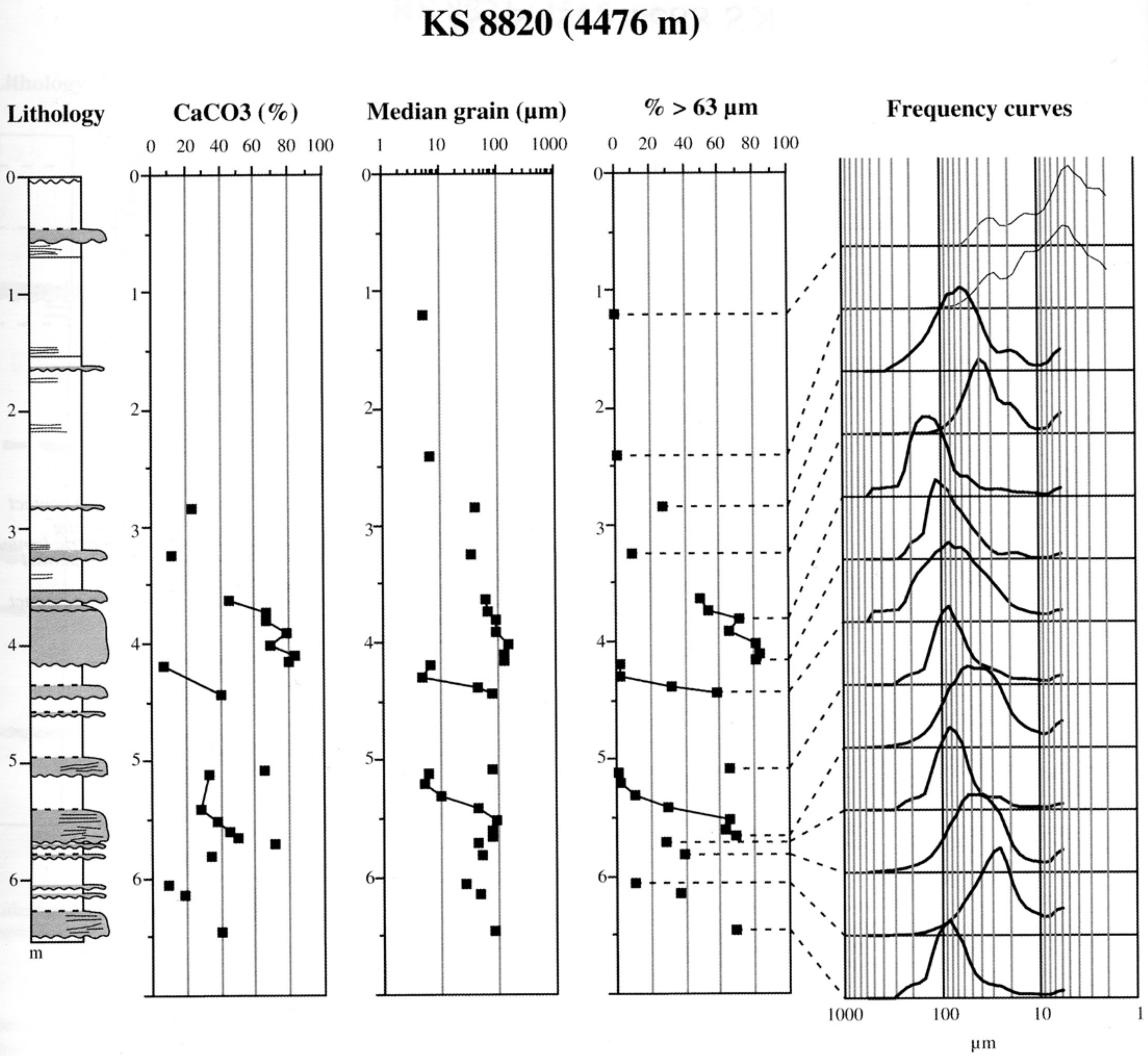

Fig. 10. Lithology of core KS 8820 (northern levee).

Discussion

The lithologic and seismic data demonstrate the contrast existing in the Columbia Channel system between the shallowest area, west of 33°W where the northern levee is parallel to the axis of the channel and characterized by abundant turbiditic deposits, and the deepest area, east of 33°E where the levee extends parallel to the path of bottom currents, and is characterized by dominant muddy contourites.

Contouritic processes and associated deposits

It has been shown in the previous sections that the silty-clay muds could be deposited by contour currents. Such a depositional process for the muds is supported by the clay contents in cores of the shallow (KS 8821) and deepest (KS 8826) part of the levee. Chlorite transported by AABW from high southerly latitudes, is considered as a good tracer of this contour current (Biscaye 1965; Massé 1993; Massé *et al.* 1996; Petschick *et al.* 1996). The C/I ratio in the muds of these two cores is very close to that of the contouritic muds deposited at the northern exit of the Vema Channel. Kaolinite is a good tracer of supply derived from the upper part of the margin and transported donwnslope by gravity processes. Values of the K/I ratio indicate far more lower kaolinite contents than on the middle continental rise, suggesting that only a part of the muddy material is derived from turbiditic flows. Similar contouritic muds with very low carbonate contents (<15%), a modal peak centred around 5 µm (fine silt and clay) are also dominant on the southern flank of the channel (cores KS 8823 and KS 8824, Fig. 7).

Despite the fact that turbiditic deposits are dominant on the shallower part of the northern levee, the whole area is located at depths greater than 4000 m and is swept by the AABW currents. Consequently, the muds deposited between the silty-sandy turbiditic sequences should experience some contour current control

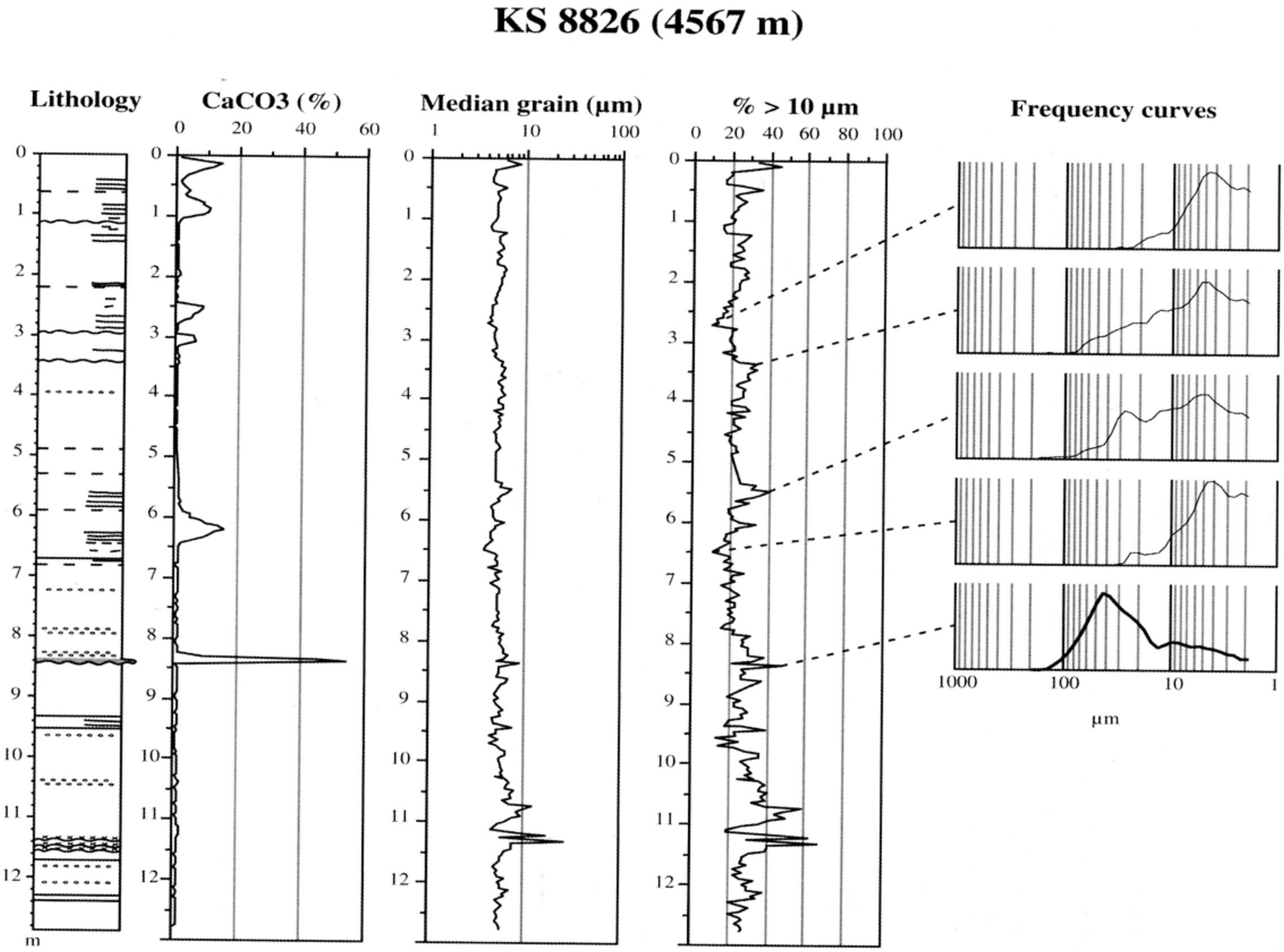

Fig. 11. Lithology of core KS 8826 (northern contouritic levee). See Figure 6 for the significance of lithologic symbols.

and may be interpreted as muddy contourites rather than hemipelagites or turbiditic muds. Distinguishing between them is not easy. However, as in core KS 8821 (Fig. 9), there is a clear lithological difference between the very homogeneous muds gradually overlying some silty beds and interpreted as muddy turbidites, and the bioturbated muds sometimes showing sharp contacts with the underlying silty beds and interpreted as contourcurrent deposits.

These Quaternary muddy contourites are fairly homogeneous but they show colour variations (yellowish, brownish, blackish to green) due to variation in the rate of terrigenous supply and to diagenetic processes. South of the channel, they are predominantly yellowish and are associated with manganiferous nodules. On the deep contouritic northern levee, they show an alternation of yellowish and greenish layers with microbrecciated muddy contourites, associated with erosional surfaces and thin cm-crusts or thin layers composed of manganese and iron oxides (Figs 11 and 12). The occurrence of some muddy layers enriched in diatoms (Fig. 14a) originating from high southern latitudes (Massé 1993), is evidence of sediment deposition under the AABW control. Most of these contouritic deposits, already observed further south in the Brazilian Basin (Faugères *et al.* 2002), display peculiar facies and do not fall in the classical contourite models (Stow & Lovell 1979; Stow 1982; Faugères *et al.* 1984; Gonthier *et al.* 1984; Stow *et al.* 1996).

Turbiditic processes and associated deposits

Typical silty-sandy turbiditic deposits (Bouma 1962) are common in cores along the western transect where their composition reveals a clear distinction between (1) quartz-rich turbidites, and (2) quartz-poor, mica- and foram-rich turbidites.

Quartz-rich sandy turbidites are found in the axis of the channel (KS 8822). This material originates from the upper continental rise to the west, where similar material is described (Massé 1993; Massé *et al.* 1996). Probably due to the great depth of the channel, the turbiditic sand loads transported in the channel are not really involved in overflows on the northern levee as displayed by the rapid disappearance of prolonged bottom echoes from the channel axis towards the north, and the absence of thick sandy turbidites in KS 8821. The finer silty-muddy turbidites observed in this core (type I silty layers) are probably derived from the Columbia Channel as the core is not very far from its axis, fairly abundant quartz grains are observed in the fraction >10 µm, and the K/I ratio close to one is similar to that on the middle continental rise.

Quartz-poor, mica- and foram-rich turbidites are abundant on the northernmost part of the levee (KS 8820). The distribution of echofacies on the northern levee (Fig. 4) with a southward decreasing trend in sand content (from KS 8820 to KS 8821) strongly suggests a distinct sediment source from that observed in

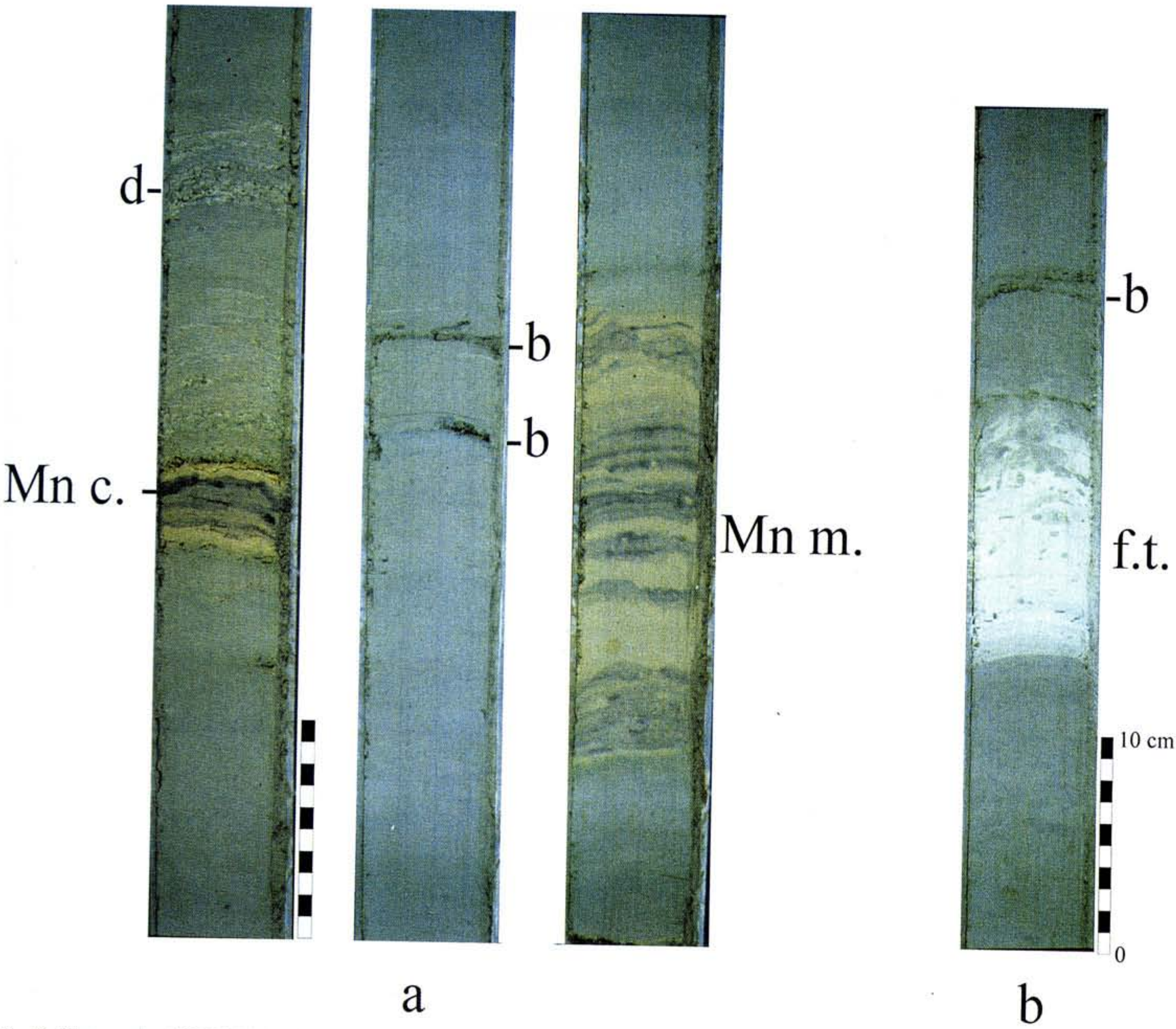

Fig. 12. Photographs of KS 8826 facies (northern contouritic levee): (**a**) yellowish manganiferous mud (Mn c, manganiferous crust; Mn m, manganiferous marbling) alternating with greenish mud showing layers of microbrecciated layers (**b**) and diatom-rich mud (**d**); (**b**) greenish muds with a white foram-rich turbidite (f.t.).

the axis of the channel, for a large part of the levee. It probably comes from the walls of the Vitoria–Trindade Seamounts directly to the north. This chain results from an accumulation of terrigenous material between the isolated seamounts (Fainstein & Summerhayes 1975), now covered by a carpet of pelagic sediments. The foram-rich turbidites certainly come from this area. The origin of the mica-rich material is more speculative: either terrigenous deposits derived from the Vitoria-Trindade chain or from the Columbia Channel, as mica particles may be transported for long distances.

The interaction between turbiditic and contouritic processes

Silty-muddy, top-truncated turbidites (type II silty layers, KS 8821) are the only sediment facies that displays direct evidence of the both turbidity and contour current activity at the same place and time. They show a basal erosive thin layer or lens of laminated silt and silty mud that could be of turbiditic origin, as they have lithological characters similar to the silty muddy turbidites. However as there is a sharp contact at the top (Fig. 9), overlain by bioturbated muds, they are interpreted as turbidite deposits truncated at the top by contour currents. The currents may have been sufficiently active to remove or to prevent the rapid deposition of the floating foram tests and muddy top of the sequence. The result is a top-cut sequence, a finer grain size and removal of the carbonate (from over 10% in the original silty muddy turbidites to 0%). The currents could also be responsible for the formation of the laminated structures. All these features strongly suggest the activity of contour currents during or shortly after the turbidite deposition. This type of deposit is typically what some authors refer to as bottom current reworked turbidites (Stanley 1993; Shanmugam *et al.* 1993*a*, *b*; Viana & Faugères 1998).

One can argue that the turbiditic flow itself could be responsible for winnowing of finer particles. This implies that type II silts are deposited from denser and faster currents than type I. However, this is inconsistent with the finer grain-size of type II silts with

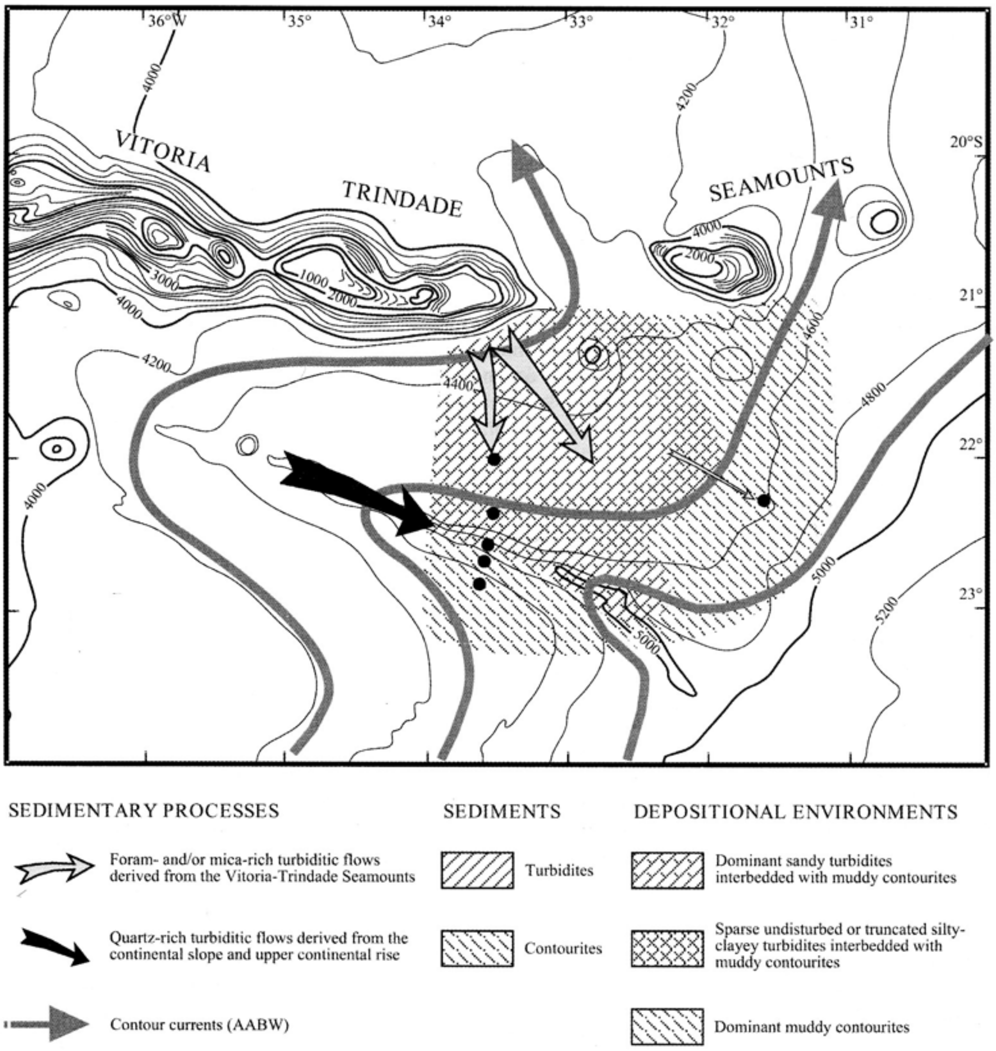

Fig. 13. Synthetic map showing the contour current pathways, and the distribution of sedimentary processes, associated deposits and depositional environments in the study area.

respect to type I silts. If mud deposition occurs above type I silts, then it is likely to occur for similar or slightly finer type II silts. Consequently, we have to assume that the reworking of type II silts is done by contour currents linked to the AABW. The velocity of AABW currents in the SW Atlantic has varied through time (e.g. Jones & Johnson 1984; Ledbetter 1986; Massé *et al.* 1994). Type II silts would be the result of distal silty-muddy turbidite reworking during periods of enhanced AABW circulation, or even benthic storm activity (Hollister & McCave 1984; Peggion & Weatherly 1991) resulting from eddies generated when the southward moving Brazil Current crosses the Vitoria–Trindade Chain (Schmid *et al.* 1995), whereas type I silts would be deposited during periods of sluggish AABW circulation.

The distribution of sedimentary processes and associated deposits is summarized on Figure 13.

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