Interaction of processes and importance of contourites: insights from the detailed morphology of sediment Drift 7, Antarctica

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Abstract: As the definition of contourites has widened to embrace a large spectrum of sediments in so-called mixed systems, the distinction between contourites and turbidites has become at times vague. The case history of sediment Drift 7 off the Antarctic Peninsula is analysed in this paper in the light of newly acquired swath bathymetry data. The co-existence of various sedimentary processes is reflected in a complex morphology: erosional gullies produced by debris flows on the upper part of the continental slope; deeply incised channels at the slope base; main trunk-type inter-drift turbidity channels separating the drifts; slide scars; undulating depositional bedforms interpreted as bottom-current sediment waves; fluid escape structures perhaps associated with deep-water coral bioherms. The data suggest that Drift 7 is a genuine sediment drift in which bottom currents pirate the sediment of the turbidity currents. Finally, we propose that the control on location and elongation of the drift is inherited from an older margin structure. The relationships between bottom current and deposition are investigated through a comparison with the SE Greenland continental margin, an analogous counterpart in the northern hemisphere.

Contourites are sediments deposited or substantially reworked by the action of bottom currents (see recent summaries by Stow & Faugères 1993, 1998; Faugères *et al.* 1999; Rebesco & Stow 2001; Stow *et al.* 2002*a*; Rebesco 2005). The term was originally introduced by Heezen *et al.* (1966) to define sediments that were deposited in the deep sea by contour currents (i.e. alongslope thermohaline bottom currents). The term was subsequently widened to embrace a larger spectrum of sediments in a wide range of water depths such as on continental shelves and slopes (e.g. Camerlenghi *et al.* 2001; Harris *et al.* 2001; Laberg *et al.* 2001), in depositional environments such as lakes (e.g. Ceramicola *et al.* 2001), formed by different type of currents (e.g. tides along canyons, Shanmugam 2003), and including newly defined sedimentary processes (e.g. sea-floor polishing, Viana *et al.* 1998). The definition of contourites applies to very large parts of the modern ocean floor and to a variety of sedimentary deposits. The present-day discussion on contourites also embraces some terminological issues. Although possibly too ample, the long-established term 'contourites' should be maintained (at least for non-specific use). Strictly speaking, the term 'contour currents' should be applied only to contour-parallel thermohaline currents (and bottom currents in other cases). The term 'contourite drifts' should be restricted to sediment accumulations formed principally by contour currents, and 'sediment drifts' for those formed principally by other types of bottom current. Depth definition has to be considered where available, but it is often of limited value for fossil contourites. Mixed systems are the norm rather than the exception for contourites.

If applied to contourite systems, the terms closely associated with downslope processes (such as fan, channel, etc.) have to be preceded by the prefix 'contourite'. The employment of modifying terms to qualify the deposit in terms of current action, depth, current type and interacting process would hence be recommended (see Rebesco 2005).

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Importance of contourites

The study of contourites is important in at least three respects: palaeoceanography, hydrocarbon exploration, and slope stability.

The depositional environment of the sediment drifts generally allows a continuous record with relatively high resolution providing priceless information for palaeoceanography and palaeoclimatology, especially regarding variability in circulation pattern, current velocity, oceanographic history and basin interconnectivity (e.g. Grützner *et al.* 2003; Hernández-Molina *et al.* 2003).

Oil and gas reservoir development in the deep sea is generally considered a prerogative of the turbidite systems. Nevertheless, the action of bottom currents (or the interaction between bottom and turbidity currents) may be crucial where weak flows favour the accumulation of source rocks and robust flows form 'clean' sands (e.g. Shanmugam 2000; Viana 2001, 2007).

Nowadays, the critical role played by fine-grained contourites in slope stability is being perceived. Potential overpressured glide planes may be provided when the high water content of these sediments is loaded, and escape is prevented by low permeability. The most representative examples lie in areas of episodically high sediment input of glacigenic sediments, such as the Norwegian margin (Laberg & Vorren 2000; Laberg *et al.* 2001, 2002), although the Antarctic Peninsula sediment drifts also appear to be prone to gravitational instability (Volpi *et al.* 2003).

Despite their significance, contourites are still relatively poorly known, especially because the nature of these complex deposits is not clear cut, and because of the dominance of the turbidite paradigm. The distinction between contourites and turbidites (Fig. 1) appears reasonably easy when the general, large-scale aspects of the end-members are considered (e.g. Faugères *et al.* 1999; Rebesco & Stow 2001; Stow *et al.* 2002*b*; Rebesco 2005). However, end-members are seldom found in the deep sea, where interaction of processes is the norm rather than the exception. For this reason, interesting insights may arise from the case history of the sediment Drift 7 off the Antarctic Peninsula (Fig. 2), where hybrid contourites, with unusual well-preserved lamination, are recognized (Lucchi & Rebesco 2006). The Antarctic Peninsula drifts are well-studied examples (McGinnis & Hayes 1995; McGinnis *et al.* 1997; Rebesco *et al.* 1997, 2002; Pudsey 2000; Lucchi *et al.* 2002; Dowdeswell *et al.* 2004; Amblas *et al.* 2006) that are relevant to palaeoceanography (Grützner *et al.* 2004; Hernández-Molina *et al.* 2004) and slope stability (Volpi *et al.* 2003). Moreover, they constitute a complement for hydrocarbon exploration by providing instructive comparison for exploration–production cases.

In this paper we analyse the detailed morphology of Drift 7 and integrate the pre-existing lithological, seismic and oceanographic data with the aim of contributing to the understanding of contourite system behaviour, with a special focus on the interaction of down- and along-slope processes.

Dataset and knowledge development

The sediment Drift 7 (Fig. 2), also named the Alexander sedimentary mound (McGinnis & Hayes 1995), was initially identified on the basis of multichannel seismic reflection profiles (Rebesco *et al.* 1994). Notwithstanding the evidence for both turbidite and contourite processes in the development of this and similar adjacent sedimentary bodies (McGinnis & Hayes 1995; McGinnis *et al.* 1997), Drift 7 was interpreted as a sediment drift according to the large-scale asymmetric geometry of the sediment wave type, in contrast to the symmetrical gull-wing geometry typical of channel–levee systems (Rebesco *et al.* 1996). The analysis of six seismostratigraphic sequences allowed the identification of three main evolutionary stages of the sedimentary history of the continental rise from the Mid-Miocene to the present (Rebesco *et al.* 1997). Successively, oceanographic data confirmed the previously inferred present-day occurrence in this area of a weak, SW-flowing, contour-following bottom current (Camerlenghi *et al.* 1997*a*; Giorgetti *et al.* 2003). The compilation of existing soundings in the area (Rebesco *et al.* 1998) allowed a better, but still rough, definition of the bathymetry and morphology of the drift and of the relationships with the adjacent morphological elements (deep-sea channels, prograding slope wedges and glacial shelf troughs). Core data allowed the detection in the Pleistocene of two alternating lithological facies. That deposited during interglacials consists of brown, bioturbated, diatom-bearing mud with Foraminifera. Conversely, that deposited during glacial stages consists of grey mud, essentially barren and non-bioturbated, with very fine laminated intervals without the appreciable normal grading and/or the systematic succession of sedimentary facies typical of turbidites (Pudsey & Camerlenghi 1998; Pudsey 2000; Lucchi *et al.* 2002; Villa *et al.* 2003). Scientific drilling (Ocean Drilling Program (ODP) Leg 178) showed that the alternation of lithofacies is less regular and evident in the Pliocene and Miocene than in the Pleistocene, and that silty and muddy turbidites are present within the glacial facies in the distal part of sediment Drift 7 (Barker & Camerlenghi 2002). The low energy of this depositional environment is confirmed by the fine grain size throughout.

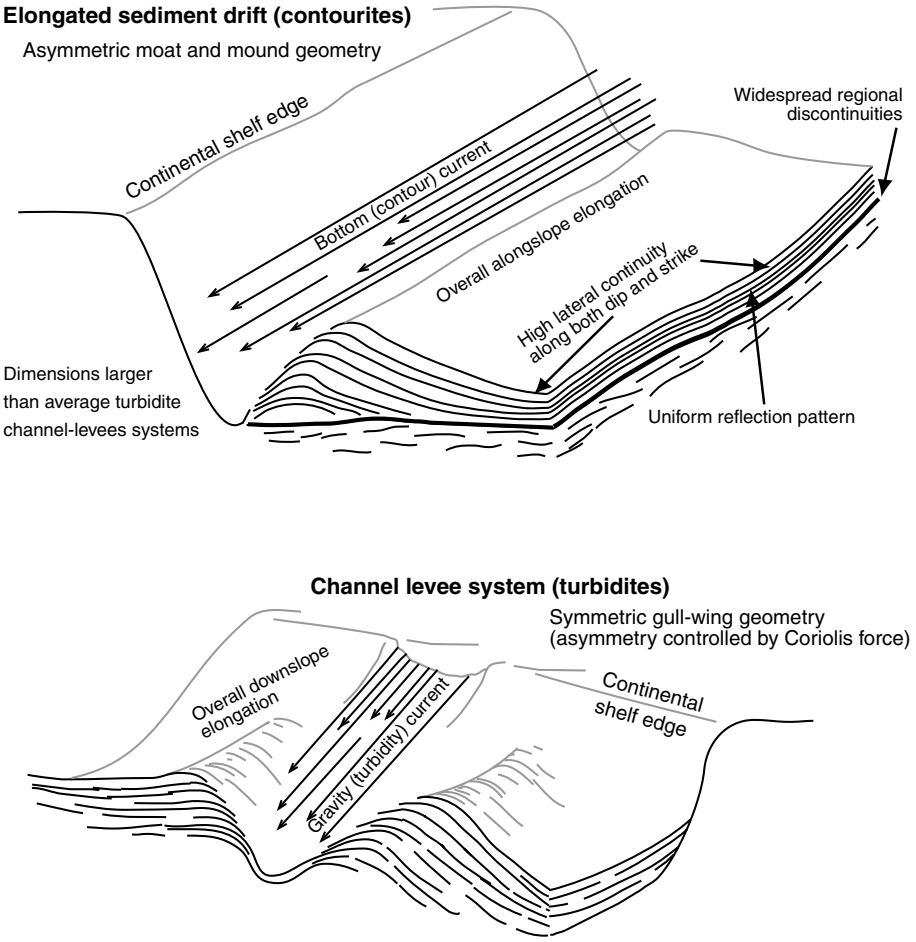


Fig. 1. Schematic model showing ideal, large-scale differences between sediment drifts and channel–levee systems (modified after Rebesco 2005; with permission from Elsevier).

The general depositional model was proposed by Rebesco *et al.* (1997) and it is still widely accepted (Amblas *et al.* 2006). It implies an interpretation of sediment Drift 7 as the product of weak SW-flowing bottom currents pirating (and depositing downstream) the suspended fine material from turbidity currents flowing during glacial stages in the adjacent channel to the NE. Enhanced deposition of the entrained sediment on the NE, gentler, upstream side facing the feeder channel (and slope instability on the SW, steeper, downstream side) generates a moderate upstream migration of the asymmetric drift (similarly to a huge sediment wave).

Methods

New swath bathymetric and sub-bottom acoustic data were acquired during the IX Antarctic Geophysical Cruise, which was part of the XIX expedition of PNRA (Programma Nazionale di Ricerche in Antartide). The MAGICO (Multibeam Antarctic Glacial system Integral COverage) cruise took place on the R.V. *OGS-Explora* from Ushuaia (Argentina), from 17 January, to the same port on 17 February 2004. The swath bathymetry of the whole sediment Drift 7 (nearly 37 000 km^2) and over 4000 km of sub-bottom profiles (Fig. 2) were collected using a Reson SeaBat 8150 multibeam echosounder and a Benthos CAP-6600 Chirp sonar, respectively.

The ship speed during acquisition was generally about 8 knots (*c.* 15 km/h), but it varied depending on weather and sea conditions. The 12 kHz multibeam system employed 234 beams with a total swath of 150°. The resulting horizontal resolution varied with the water depth and the ship speed.

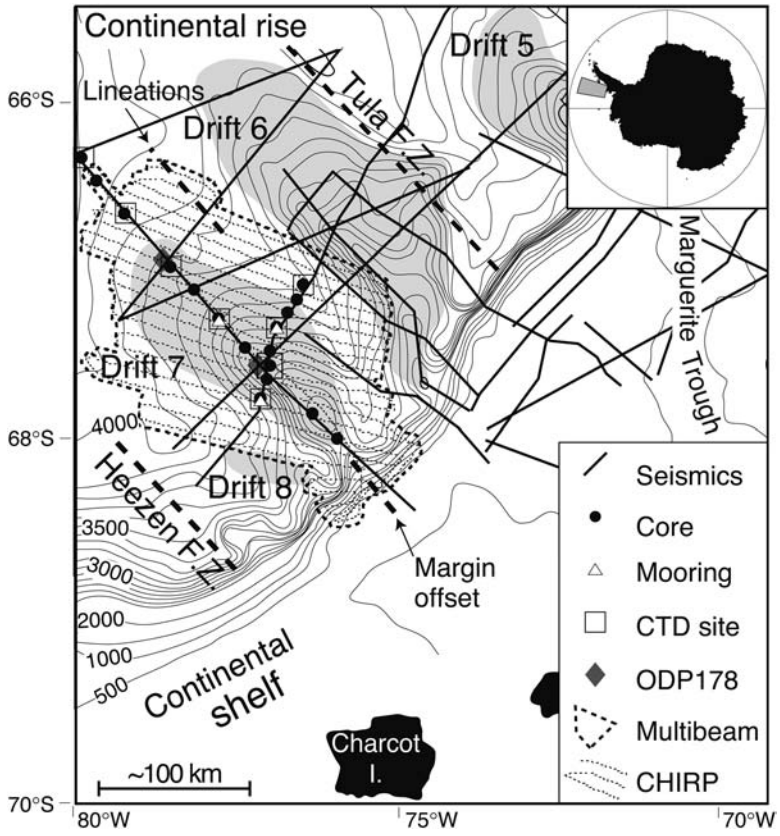


Fig. 2. Position map of the case study of sediment Drift 7 with location of PNRA data.

The maximum resolution attained during the survey in the deepest water depth (over 4000 m depth) was about 100 m on average (depending on sea and weather conditions and the ship's speed). The sub-bottom profiler employed 16 transducers with a sweep of 2–7 kHz. The trigger rate was 8 s and the recording rate 8192 records per ping (1024 record s^{-1}). The swath bathymetry data were first edited onboard to produce preliminary maps and then reprocessed at the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS). Only display-during-acquisition (both on paper and on screen) was performed onboard for sub-bottom data, which were then replotted at OGS using the SEISPRO software.

Morphology

A shaded relief display of the multibeam dataset collected on sediment Drift 7 (Fig. 3) reveals a complex morphology, which provides new insights into the recent sedimentary processes that have shaped this part of the Antarctic Peninsula Pacific margin.

Continental slope

As in many other parts of the Antarctic Peninsula Pacific margin (e.g. Ambals *et al.* 2006), the continental slope is very steep (up to $>13^{\circ}$), and it is not incised by any canyons or major channels or by recent large-scale slide scars. Conversely, similarly to the Marguerite Bay margin (Dowdeswell *et al.* 2004), a series of large straight subparallel gullies cut the upper slope (Fig. 3) just beyond the shelf edge. Gullies are V-shaped, about 100 m deep on average and up to about 500 m wide. At their down-slope mouth, at about mid-slope they fade into a smooth sea floor where there is no evidence, at the scale of this survey, of sediment accumulation (such as debris lobes or mid-slope fans) resulting from the deposition of sediments transported in the gullies. The base of the continental slope has a rough topography, being incised by a large number of channels within a dendritic network.

The channels converge in the upper rise to form single, trunk-type, deep-sea channels such as the Alexander and Charcot channels (Fig. 3). An analogous pattern was described in the northern part of the Pacific margin of the Antarctic Peninsula on the basis of swath bathymetry (Rebesco *et al.* 2002) and long-range sidescan sonar data (Tomlinson *et al.* 1992).

The MAGICO survey outlines the presence of a sharp offset of the continental slope facing Drift 7 (Fig. 3). The straight slope, trending NE–SW for the length imaged in the survey, is offset by about 3 km for its entire extent from its base to the shelf edge.

The proximal part of the drift

The SE, proximal part of the drift approximately occupies the upper continental rise and includes the transition between the sediment drift and the continental slope (Fig. 3). Closer to the slope, the drift undergoes erosion on both sides through a dendritc pattern of small channels converging in two major the channels, the Charcot and Alexander channels, bounding the drift to the SW and NE, respectively. Further oceanwards, the drift enlarges and develops the typical asymmetric cross-section, with a SW rough, eroded side and a NE smooth, depositional side. Two arcuate slide scars occur on the NE gentle side, close to the top of the drift. One of the scars erodes the sediment surface up to the drift crest. The slide deposit is not obvious in the morphology or in the seismic record, although sediment blocks are present downslope from the scars. It is clear that any sedimentary product of these slides has fed the Alexander Channel. At the moment we have no elements to determine age and volume of these slides, but the freshness of the morphology suggests a relatively recent age.

Alexander Channel

The depressed area between drifts 6 and 7 is incised by the Alexander Channel (Fig. 3). The channel originates at the base of the continental slope from the convergence of a dendritic network of tributary channels conveying sediments from the base of the continental slope as well as from the proximal parts of Drift 7 and, probably, Drift 6. In the upper rise the main channel is flat floored and about 10 km wide. About 150 km seaward from the base of the continental slope, in about 3800 m water depth, there is a slight change in the sea-floor gradient that delineates the transition between the upper and lower rise. Here the depression between the drifts widens and the channel loses its morphological expression. This is where the transition between confined and unconfined gravity flows is suggested to have occurred in the past (Lucchi *et al.* 2002; Diviacco *et al.* 2006). Chirp profiles and coring data suggest that this channel has been inactive recently, at least since the last interglacial period (Marine Isotope Stage 5, Lucchi *et al.* 2002). The Charcot Channel, bounding Drift 7 on the SW side, originates at the base of the continental slope similarly to the Alexander Channel and has a comparable width, but is shorter and more sinuous.

Mass wasting on the steep side of the drift

Widespread sediment mass wasting affects the steep side of Drift 7 in the form of several subparallel erosional channels and gullies cutting into the sediment drift sequence up to the sharp crest separating the SW steep flank from the NE gentler one (Figs 3 and 4). This crest is formed by coalescent slide scars that give it an overall regularly undulated shape with concavity consistently oriented towards the SW. Sediment drainage is towards the Charcot Channel.

Undulating depositional bedforms on the gentler side

The gentle NE side of the drift is characterized by the presence of sediment waves and previously unreported sedimentary ridges. The sediment wave field to the north of ODP Site 1095, already observed in seismic profiles (Camerlenghi *et al.* 1997*b*), is located in the distal part of the drift, separated from the Alexander Channel by an area about 30 km wide in which waves are not recognized. The geometry of the sediment waves is variable, with average height less than 20 m and length less than 2 km. The orientation, barely visible in the map of Figure 3, is SW–NE, subparallel to the sea-floor slope. Most (although not all) of them show an apparent upslope migration (Fig. 5). Depositional ridges (Figs 3, 6 and 7), which are 5–10 km wide, a few tens of kilometres long and up to 100 m high, occur with orientation oblique (SSW–NNE) to the drift main axis of elongation. The flanks are mostly even, or concave upwards, and no appreciable migration is visible in the sub-bottom profiles. They are subparallel, at times bifurcated, and they lie in the most elevated part of the drift. Their dimensions are peculiar, being smaller than those typical of sediment drifts and channel–levees, but definitely larger than those of turbidity current sediment waves, and just at the upper limit of those of bottom-current sediment waves. Bottom-current related bedforms of comparable dimensions have

been described to occur as large sediment waves (Flood *et al.* 1993), as series of elongated mounds (e.g. Bulat & Long 2001), or within a multicrested drift (Lu *et al.* 2003).

Lineations beside the Alexander Channel

A series of subparallel NW–SE-trending lineations occurs beyond the distal part of the Alexander Channel (Fig. 3). Their origin is unclear. Some Chirp data across these lineations show the presence of sharp steps where the sea floor and the underlying reflectors are offset by a few tens of metres (see also the 18 kHz data of Fig. 8). Conversely, the seismic data crossing the southernmost part of these lineations show the presence of undulations of the sea floor about 1 km in wavelength and a few tens of metres high. Only the shallowest reflectors appear to be affected by these undulations (in the form of terminations and/or changes in amplitude of the reflectors), whereas the reflectors beneath are not affected.

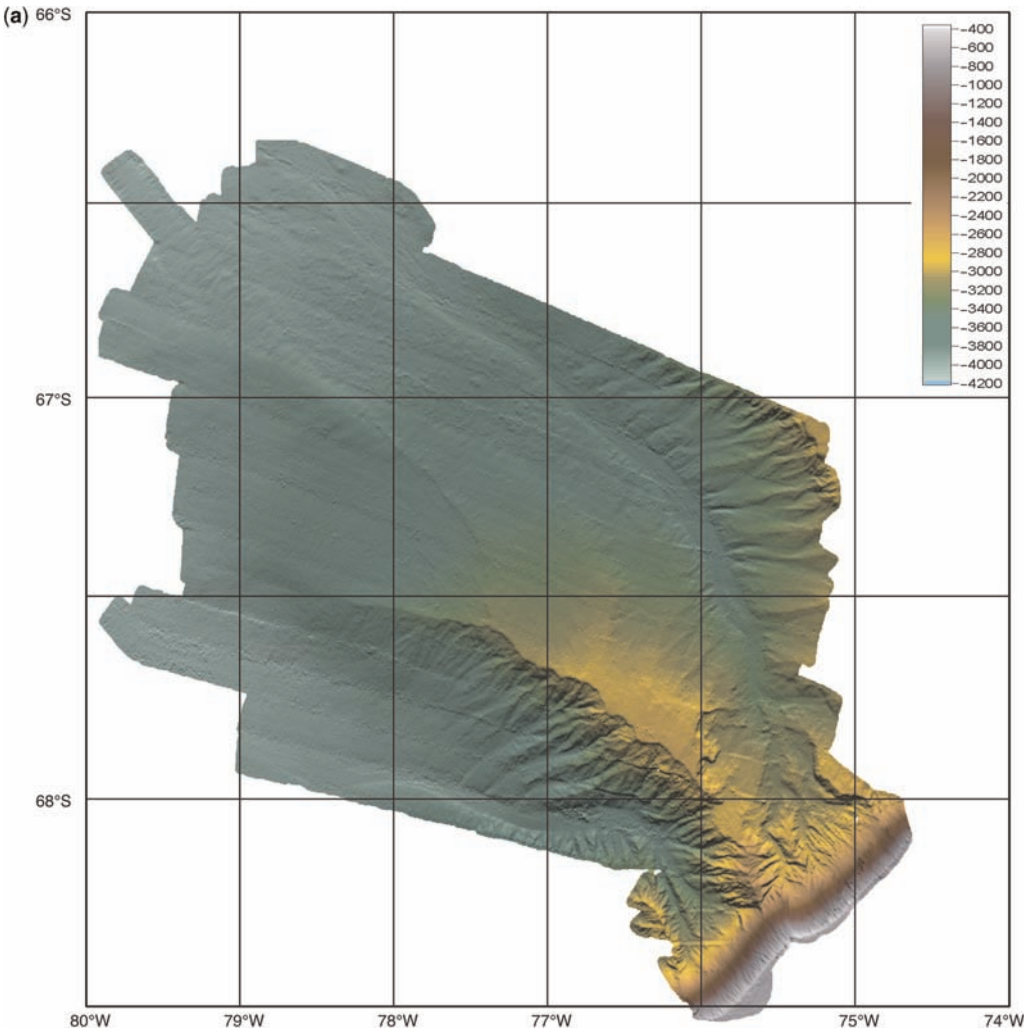


Fig. 3. Colour shaded relief bathymetric map produced from a regularly spaced 200 m grid on the basis of the multibeam data collected within the MAGICO project. Mercator projection, WGS 1984 spheroid, true-scale latitude 65°S, vertical exaggeration ×7.5, illumination from north. (**a**) Uninterpreted; (**b**) with superimposed interpretation and data location.

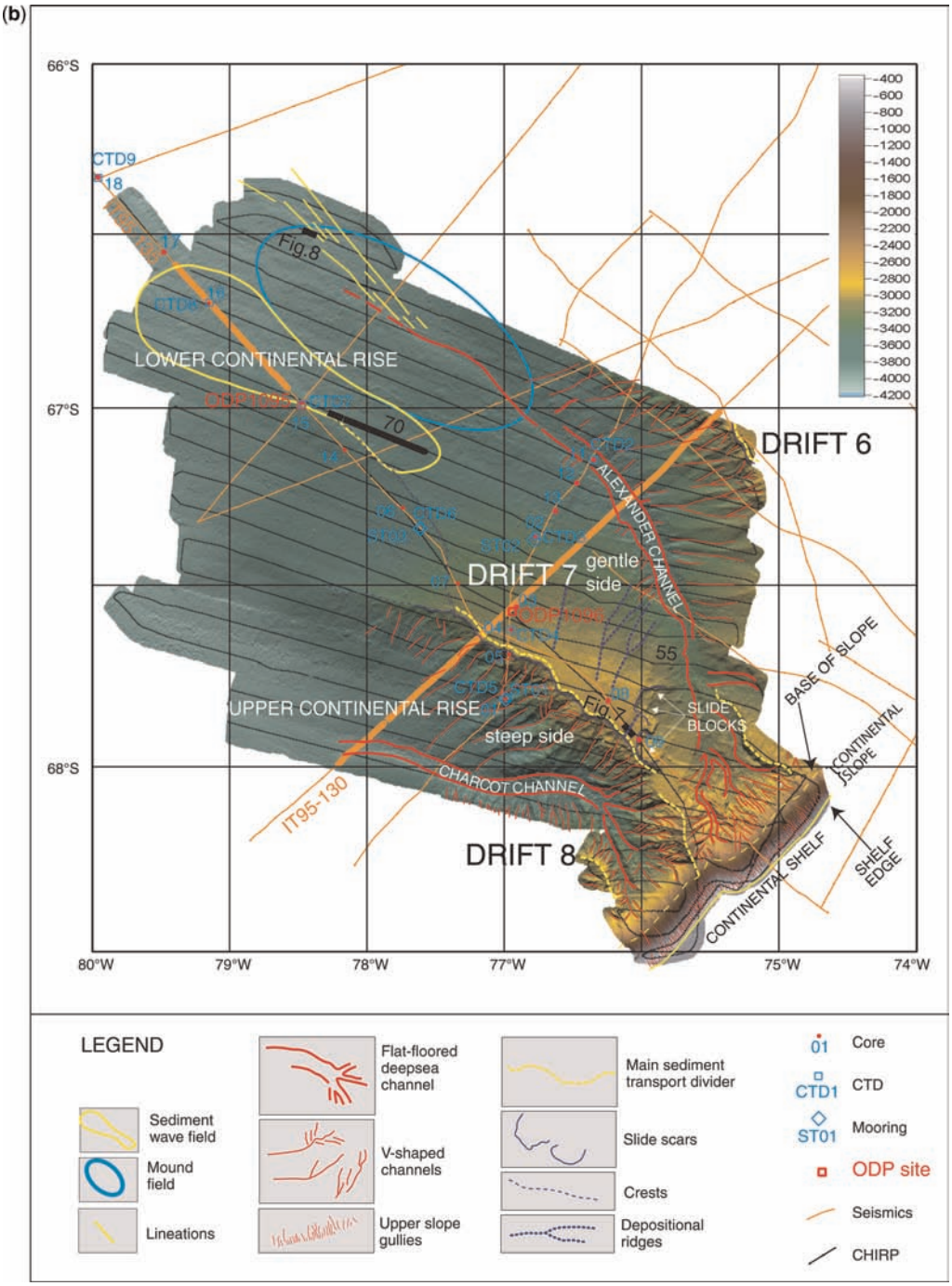


Fig. 3. *Continued*

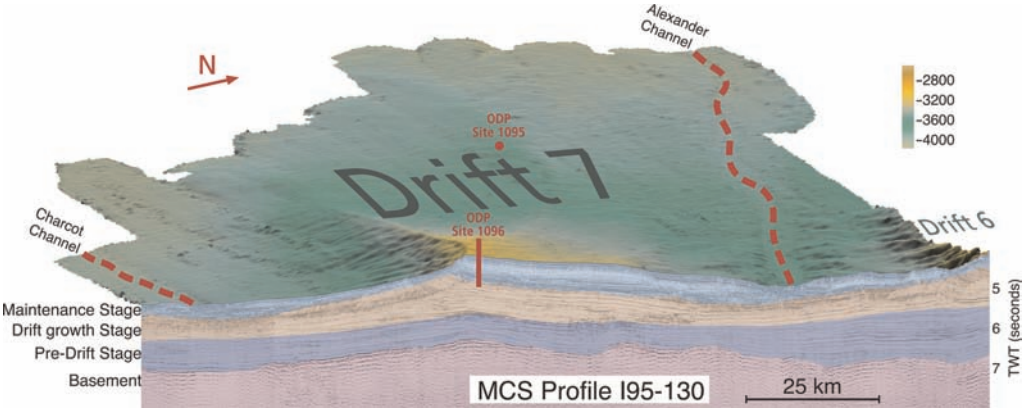


Fig. 4. Perspective view of multibeam data from the distal part of Drift 7, cut by seismic profile I95-130A (location shown in Fig. 3b). TWT, two-way travel time.

Acoustically transparent, cone-shaped mounds

In the deepest part of the MAGICO survey, a number of acoustically transparent, cone-shaped mounds were imaged on both sub-bottom profiler and 18 kHz echosounder data (Fig. 8). The mounds are variable in dimensions and geometry, but are generally subcircular, several hundred metres wide and a few tens to over 70 m high. They were observed to occur in two different settings: aligned along the faults beside the Alexander Channel and scattered in a vast field in the most distal part of Drift 7 (Fig. 3).

Interpretation and discussion

Downslope sediment transfer on the Antarctic Peninsula Pacific margin is inferred to occur by numerous small-scale slumps on the upper slope, and debris flows and turbidity currents on the lower slope and continental rise (Larter & Cunningham 1993; Rebesco *et al.* 1997). The gullies on the upper slope (Fig. 3) are therefore the expression of sediment transport from the shelf, occurring presumably during stages of ice grounding at the shelf edge. They may be interpreted as channelized paths of debris flows or as a series of small slumps. The disappearance of the gullies in the smooth mid-slope may suggest that the erosive process ends there, whereas sediment transport continues further down to the base of the continental slope. Alternatively, channelized erosion from shelf to rise may have been continuous from gullies to deep-water channels earlier in the history of this margin, and the gullies on the mid-slope may have been infilled in later stages (during ice sheet retreat). None the less, the roughness at the base of slope suggests that the debris flows evolve downslope into density flows (turbidity currents) that erode the substrate to form deep-sea channels in a dendritic centripetal pattern. Moreover, it has been recently observed that the stiff glacial diamictons of the steep prograding wedge produced during the last 3 Ma of polar history of the margin show a significant downlap over a regional surface, eroding the underlying sediments deposited during the earlier polythermal history of the glacial margin (Rebesco *et al.* 2006). Channel incision at the base of the slope may hence be inferred to develop at the transition from the stiff glacial diamictons to the softer, more erodible polythermal sediment, which can be exposed, or subcropping only at the base of the slope.

The origin of the offset in the straight margin (Fig. 3) is puzzling and probably is not identifiable in the erosional processes affecting the base of the slope. In fact, either retrogressive erosion at the head of a deep-sea channel or a slide scar would have resulted in a semicircular scar with relatively sharp flanks. An interpretation of the displacement of the slope as one flank of a mega slide scar would require the existence of an opposite flank and an intervening semicircular shape. Furthermore, the available deep penetration multichannel seismic data do not favour this hypothesis.

A recent tectonic origin appears unlikely, because any activity in this area should have ceased sometime between 30 and 20 Ma ago when the Heezen–Tula ridge-crest segment of the Antarctic–Phoenix spreading centre migrated into the trench of the formerly active Antarctic Peninsula margin (Larter *et al.* 1997).

More reasonably, this offset could be derived by horizontal displacement between plates produced between 30 and 20 Ma ago. The dextral

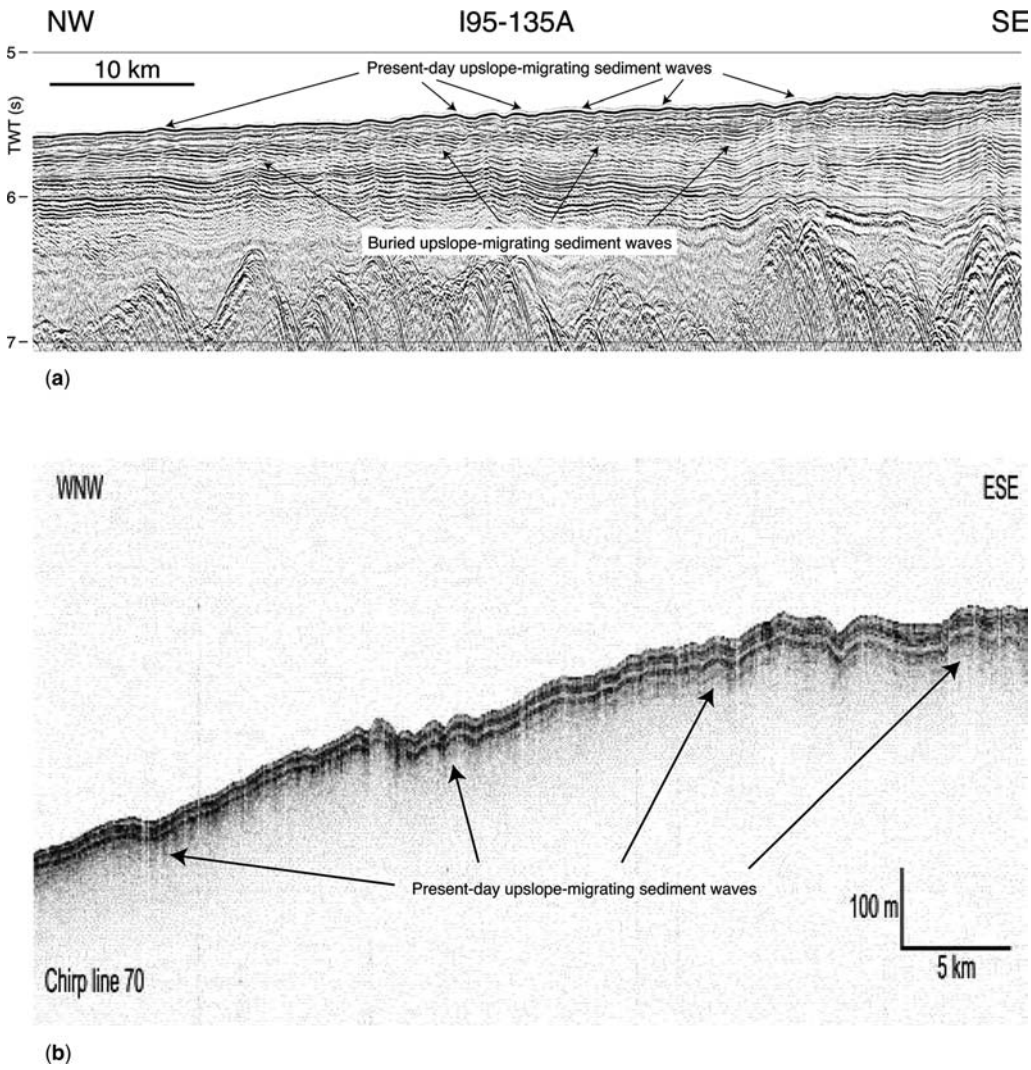


Fig. 5. Examples of buried and outcropping upslope-migrating sediment waves. (**a**) Seismic profile I95-135A; (**b**) sub-bottom profile 70. (Locations shown in Fig. 3b.)

displacement and the orientation of the fault plane (roughly perpendicular to the margin) are consistent with the orientation and horizontal displacement of the Antarctic Plate fracture zones. Moreover, the presence of a fracture zone in the oceanic basement below Drift 7 was suggested by deep penetration multichannel seismic data showing moderate oceanic basement offsets (McGinnis & Hayes 1995). The lineations beyond the distal part of the Alexander Channel correspond to this fracture zone and are oriented subparallel to it and to the Tula and Heezen fracture zones (Fig. 2). These lineations, if interpreted as faults, may have been produced by remobilization, subsequent to debris-flow loading, of the sedimentary succession overlying this fracture zone (Diviacco *et al.* 2006). Alternatively, they may be interpreted as gravity faults at the base of Drift 6 induced by underconsolidation of biogenic silica-containing sediments (Volpi *et al.* 2003), or as a result of unknown neo-tectonic deformation. Nevertheless, the seismic data available in the southern part of these lineations do not show any displacement of the underlying sedimentary succession, hence suggesting a sedimentary origin as flow structures related to the Alexander Channel. It is also possible

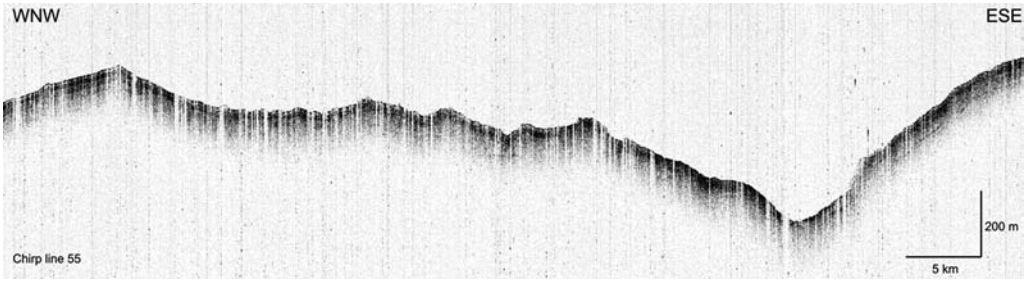


Fig. 6. Sub-bottom Profile 55 (location shown in Fig. 3b) showing the depositional ridges on the gentler side of Drift 7, elevated above the adjacent thalweg of the Alexander Channel.

that some of these lineations (the southern ones) are of sedimentary origin and others (the northern ones) are of structural origin.

The present margin offset, which lies approximately on the landward projection of the fracture zone identified by McGinnis & Hayes (1995) and of the lineations beyond the Alexander Channel (Fig. 3), may hence be reasonably considered as the remnant of a larger ancestral offset at the ocean–continental transition, now buried by the Plio-Pleistocene glacial wedge development.

The presence of such an offset and of the fracture zone may be relevant for the understanding of the processes that led to the drift growth in the Miocene. A comparison may be attempted with other changes in the margin's trend that have been considered relevant in controlling the direction of elongation of sediment drifts. This direction is generally subparallel to the margin, but the development of drifts with a trend perpendicular to the margin may result in response to a change in the margin's trend (Faugères *et al.* 1999), as in the case of the Eirik drift (Arthur *et al.* 1989) or the Greater Antilles Outer Ridge (Tucholke & Ewing 1974). Moreover, the orientation of Drift 7 may have been controlled by the underlying fracture zone, similarly to the drift that developed corresponding to the subducted oceanic slab off Peter I Island in the Bellingshausen Sea (Nitsche *et al.* 2000). The answer to the hitherto unsolved questions regarding location and orientation of Drift 7 (whose contouritic origin was challenged by some because of its elongation perpendicular to the margin) may lie in the presence of the offset of the margin and/or of the fracture zone.

The lesson that may come from the more than 10 years of persistent research surrounding Drift 7 is that a reliable understanding of deep-sea processes may come only from complementary datasets and multidisciplinary approaches. Similarly, the answer to the question of the direction of elongation and location of the other drifts may come after the acquisition of additional, more detailed datasets.

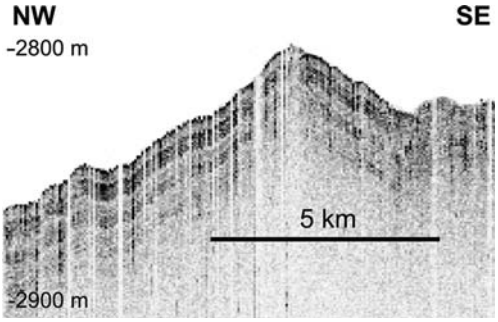


Fig. 7. Sub-bottom Profile 04 (location shown in Fig. 3b) showing how sub-bottom reflections are continuous and parallel to the sea floor on both sides of the ridges. The ridges are therefore interpreted as depositional features rather than being related to fault activity or to erosional processes.

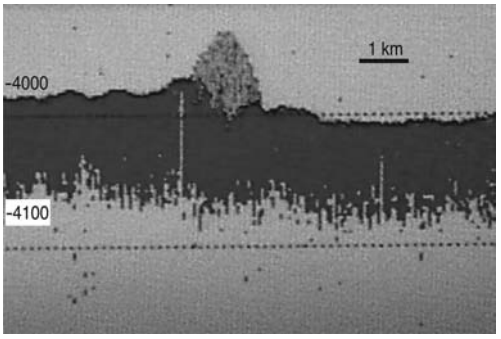


Fig. 8. An 18 kHz echosounder profile showing a conical diffraction about 75 m high and several hundreds of meters wide (location shown in Fig. 3b).

The very rough morphology of the proximal part of the drift (Fig. 3) clearly suggests that it is affected by sediment mass wasting that originated on the continental slope. However, the smooth, depressed, depositional nature of the gentle side in this most proximal part of the drift strongly suggests reduced deposition with respect to the top of the drift in consequence of a flow of bottom current confined along slope by the Coriolis force (i.e. SW of the depositional ridge of Fig. 7). This part of the drift hence appears to result from the combined action of reduced deposition by a bottom current, and sediment mass wasting, with the former being more evident south of the top of the drift and the latter prevailing closer to the slope. Therefore the action of bottom currents is one of the most effective processes on the continental rise, masked by mass wasting only in the most proximal part of the drift.

The erosion of the steep, SW side of the drift (Fig. 3) was attributed before the MAGICO survey to the gullies and small tributary channels feeding the Charcot Channel (Rebesco *et al.* 2002). In other words, the process controlling the morphology of this side was inferred to be that operated by turbidity flows undercutting and deepening the base of the SW slope of the drift. However, this process is justified by swath bathymetry only in the proximal part of the SW side of the drift, where the gullies coalesce and reach the thalweg of the Charcot Channel. Conversely, the incisions affecting the distal part are too far and disconnected from the Charcot Channel for us to infer a genetic connection (Fig. 3). The reasons for the instability have hence to be sought in other processes.

By analogy with smaller-scale, fine-grained sediment waves that originated from bottom currents, non-deposition or erosion on the steep side of the drift may occur as a consequence of the greater flow speed (supposed to be about >16 cm s^{-1}) on the downstream side (Wynn & Stow 2002). The contrast between relief building by sediment deposition of the gentle side and non-deposition or erosion on the steep side favours the progressive steepening of the steep side until gravitational instability is generated. Drift 7 sediments, which contain large amounts of biogenic silica, have anomalously high porosities at depth (Hillenbrand & Fütterer 2001) because of the low compressibility of the skeletons of the siliceous microfossils (Volpi *et al.* 2003). The fine grain size and high porosity at depth favour a reduced shear resistance to applied stresses and enhanced gravitational instability. The average gradient of the steep slope of the drift is 2°, close to the 3–4° average slope gradient of low-latitude continental slopes at which sediment mass wasting occurs normally throughout the evolution of a continental margin. The occasional character of the erosion on the SW side is indicated by the non-steady migration of the crest of the initially symmetrical drift visible on seismic profiles (Fig. 4).

The causes of the instability are therefore inherent in the bottom-current processes that control the growth of the drift: (1) persisting enhanced accumulation of opal-rich fine-grained sediment on the upstream (NE) side; (2) reduced accumulation and occasional erosion on the downstream (SW) side. Both processes have produced the northeastward migration of the crest and the present asymmetric morphology.

The origin of the sediment failure on the proximal gentle side of the drift (Fig. 3), where the sea-floor gradient is in the range of 0–1°, appears to be, as in the case of the steep side, the high porosity at depth produced by siliceous microfossils (Volpi *et al.* 2003) combined with the relatively high accumulation rate, which has been shown to decrease from proximal to distal parts of the drift (Lucchi *et al.* 2002). The downslope dip of the depositional surfaces, which are parallel to the sea floor throughout the sedimentary succession, may also contribute to sliding along weak surfaces. The blocks visible within the slide scar close to the slide headwall suggest that the lower sea-floor gradient of these slides has resulted in a shorter run-out compared with the slides of the steep side of the drift. Probably, the rest of the slide sediments were transferred to the deepest part of the rise along with the density flows moving within the Alexander Channel.

According to their dimensions and characteristics, the sediment waves in the distal part of the drift (Figs 3 and 5) may be produced by both turbidity current and bottom-current processes. However, turbidity current-generated waves usually show greater regularity, a downslope trend of decreasing dimensions, and a relationship with the parent turbidity channel (Wynn & Stow 2002). As none of these criteria are observed here, a contour-current origin is preferentially envisaged. Moreover, because of their dimension, orientation and setting, we interpret the depositional ridges in the most elevated part of the drift (Figs 3, 6 and 7) as a novel type of sharp-crested large fine-grained bottom-current sediment wave.

It must be noted, however, that Volpi *et al.* (2003) described long-wavelength folds induced by creep of the sedimentary sequence of Drift 7 above the biogenic opal-A to opal-CT diagenetic boundary, outlined in seismic profile by a bottom-simulating reflector. We think that these folds, undoubtedly affecting a few hundred metres of sedimentary sections, may overlap and imprint the depositional ridges only SE of the location of ODP Site 1095.

Apart from the locally overlapping creep effect, the most likely process controlling the production

of sediment waves on the distal NW side and depositional ridges on the gentle NE side is hence that of bottom currents.

The acoustically transparent, cone-shaped mounds in the deepest part of the MAGICO survey (Figs 3 and 8) are interpreted as fluid escape structures indicating the presence of overpressured fluids within the sedimentary column. In this preliminary phase of the study, where we await additional information from future investigation, the origin of the overpressured fluids can be generally identified in two types of mechanisms: (1) sediment compaction at the Opal A–CT transition at depth; (2) shallow depth sediment overloading by large debris-flow accumulations between drifts in the distal part of the continental rise. The former hypothesis was introduced by Volpi *et al.* (2003). The latter originated in a recent study through reprocessing of multichannel seismic reflection profiles between the distal part of Drifts 6 and 7, which identified large debris-flow deposits that originated during the Late Pliocene associated with seismic evidence of fluid mobilization and venting (Diviacco *et al.* 2006).

Some of these mounds may be alternatively interpreted as deep, cold-water coral bioherms, as their acoustic signature is similar to that of the Norwegian margin (e.g. Lindberg *et al.* 2006). However, framework or reef-building corals have not previously been described in similar water depths. The possibility that local favourable conditions are provided by the observed fluid escapes will form the focus of further research.

Relationship between bottom current and deposition

Considering the numerous features that suggest the predominant action of bottom-current processes, Drift 7 is interpreted as a genuine sediment drift in which bottom currents pirate the sediment of turbidity currents.

The newly collected swath and sub-bottom data confirm the interpretation of Drift 7 as having been produced by the interactions of dip- and along-slope processes. The model proposing that turbidity currents provide the sedimentary input and bottom currents control the geometry and morphology of the deposit is consistent with the new information. Turbidity currents alone cannot explain the undulating depositional bedforms on the gentler side (especially those towards its top), whereas bottom-current deflection produced by the margin offset and/or by the fracture zone may explain the dipslope elongation of the sedimentary body. Moreover, the mass wasting on the steep side is certainly not related to turbidity-current undercutting, but is probably inherent in the bottom-current controlled depositional process.

Given the essence of sediment Drift 7, it is interesting to analyse the relationship between bottom current and deposition and to attempt a comparison with an analogous high-latitude counterpart. Within the northern hemisphere many analogies are found on the SE Greenland continental margin, where a series of sedimentary mounds have been interpreted to result from the interplay between turbidity and bottom currents (Rasmussen *et al.* 2003). In both cases very large asymmetric sedimentary mounds separated by deep-sea channels lie within an overall alongslope-flowing contour current (Fig. 9). However, whereas the setting of the SE Greenland mounds is consistent with a channel–levee model in which the asymmetry may be explained by the Coriolis force alone (towards the right in the northern hemisphere), that of the Antarctic Peninsula drifts requires a bottom-current influence (as discussed by Rebesco *et al.* 1997). The stronger influence of turbidity currents in the case of the SE Greenland margin was acknowledged by Rasmussen *et al.* (2003). Moreover, in both cases the mounds are dipslope elongated, slightly oblique with respect to the trend of the margin (Fig. 9), but whereas the Antarctic Peninsula examples lean and prograde upstream (like huge sediment waves), the SE Greenland mounds lean and prograde downstream (like current-deflected levees). Similarly, the orientation of the steep side of the mound is opposite (downstream in the Antarctic Peninsula and upstream in SE Greenland).

This comparison hence suggests that the sediment drifts of the Antarctic Peninsula, although similar in shape to asymmetric channel–levees, behave differently and require the action of bottom currents for their growth. Moreover, a comparative examination of the geometry and morphology of deep-sea deposits may allow the assessment of the relative importance of bottom and turbidity currents.

Conclusions

(1) Studies in the Antarctic Peninsula Pacific margin confirm once again that a reliable understanding of deep-sea processes may come only from complementary datasets and multidisciplinary approaches, and that the assessment of the relative importance of bottom and turbidity currents may be effectively assisted by an accurate examination of the geometry and morphology of deep-sea deposits.

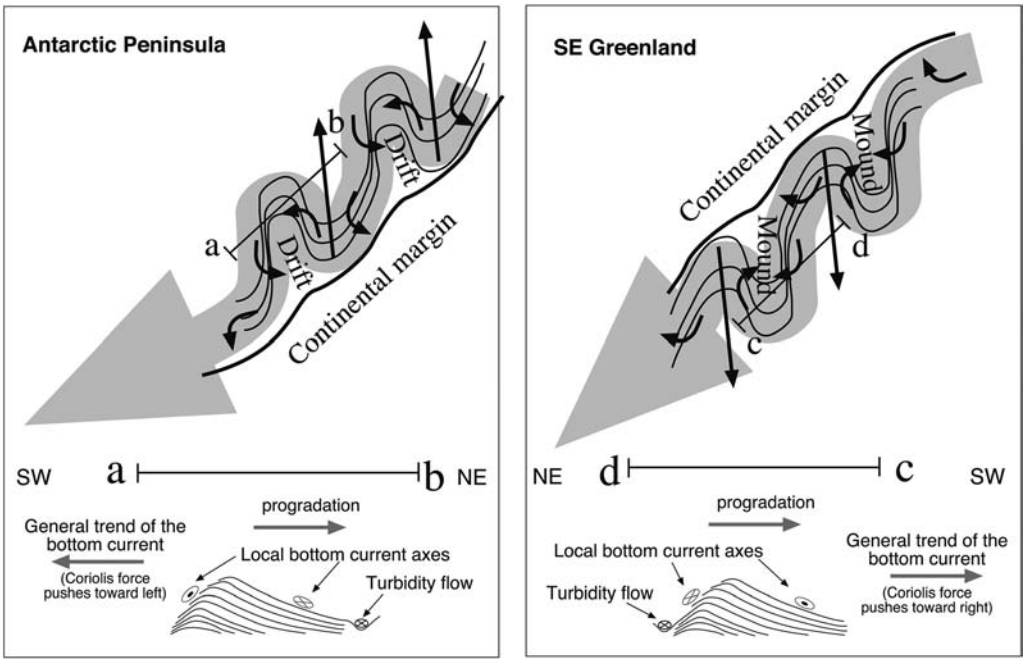


Fig. 9. Schematic diagram showing the comparison between the sedimentary mounds of the Pacific margin of the Antarctic Peninsula and those of the SE Greenland margin. The wide grey arrow shows the general path of the bottom current and the small black arrows show the deviating trend of the Coriolis force.

(2) In particular, the genuine sediment drift nature of Drift 7, in which bottom currents pirate and control the deposition of the sediment of turbidity currents, is suggested by a number of features: (a) the location and elongation perpendicular to the margin of Drift 7 can be explained by the presence of a fracture zone beneath it and of an associated offset in the margin in front of it; (b) the geometry of the proximal, depressed part of the drift suggests the combined action of reduced deposition by bottom currents confined along slope by the Coriolis force, and sediment mass wasting; (c) the persisting accumulation on the upstream side and reduced accumulation or occasional erosion on the downstream side (inherent in the bottom-current process) have produced the asymmetric morphology and caused of the instability of the steep downstream side; (d) sediment waves on the distal NW side and depositional ridges on the gentle NE side are probably produced by bottom currents.

(3) Additional features imaged by the multibeam survey are: the whole extent of the Alexander and Charcot channels; previously unreported lineations of enigmatic origin in the distal part of the drift; acoustically transparent, cone-shaped mounds in the distal part of the drift interpreted as fluid escape structures.

(4) Comparison with an analogous high-latitude counterpart suggests that the bottom currents appear to have a crucial influence on the geometry and progradation direction of Drift 7.

Further developments in the understanding of contourite system behaviour and of the interaction of down- and along-slope processes, relevant for palaeoclimatic studies and for oil exploration, will come from comprehensive datasets from well-studied examples.

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