

Glacial contourites on the Antarctic Peninsula margin: insight for palaeoenvironmental and palaeoclimatic conditions

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Abstract: Deep-sea finely laminated and barren glacial sediments occur in the sediment drift field offshore the Pacific margin of the Antarctic Peninsula where a weak contour current flows at present to the SW. Atypical sedimentary facies were related to the coexistence and interaction of different sedimentary processes. Three 'end-members' of radiograph facies were defined to represent the sedimentary sequences controlled by a dominant process, as follows. (1) Direct influence of turbidity currents on sedimentation is observed in the area surrounding the Alexander Channel system with silty layers interbedded with laminated mud free of ice-rafted debris (IRD). (2) Distal meltwater turbid flows dominate the more proximal area of the top plateau with structureless and coarser-grained sediments containing IRD. (3) Along the crest of the drift, persistent weak bottom currents control the deposition of fine-grained sediments conveyed into the system through other processes. These laminated sediments contain IRD and are, atypically, not bioturbated, because of unusual, climatically related, environmental conditions of suppressed primary productivity and oxygen-reduced deep waters. These glacial contourites were observed on most of the Antarctic margin with the exception of the areas in which polynyas were maintained during the glacial stages. Glacial contourites can be used as a proxy to define temporal and spatial extension of the Antarctic sea-ice.

Deep-sea sediments of the sediment drifts offshore the Pacific margin of the Antarctic Peninsula were investigated within the SEDANO (Sediment Drifts of the Antarctic Offshore) and MOGAM (Morphology and Geology of Antarctic Margins (Antarctic Peninsula and Wilkes Land)) projects of the Italian Programma Nazionale di Ricerche in Antartide (Fig. 1). The continental shelf of the Pacific margin of the Antarctic Peninsula is dissected by a number of modern, U-shaped troughs that reflect the Neogene path of large ice-streams (Rebesco *et al.* 1998, 2002). Sediments across the continental shelf were transported mainly by ice-streams and delivered to the continental slope and rise during the periods of maximum glacial expansion. The continental rise hosts a number of large sediment drifts separated by dendritic deep-sea channel systems that originated on the lower continental slope in alignment with the reaches of each glacial trough (Amblas *et al.* 2006; Rebesco *et al.* 2007).

Two main alternating lithologies related to climatic changes were initially distinguished (Pudsey & Camerlenghi 1998; Pudsey 2000): interglacial brown bioturbated mud containing sparse ice-rafted debris (IRD), and glacial grey laminated mud. Further detailed studies consisting of over

1000 sedimentological, compositional and biostratigraphic analyses (diatoms, foraminifers, and nannofossils) allowed Lucchi *et al.* (2002a) to distinguish four distinctive sets of sedimentary facies connected to a sequence of four climatic stages, each characterized by the onset of typical sedimentary processes (Fig. 2), as follows. (1) Strongly bioturbated mud with abundant IRD and aeolian sediment input was produced during the interglacial phase (Fig. 2a). The increased bioactivity is matched by insignificant down- and along-slope processes. Negligible suspended load and sediment transport by the southwesterly flowing bottom currents is occurring at present on the continental rise (Giorgetti *et al.* 2003). (2) Terrigenous structureless mud including a series of close-spaced IRD layers was produced during the deglaciation (transition from glacial to interglacial conditions) by the disintegration of the retreating grounded ice sheet (Fig. 2b). The absence of calcareous microfossils is related to strong carbonate dissolution and rise of the carbonate compensation depth (CCD) as a result of major meltwater discharge, which in turn caused water stratification (with less oxygenated and nutrient-enriched conditions at the sea bottom). (3) A large variety of

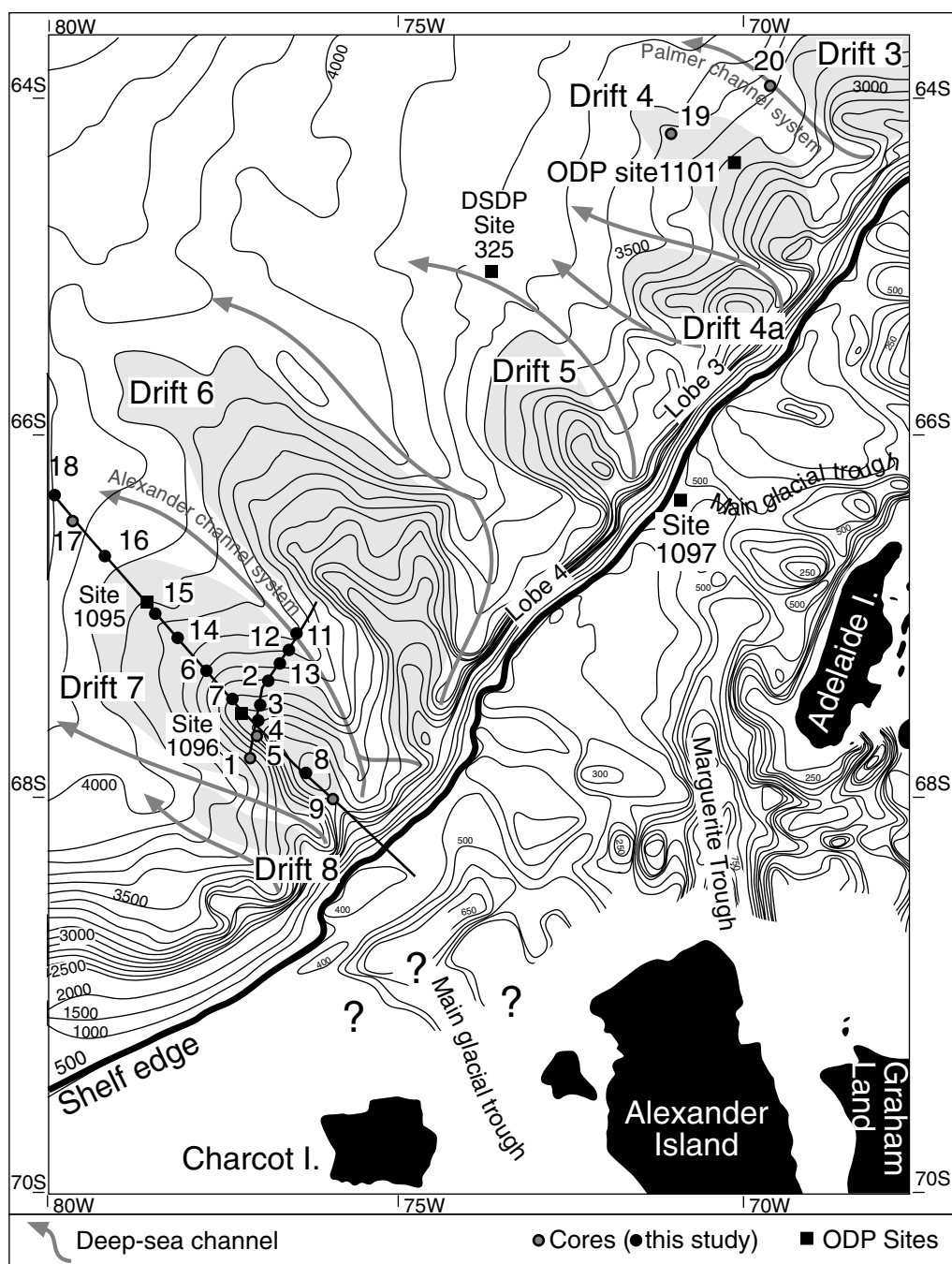


Fig. 1. Location map of the study area (bathymetry after Rebescio *et al.* 1998). The whole set of SEDANO cores is shown along the strike- and dip-oriented seismic lines. ●, Cores used for this study; ■, ODP Leg 178 drilling sites.

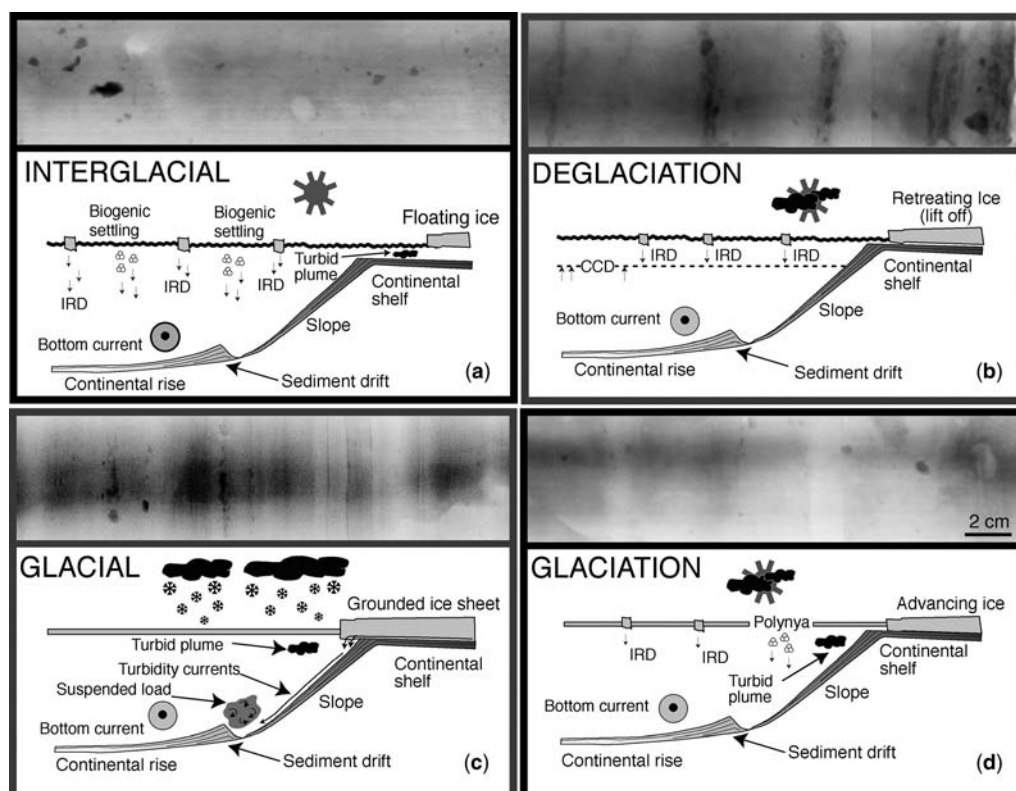


Fig. 2. Schematic model of the four climatic stages proposed to explain the repeated succession of four distinctive sedimentary facies related to the onset of different sedimentary processes (after Lucchi *et al.* 2002a).

almost barren facies was produced during the glacial conditions, suggesting the presence of different interacting sedimentary processes. Sediments appear generally laminated (Fig. 2c) with planar and/or ripple-like lamination, and can contain silty layers, laminae and lenses, and IRD layers or sparse pebbles. Typical mass gravity flow facies are also present, including slumps and turbidites. (4) Terrigenous structureless mud with rare and sparse IRD and bioclasts was produced during the glaciation phase (transition from interglacial to glacial conditions; Fig. 2d). Sediment input probably occurred through meltwater turbid plumes, wind and ice-rafted detritus, with biological activity reduced to polynyas.

Several researchers have advocated the possible concurrence of turbiditic and contouritic processes on the Antarctic Peninsula continental slope and rise as well as meltwater turbid plumes and the existence of benthic nepheloid layers at the sea bottom (Pudsey & Camerlenghi 1998; Pudsey 2000; Lucchi *et al.* 2002a). Nevertheless, sedimentary processes have not been associated with the corresponding facies, which in this area appear

significantly different from those defined by the 'classic' tests.

In this study we investigate in detail the last glacial interval corresponding to isotopic stages 2–4 (the above set of facies (3)) in order to: (1) specify the type of sedimentary process, or coupled sedimentary processes, that were responsible for the large variety of sub-facies observed in our sediment cores; (2) define the environmental and palaeoclimatic conditions during last glacial maximum with a possible extrapolation to the older glacial intervals; (3) compare the glacial sedimentation on the Pacific margin of the Antarctic Peninsula with other Antarctic margins.

Materials and methods

This study has been carried out on the last glacial interval (IS 2–4, spanning 74–13 ka) identified by Lucchi *et al.* (2002a) on the basis of biostratigraphy, magnetic susceptibility logs, clay mineral assemblage, sediment facies and textural characteristics (Fig. 3). The stratigraphic scheme employed has been developed without the aid of isotope

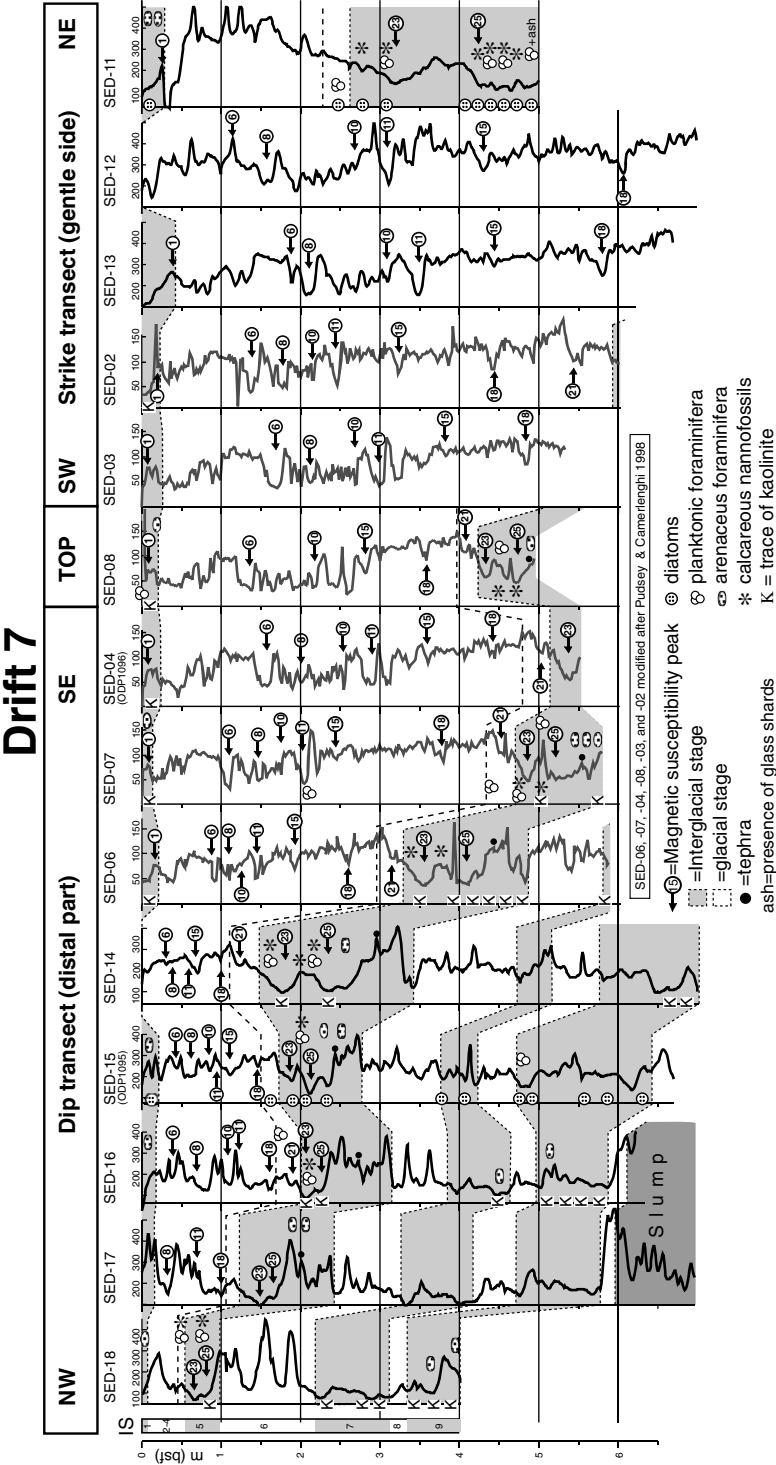


Fig. 3. Magnetic susceptibility logs with correlation of the SEDANO cores based on magnetic susceptibility peaks, biostratigraphy, visual core description, X-radiograph facies, and clay mineral analyses (core location is shown in Fig. 1). In this study we investigated last glacial sediments corresponding to Isotopic Stages 2–4 spanning 74–13 ka. Stratigraphic framework and core logs have been given by Lucchi *et al.* (2002a).

Table 1. Core location and sedimentological investigation

Core	Length (m)	Water depth (m)	Location within or around Drift 7	Sedimentology	
				Grain size	X-ray
SED-02	6.11	3313	Mid-part of the NE gentle side		•
SED-03	5.32	3176	Upper part of the NE gentle side		•
SED-04	5.52	3066	Proximal to the crest of Drift 7		•
SED-06	5.89	3606	Distal part of Drift 7		•
SED-07	5.79	3266	Distal part of Drift 7	•	•
SED-08	4.95	2750	Crest of drift 7	•	•
SED-11	5.00	3725	Upper reaches of Alexander Channel	•	•*
SED-12	6.97	3620	Base of the NE gentle side		•
SED-13	6.67	3559	Lower part of the NE gentle side	•	
SED-14	6.98	3768	Distal part of Drift 7		•
SED-15	6.68	3880	Distal part of Drift 7	•	
SED-16	6.31	4055	Distal part of Drift 7	•	
SED-17	6.60	4130	Distal part of Drift 7		
SED-18	4.00	4215	Lower reaches of Alexander Channel	•	•*

*On significant sections only.

stratigraphy because the foraminiferal record is discontinuous in the sedimentary record (Barker *et al.* 2001). However, it has been confirmed by the chronology derived from the palaeointensity of the magnetic record (Sagnotti *et al.* 2001).

From the original set of 17 SEDANO cores collected in and around sediment Drift 7, we selected 14 cores located along two orthogonal transects: a strike line through the NE gentle side of Drift 7, facing the Alexander Channel system, and a dip line along the NW-oriented crest of Drift 7 (Fig. 1 and Table 1). None of the cores collected on the steep sides of Drift 7 have been considered for this study as their sedimentary sequences are possibly affected by local sediment instability and hence are not unquestionably continuous.

Glacial sediments have been studied for lithological properties and sedimentary structures by visual description of the fresh core surface and by use of X-radiographs.

The textural characteristics of sediments have been studied by grain-size analysis of 168 samples at 10 cm spacing. The sediments were initially dried at 30 °C to determine the total weight, and then were left to disaggregate for 24 h in a 0.05% Calgon solution. Sand and silt–clay (mud) fractions were separated by wet sieving at 63 µm, and the fine fraction was analysed using a SedigraphTM 5100. The analytical results were compared using cluster analysis with *k*-means.

Results

Glacial sediments are grey in colour (typically 5Y 5/1 on the Munsell Soil Colour Chart), very fine

grained (dominated by mud), and they can occasionally contain both silty layers or laminae and IRD layers (unsorted sand or gravelly mud layers with clasts usually >63 µm and <1 cm).

A statistical approach to grain-size analysis allowed an initial distinction of three sediment types forming glacial sediments (Fig. 4a): (1) *terrigenous mud*, which forms the bulk of glacial sediments, is characterized by the highest clay content (over 65%) and the lowest sand content (<0.5%); (2) *silty layers*, which have a mode within the coarse silt range (5–6φ); (3) *gravelly mud layers* (IRD layers), which contain a significant amount (up to 40%) of sand, gravel and rare pebbles, with a minimum of very coarse silt (4–5φ) and a large tail of fine-grained sediments.

The *terrigenous mud* is generally poorly sorted and negatively skewed. Figure 5a and b and Table 2 indicate the textural variability of the *terrigenous mud* along the dip transect. Core SED-08, located at the top of Drift 7, contains the ‘coarsest’ sediments, with a relatively higher percentage of non-cohesive fraction (from very fine sand to coarse silt). These values exceed those observed in core SED-13 located on the strike transect in the area close to the Alexander Channel system (Table 2). In the distal area (SED-15 and -16), some intervals have a relatively high fine sand content compared with the proximal cores. Nevertheless, the overall grain-size distribution of the *terrigenous mud* fines oceanward, where sediments have the mean size of clay (>9φ) and appear better sorted (Fig. 5b).

A statistical investigation conducted on the silt fraction of the *terrigenous mud* indicated the presence of four sediment groups (clusters), named

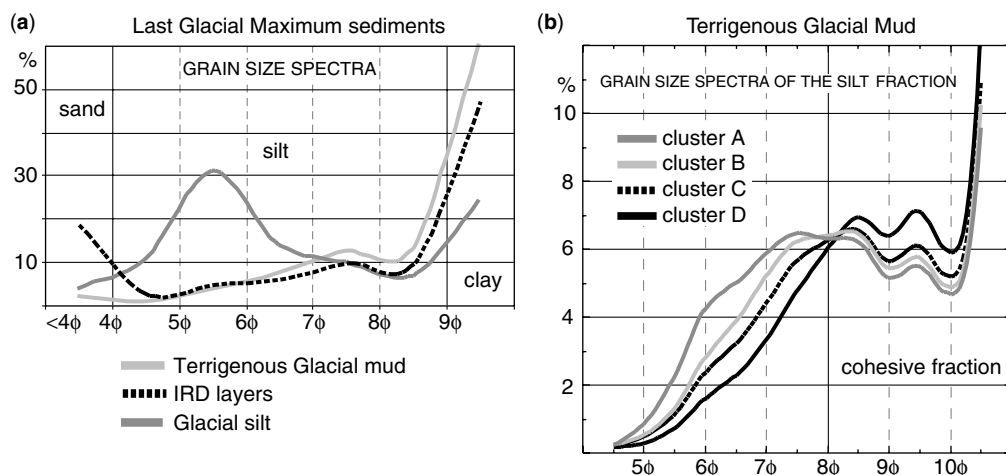


Fig. 4. Textural characterization of last glacial sediments. (a) Distinctive grain-size spectra of the three sediment types forming the glacial sequences; (b) grain-size spectra of the silty fraction of the terrigenous mud forming the bulk of glacial sediments.

A–D, that reflect a progressive decrease of environmental energy and/or dynamics of sedimentary processes (Fig. 4b). According to Table 3, which shows the distribution of the four classes of cluster, cores SED-13 (close to the channel system) and SED-08 (top of the drift) are very similar. These cores contain a few samples belonging to cluster A (medium–high energy) with a predominance of medium–low (cluster B) and low-energy (cluster C) related deposits. Core

SED-07 (crest of Drift 7) contains samples belonging to only clusters B and C, whereas in the distal area core SED-15 contains all classes of clusters with predominance of cluster D, which forms the entire glacial interval of core SED-16.

Visual core description and X-radiograph analysis indicated that on the NE gentle side of Drift 7 towards the Alexander Channel system, the last glacial interval is over 7 m thick close to the Alexander Channel (core SED-12) and thins

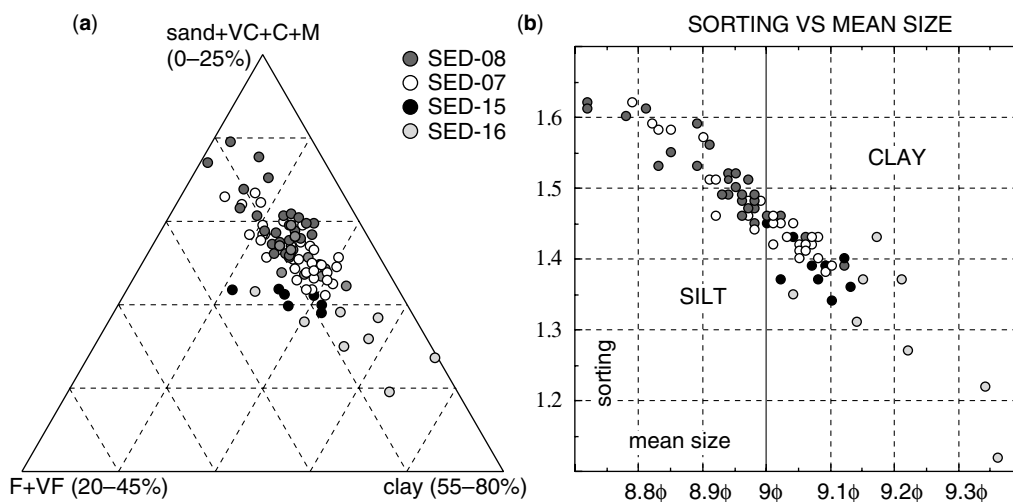


Fig. 5. Grain-size characteristics of the terrigenous mud using (a) the triangle plot for fine-grained sediments suggested by Lucchi *et al.* (2002a) (values in wt%), and (b) diagram of sorting v. mean grain size. VC, very coarse silt; C, coarse silt; M, medium silt; F, fine silt; VF, very fine silt.

Table 2. Grain-size averages of last glacial sediments (wt%)

Cores	Sand	VC silt	C silt	M silt	F silt	VF silt	Clay
SED-13	0.11	0.75	3.84	8.69	12.72	11.74	62.17
SED-08	0.22	0.83	4.70	8.68	12.28	11.87	61.42
SED-07	0.15	0.69	4.01	8.30	12.19	11.93	62.74
SED-15	0.45	0.36	3.03	7.40	12.46	13.71	62.59
SED-16	0.43	0.50	2.27	6.20	11.35	12.75	66.50

VC, very coarse; C, coarse; M, medium; F, fine; VF, very fine.

toward the crest of the drift. Pervasive lamination is produced by faintly laminating mud alternating with closely spaced silty laminae, lenses (millimetre-thick) and layers (up to 4 cm thick; Fig. 6a). These coarser-grained deposits drastically decrease in thickness and frequency towards the crest of the drift (from SED-12 to -02, Table 4) where silty laminae are detectable only in radiographs (SED-03, Fig. 6a). On the lower part of the NE gentle slope, centimetre-thick silty layers appear massive, without lamination or bioturbation, often with irregular or erosive bases (SED-12). Moving upslope toward the crest of the drift, the silty layers are finely laminated with sharp not erosive bases (core SED-13, not illustrated).

At the plateau on top of Drift 7 (SED-08) the last glacial sediments consist of homogeneous layers (2–10 cm thick) and laminae of alternating dark and light grey mud (5Y 5/1 grey and 5Y 4/1 dark grey). This sediment arrangement can locally appear on the fresh surface as a faint lamination, whereas in X-radiographs it is structureless with alternating dark and light grey intervals separated by sharp and irregular boundaries (Fig. 6b). The X-radiographs also indicate the presence of 1–2 cm thick intervals of scattered fine-grained sand and silt.

Along the crest of Drift 7, the thickness of the last glacial interval increases from the centre of the plateau topping of Drift 7 (SED-08, 4 m thick) to its distal part (SED-04, 5 m thick), and then decreases oceanward (Fig. 3). Also along the dip-transect, millimetre-thick silty laminae are common. Their occurrence increases from SED-06 oceanward to SED-15. Beyond this point the silty

laminae decrease in frequency but increase in thickness (centimetre-thick silty layers were found in the most distal cores, see Table 4).

The last glacial sediments of cores SED-11 and SED-18, located within the Alexander Channel system, were a series of coarse-grained deposits, often graded and/or laminated, of unequivocal turbiditic origin. Core SED-11 (upper reaches of the channel) contains silty layers 4 cm thick and a 20 cm thick turbidite with an erosive base overlain by 4 cm of coarse and massive sand. The upper part of this turbidite is faintly laminated and contains a sequence of four medium-grained sandy intervals topped by very fine sand, suggesting scattering of the main turbidity flow (the overall grain size fines upward). Core SED-18 (lower reaches of the channel) contains a 19 cm thick turbidite and at least three amalgamated turbidity intervals, each formed of graded and laminated fine sand with a mud cap. The 19 cm thick turbidite has a sharp non-erosive base and inverse–normal grading within medium-grained sands.

Discussion

Last glacial sedimentary facies and depositional processes

The last glacial sediments of Drift 7 indicate a mixed system responsible for atypical sedimentary facies related to the coexistence of different depositional processes. Three of the facies we identified were called ‘end-members’ (turbidites, contourites, plumites), as we relate them to the predominance of a single process (Fig. 7). The degree of interplay between these processes is then responsible for the large variety of sub-facies observed within Drift 7.

The Alexander Channel system and the NE gentle side of Drift 7: turbidites v. contourites. The Alexander Channel system is the area directly influenced by turbidity currents. Decimetre-thick turbidites have been recovered from both the upper (SED-11) and lower (SED-18) reaches. Sedimentary structures and textural characteristics of these

Table 3. Occurrence of the silty fraction clusters (percentages) in the terrigenous mud

Cores	Cluster A	Cluster B	Cluster C	Cluster D
SED-13	11	59	29	2
SED-08	14	50	36	–
SED-07	–	49	51	–
SED-15	10	10	30	60
SED-16	–	10	10	80

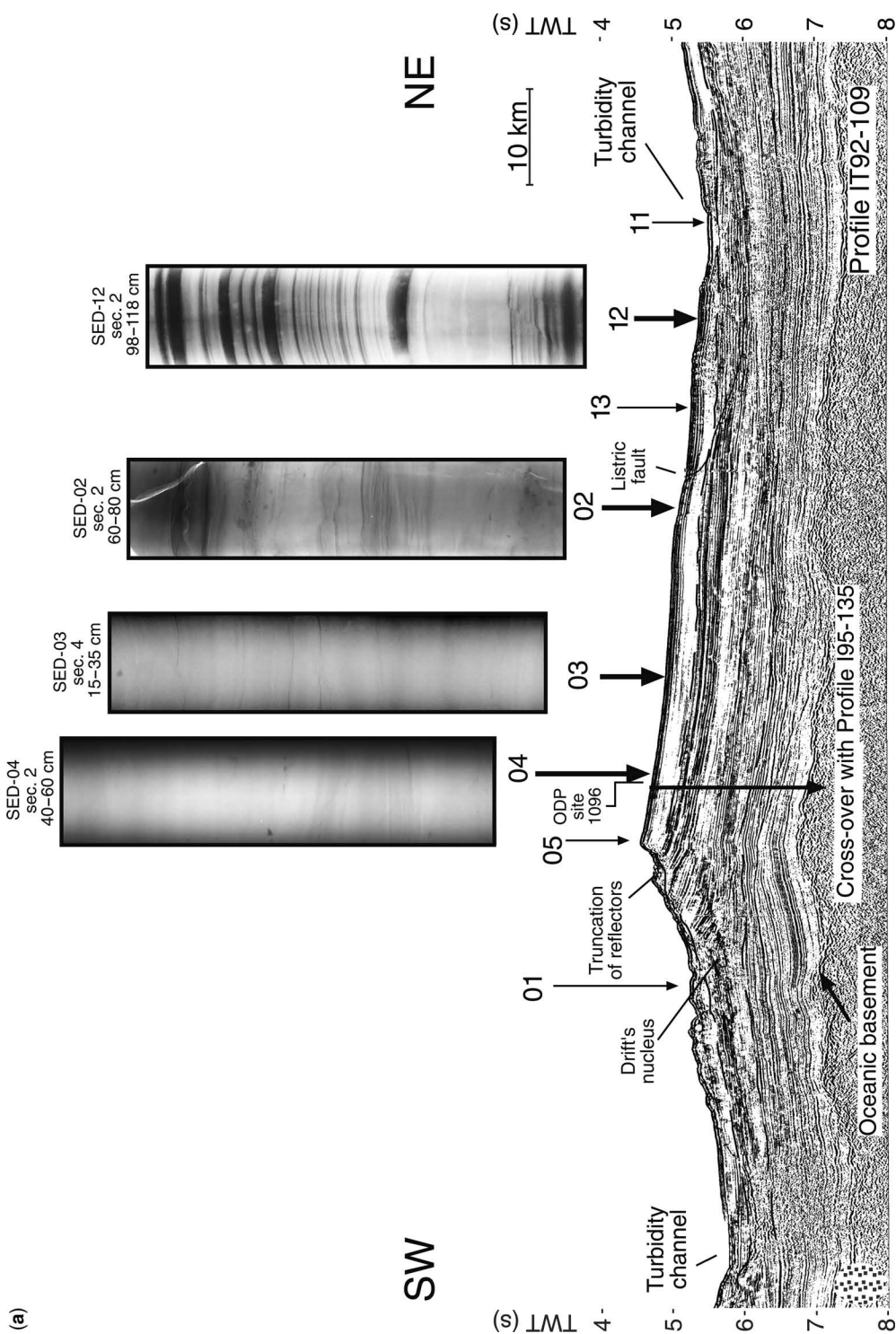


Fig. 6. Seismic profiles with SEDANO core locations and radiograph facies of significant sites (bold arrows). The radiograph intervals reported from each core have been chosen to represent the same chrono-stratigraphic interval. However, for each core the radiograph pattern is consistent within last glacial sediments. (a) Strike transect (OGS seismic line IT92-109); (b) dip transect (OGS seismic line I95-135).

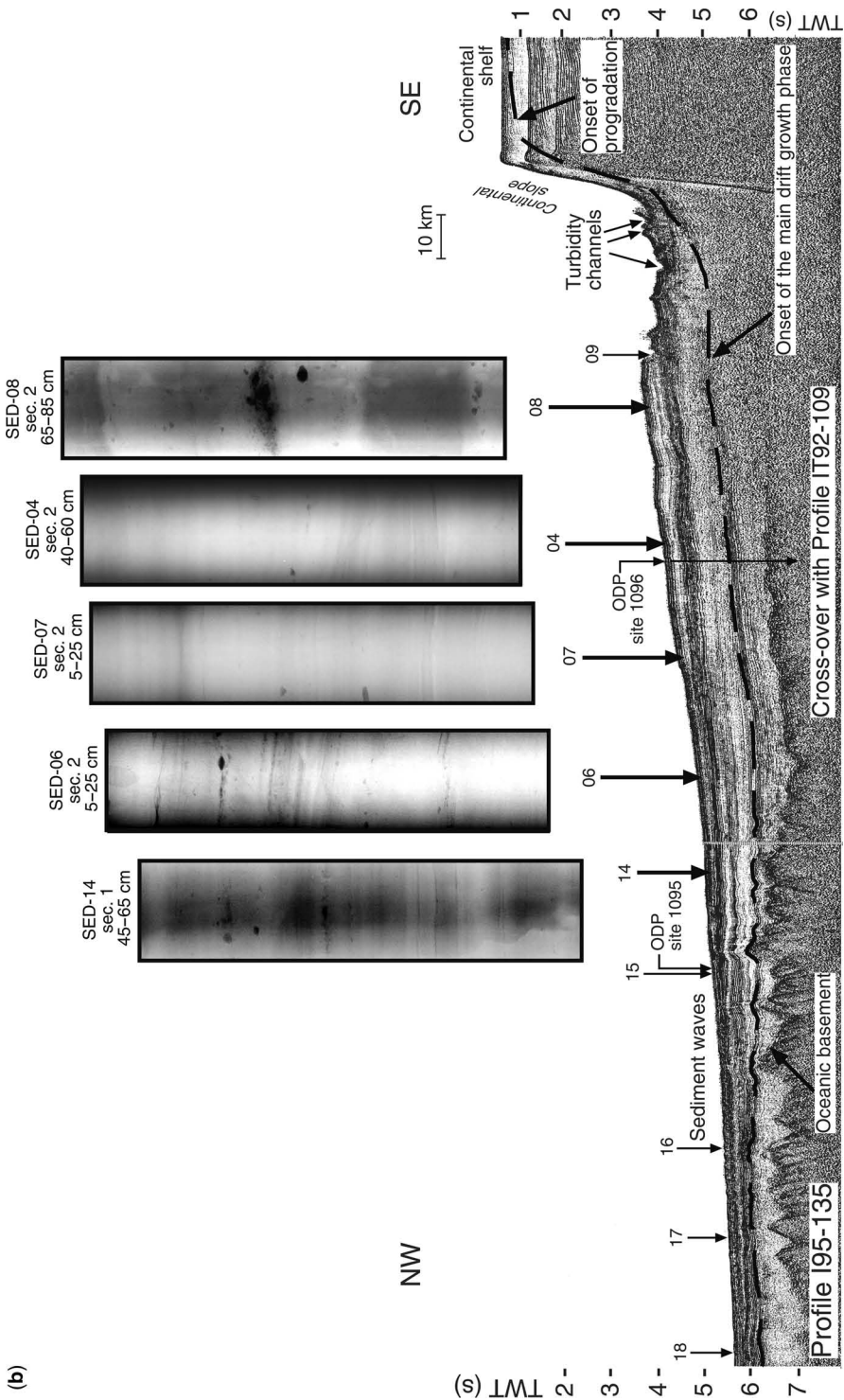


Fig. 6. Continued.

Table 4. Frequency and thickness of silty deposits within last glacial sediments

Core	Water depth (m)	Number of laminae (mm thick)	Number of layers and lenses (cm thick)
SED-11	3725	Amalgamated turbidites decimetre thick	
SED-12	3620	164	36 (up to 4 cm thick)
SED-13	3559	70	2 (up to 1 cm thick)
SED-02	3313	8	—
SED-03	3176	A few laminae visible only on X-radiographs	—
SED-08	2750	—	—
SED-04	3066	—	—
SED-07	3266	—	—
SED-06	3606	6	—
SED-14	3768	10	—
SED-15	3880	20	5 (1 cm thick)
SED-16	4055	5	3 (up to 3 cm thick)
SED-17	4130	—	>10 (up to 3 cm thick)
SED-18	4215	Amalgamated turbidites decimetre thick	

deposits suggest scattering of the original flow, and high efficiency of the system.

In core SED-11 the presence of a 1 m thick sequence of structureless or thinly laminated mud containing sparse IRD pebbles can be related to

sediment settling through nepheloid layers with suspended sediment reworking by weak local bottom currents. Analogous facies have been described by Gilbert *et al.* (1998) for continental rise deposits in the NW Weddell Sea. We believe that during

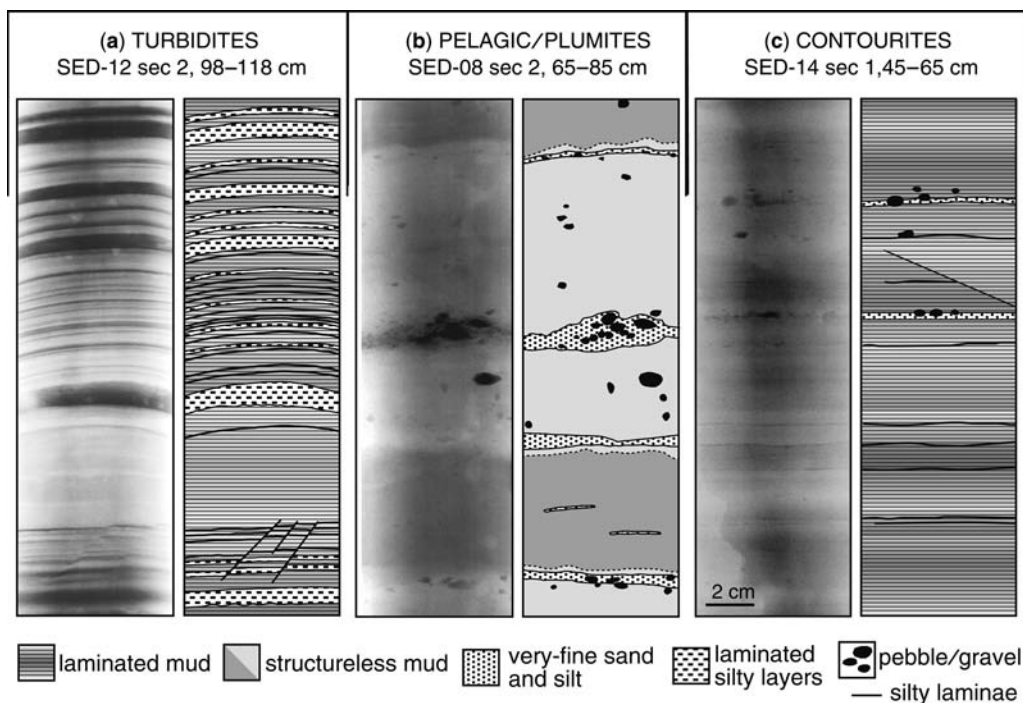


Fig. 7. ‘End-members’ of radiograph patterns, and interpreted illustrations, related to the predominance of one sedimentary process: (a) turbidity flows producing laminated mud with IRD-free silty layers; (b) meltwater plumes generating structureless mud with IRD layers, sparse pebbles, and coarse-silt-rich layers; (c) contour currents producing finely laminated mud with IRD layers and sparse pebbles (see text for discussion).

glacial periods the area of the Alexander Channel system as well as the surrounding areas were overrun by a thick persistent nepheloid layer in which turbidity currents, ice rafting and meltwater plumes periodically contributed sediment. Persistent weak bottom currents controlled the deposition of this episodically nourished nepheloid layer, resulting in faintly laminated sediments.

On the strike transect along the NE gentle side of Drift 7 the sedimentary facies in the area close to the Alexander Channel system consist of laminated mud interbedded with very fine-grained sand and silty layers (Fig. 7a). We infer that the silty layers recovered in cores SED-12 and -13 originated from spillout of the turbidity currents that moved along the Alexander Channel system enhanced by both the Coriolis force and the NW-flowing contour current. This hypothesis is consistent with the sedimentological characteristics of the silty layers, including textural variation along the NE gentle slope (fining upslope) and the frequency and thickness of the layers.

On the lower slope (core SED-12, c. 100 m above the channel's thalweg), silty laminae are common and centimetre-thick layers appear massive, often with erosive bases (proximal area of spillout of turbid flows). Here, the presence of cross-stratified mud (ripple-like lamination) suggests a direct influence of turbidity currents on sedimentation. In core SED-13 (only 60 m more elevated than core SED-12) the occurrence of silty layers and laminae is drastically reduced (Table 4), and they have sharp but not erosive bases (reduced energy). The frequency and thickness of silty layers, hence, rapidly decreases towards the crest of the drift, where silty laminae are detectable only on radiographs (core SED-03, Fig. 6a).

Silty layers appear on X-radiographs to contain no ice-rafted detritus, suggesting that the silt settled under a fast depositional process such as a turbidity current. Moreover, the grain-size spectra of these deposits are comparable with those of the turbiditic sand units described from the Weddell Sea slope and rise by Gilbert *et al.* (1998). However, the sediments described in Drift 7 contain a lower percentage of sand with a consistent fine-grained tail suggesting low-density turbidity currents.

The predominance of turbidity flow processes in the sedimentation in the area surrounding the channel system is shown also by the variation in thickness of the last glacial sediment across the continental rise, which exceeds 7 m near the Alexander Channel system and thins up the drift slope to 5.50 m (Fig. 3). In core SED-12 (base of NE slope) the presence of finely laminated, IRD-free mud can be related to turbiditic events, whereas in core SED-03 (summit of NE slope) laminated fine-grained sediments containing IRD layers and sparse pebbles are interpreted as contourites, as

deposition of an IRD layer is not compatible with the relatively fast deposition from a turbidity flow.

Crest of Drift 7: plumites v. contourites. The structureless, colour banded, coarser-grained sediments described at the topmost, proximal part of Drift 7 (core SED-08) are interpreted to originate from settling of suspended particles of very distal overflowing plumes undisturbed by bottom currents (Fig. 7b).

This interpretation is consistent with the textural and compositional characteristics of these deposits. The most elevated and proximal areas of Drift 7 contain the highest percentages of very-coarse and coarse silt (5–6 ϕ) and the clay mineral assemblage is dominated by illite, whose crystallinity index indicates a generally low alteration consistent with a continental provenance of detritus through meltwater interflows and/or overflowing turbid plumes (Lucchi *et al.* 2002a). Nevertheless, the sedimentary facies of core SED-08 sediments largely differ from the plumite facies described by several researchers in Quaternary and modern sediments from polar and sub-polar margins (e.g. Mackiewicz *et al.* 1984; Cowan & Powell 1990; Cowan *et al.* 1997; Hesse *et al.* 1997, 1999; Yoon *et al.* 1997, 1998; Ó-Cofaigh *et al.* 2001; Evans *et al.* 2002; Curran *et al.* 2004). These deposits appear as cyclic couplets of a thin fine-grained sand or silt lamina that grades normally into a thicker poorly to very poorly sorted mud lamina. The laminations are defined by the alternation of coarse- and fine-grained sediments forming interlaminated deposits (textural laminations). This facies has been described for sediments recovered at up to 20 km distance from glacial outlet sources (Hesse *et al.* 1997). Mackiewicz *et al.* (1984), however, indicated that fine-grained muddy sediments dominate the distal deposition in fjords at 50 km from the efflux point. These sediments derived from overflows have a mean grain size of fine to very fine silt and are structureless or thinly interlaminated.

We argue that the absence of the 'typical' plumite facies in our deposits can be attributed to their distal characteristics (mean grain size of 8.7–9.4 ϕ corresponding to very fine silt and clay). Very fine sand and coarse silt particles in overflowing plumes settle as individual grains whereas fine silt and clay particles, in a marine environment, aggregate to form floccules that settle as discrete turbid layers (Syvitski *et al.* 1985; Cowan & Powell 1990; Curran *et al.* 2004). Each turbid layer represents a pulsing event of a sediment-laden meltwater plume. In the sediments studied here, the faint colour contrast on the fresh sediment surface defines horizontal laminations for which we cannot find a textural correspondence on the fresh surface or a structural correspondence on X-radiographs. These types of lamination may represent separated sediment

incursions by very distal turbid overflows depositing very fine-grained sediments, whereas textural inter-laminations cannot be observed because of the homogeneity of the distal very fine-grained sediments involved. Further in support of this hypothesis, we observed that the grain-size spectra of our sediments present some similarities to the upper finer-grained interval of the individual plumites studied in the Labrador Sea (Hesse *et al.* 1997). In that area, deposits with the seismic characteristics of plumes have been recognized up to 130 km seawards from the Hudson Strait as a result of the composition of the suspended sediments, which suppressed flocculation.

It is proposed that around the Drift 7 area overflowing plumes, during glacial periods, were able to run for long distances, transporting large quantities of fine-grained particulate matter (glacial flour) before settling, as a result of their physical and compositional properties and uncommon environmental conditions. In the marine environment, fine-grained sediment flocculation and settling within an overflowing plume is enhanced by the presence of organic matter and/or salt (Syvitski *et al.* 1985; Curran *et al.* 2004). Overflows in Antarctica consist of fresh waters with almost no biogenic detritus suspended with the particulate terrigenous matter (Yoon *et al.* 1998). Moreover, the presence of a thick oceanwards extended sea-ice coverage during glacial periods inhibited the surface water mixing normally caused by katabatic winds and/or tidal action.

In core SED-08 the lack of laminations suggests insignificant reworking by bottom currents. This idea is also supported by the clay mineral assemblage, which contains only traces of smectite supposed to be transported by the SW-flowing bottom currents (Hillenbrand & Ehrmann 2001; Lucchi *et al.* 2002a; Hillenbrand *et al.* 2003). Conversely, laminations become progressively more evident oceanwards along the dip transect of Drift 7 (cores SED-04, -07, -06, -14; see Fig. 6b) where persistent bottom currents are supposed to have been present (Fig. 7c). Here very low-energy (cluster D), poorly sorted and negatively skewed laminated mud containing sparse IRD has been related to contour-current deposition, whereas the presence of millimetre-thick, faintly laminated silty layers with sharp non-erosive bases is attributed to pulsing events of weak very distal turbid flows (oceanward decrease in silty layers frequency and mean grain size).

'Glacial' contourites: palaeoenvironmental and palaeoclimatic significance

In the discussion above, we argue for a contouritic origin of most of the sediments recovered along

the crest of Drift 7 and in its distal area. This type of contourite has been defined as 'hybrid' by Stow *et al.* (2002) because it has characteristics attributable to both contour and turbidity currents. In contrast to the 'classic' contouritic facies described by several workers (e.g. Stow & Lovell 1979; McCave *et al.* 1980; Stow 1982; Stow & Holbrook 1984; Wang & Hesse 1996; Armishaw *et al.* 2000), our sediments do not show bioturbation, and the lamination is generally more pronounced and laterally continuous. These characters are generally used to indicate turbidity current related deposits (Stow 1979). Piper & Brisco (1975) described the facies of contour-current deposits in Antarctica as indistinctly layered bioturbated mud. We relate the preservation of lamination in our study case to the absence of bioturbation. Reduced bioturbation in contourites has been attributed to both high-energy conditions at the sea bottom (Yoon & Chough 1993) and a high sedimentation rate (e.g. 190 cm ka^{-1} of the Lofoten Contourite Drift, Laberg & Vorren 2004). We believe that neither of these causes can be applied to our study case. Low-velocity bottom current are currently measured in the area of Drift 7 (Camerlenghi *et al.* 1997; Giorgetti *et al.* 2003), and a low velocity has been inferred for glacial stages on the basis of the grain size of the sediment forming Drift 7 (Pudsey & Camerlenghi 1998; Pudsey 2000, 2001; Lucchi *et al.* 2002a). Moreover, the higher sedimentation rate recorded in the Drift 7 glacial sediments (c. 12 cm ka^{-1} in core SED-12) with respect to the interglacial stages ($2\text{--}3.5 \text{ cm ka}^{-1}$) is still a much lower value compared with those of the Weichselian contourites described from the Lofoten Contourite Drift (Norway continental slope) by Laberg & Vorren (2004).

Laminated, not bioturbated contourites have been described for shallow-water organic-rich muddy contourites from the Baltic Sea, where high biological productivity associated with periodic stagnation of near-bottom waters generated an anoxic condition at the sea bottom (Sivkov *et al.* 2002). In Drift 7, sediments contain a low percentage of organic carbon (usually $<0.2\%$, Lucchi *et al.* 2002b) compatible with other oceanic contourites, and are almost exclusively barren (both benthic and planktonic fauna are absent). We attribute the lack of bioturbation in Drift 7 glacial sediments to the absence of biological activity at the sea bottom.

We argue that during the last glacial stage the presence of a long-lasting sea-ice cover suppressed planktonic biological activity by preventing sunlight from reaching the upper part of the water column and gas exchanges (O_2 and CO_2) with the atmosphere (Fig. 8). This would have caused a drastic reduction of nutrient supply through the water column, which is necessary to sustain the benthic fauna.

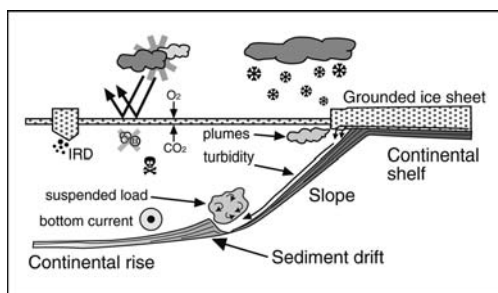


Fig. 8. Schematic representation of the environmental conditions during glacial periods. The absence of bioturbation in barren sediments has been related to the presence of long-lasting sea-ice that prevents the sunlight from reaching the upper part of the water column and gas exchange with the atmosphere. In these conditions the phytoplankton (i.e. diatoms), and consequently the zooplankton, is unable to survive. This would have caused a drastic reduction of nutrient supply, necessary to sustain the benthic fauna, throughout the water column. Life at the sea bottom is also limited by oxygen-reducing conditions (presence of pyrrhotite in the sediments) and possibly nutrient-depleted bottom currents (low organic carbon in the sediments).

The distribution of diatoms, which form the siliceous Antarctic phytoplankton (primary productivity), is sensitive to small changes in environmental parameters including light, temperature, water circulation and sea-ice cover (Dunbar *et al.* 1985; Leventer & Harwood 1993; Cunningham & Leventer 1998). Abelmann & Gersonde (1991), using time-series sediment traps, observed that at present the surface planktonic productivity is restricted to ice-free periods (peaks of vertical particle flux), whereas under sea-ice cover the vertical flux of siliceous organisms is extremely low.

Evidence of reduced or low-diversity and/or suppressed planktonic biological activity related to sea-ice extension has been reported from modern and old sedimentary records of northern and southern high-latitude margins (Barcena *et al.* 1998; Armand 2000; Pudsey 2001; Barcena *et al.* 2002; Włodarska-Kowalczyk *et al.* 2004; Gersonde *et al.* 2005). Dowdeswell *et al.* (2000) reported barren neoglacial sediments in East Greenland as the result of multi-year shorefast sea-ice. In particular, the sediments that they attributed to the 'Little Ice Age' (Lamb 1965) were deposited during a period of several hundred years when temperatures were often a few degrees lower than today. Evidence of this period in Antarctica has been found in marine sediments by Leventer & Dunbar (1988) and Leventer *et al.* (1996), and in ice cores by Barnola *et al.* (1995). This means that severe

low temperatures are not needed to maintain the sea-ice cover.

The presence of pervasive bioturbation is considered as one of the diagnostic characteristics for the identification of muddy contourites, as bottom currents are supposed to provide a continuous supply of oxygen and nutrients favourable to benthic proliferation (Stow & Holbrook 1984; Chough & Hesse 1985). The absence of benthos in the Antarctic Peninsula Pacific margin sediments is related to decreased nutrient supply through the water column but also possibly to oxygen-reduced conditions and nutrient-depleted bottom currents.

The lack of sapropelic sediments excludes anoxic conditions at the sea bottom during glacial periods (low organic carbon in the sediments). Nevertheless, the presence of pyrrhotite in the sediments suggests oxygen-reduced environmental conditions, as it represents one of the intermediate products along the pathway of pyrite formation (Sagnotti *et al.* 2001; Macri 2004). This hypothesis is consistent with the calculation model for Antarctic glacial–interglacial atmospheric CO₂ variations of Stephens & Keeling (2000). They stated that because dissolved O₂ equilibrates with the atmosphere more rapidly than CO₂, the gas-exchange limitation imposed by the glacial sea-ice would have a lesser effect on O₂ entering the deep ocean than on CO₂ leaving, and thus would not produce deep-water anoxia. Low glacial atmospheric CO₂ concentrations might result from reduced deep-water ventilation associated with environmental and/or physical conditions that prevented air–sea gas exchanges.

The atypical facies of the muddy contourites described within the last glacial interval of Drift 7 is present in the older glacial stages (down to *c.* 340 ka of IS 10) of the sediment cores recovered from this area of the Pacific margin of the Antarctica Peninsula (Lucchi *et al.* 2002a), and it has also been described from other areas of deep-sea Antarctic margins (e.g. Anderson *et al.* 1979; Pudsey *et al.* 1988; Mackensen *et al.*, 1989; Grobe & Mackensen 1992; Pudsey 1992; Gilbert *et al.* 1998; Anderson 1999; Yoon *et al.* 2000). In contrast, in Wilkes Land (East Antarctica), the last glacial sediments recovered from the Weddell Channel and surrounding sediment mounds are faintly laminated, bioturbated (Buseti *et al.* 2003; Caburlotto 2003), and contain maghemite (an oxidized form of magnetite), suggesting the presence of oxygen during deposition (Macri, 2004; Macri *et al.* 2005). At present, this area is characterized by the presence of a long-lasting polynya, west of the Mertz glacier, that is responsible for the production of High Salinity Shelf Waters (HSSW, Bindoff *et al.* 2000). The HSSW mix with the Modified Circumpolar Deep Waters in the proximity of

the shelf break, producing the cold and saline Antarctic Bottom Water (AABW), which transports oxygen and nutrients downslope towards deeper environments. We believe that during glacial periods, oxygen- and nutrient-rich deep waters had only a local impact on sedimentation, and their biological content was rapidly depleted during the motion around the continent driven by bottom-current flow. As the Antarctic margins are overrun by circumpolar currents, we believe that reduced oxygen and nutrient conditions in deep-sea environments had a circum-Antarctic relevance during glacial periods, except in the areas where a polynya was maintained during sea-ice conditions.

Conclusion

Detailed study of sediments from the last glacial interval has shown a large variety of coexisting sedimentary processes in sediment Drift 7 on the Pacific margin of the Antarctic Peninsula. Despite the variety of sedimentary facies described, three end-members were identified, representing turbidity flows, meltwater plumes and contour-current deposits.

Low-density turbidity flows moved along the Alexander Channel system and contributed fine-grained sediments to the nepheloid layer. These gravity-driven currents were concurrently affected by both the Coriolis force and NW-flowing contour currents, and their direct influence on sedimentation rapidly decreased with distance and elevation from the thalweg of the Alexander Channel system. These deposits appear laminated and non-bioturbated, and do not contain ice-rafted debris, as this is not compatible with their fast deposition.

Meltwater sediment-laden interflows and/or overflowing turbid plumes represented in West Antarctica an important sedimentary process conveying large amounts of fine-grained particulate matter into the depositional system as far as very distal areas. These deposits appear structureless in X-radiographs but finely laminated on a fresh sediment surface, and can contain sparse IRD.

The presence of IRD layers and sparse pebbles within finely laminated, non-bioturbated glacial sediments of Drift 7 allowed the identification of the 'glacial contourites'. This atypical contouritic facies originated from the piracy of the sediments delivered into the system by other sedimentary processes and indicates unusual, climatically related, environmental conditions of suppressed primary productivity and oxygen-reduced deep waters. The presence of this facies in most of the Antarctic margins indicates that this unusual condition had a circumpolar importance, except in those areas

where polynyas were maintained during the glacial stages.

Barren, non-bioturbated Antarctic contourites (*glacial contourites*) can be used as a proxy to define the temporal and spatial extension of the Antarctic sea-ice.

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