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Late Pliocene mega debris flow deposit and related fluid escapes identified on the Antarctic Peninsula continental margin by seismic reflection data analysis

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Abstract

We have obtained improved images of a debris flow deposit through the reprocessing of multichannel seismic reflection data between Drifts 6 and 7 of the continental rise of the Pacific margin of the Antarctic Peninsula. The reprocessing, primarily aimed at the reduction of noise, relative to amplitude preservation, deconvolution, also included accurate velocity analyses. The deposit is dated as upper Pliocene (nearly 3.0 Ma) via correlation to Sites 1095 and 1096 of the Ocean Drilling Program (ODP) Leg 178. The estimated volume is about 1800 km^3 and the inferred provenance from the continental slope implies a run out distance exceeding 250 km. The dramatic mass-wasting event that produced this deposit, unique in the sedimentary history of this margin, is related to widespread late Pliocene margin erosion. This was associated with a catastrophic continental margin collapse, following the Antarctic ice sheet expansion in response to global cooling. The seismic data analysis also allowed us to identify diffractions and amplitude anomalies interpreted as expressions of sedimentary mounds at the seafloor overlying narrow high-velocity zones that we interpret as conduits of fluid expulsion hosting either methane hydrates or authigenic carbonates. Fluid expulsion was triggered by loading of underlying sediments by the debris flow deposits and may have continued until today by input of fluids from sediment compaction following the deep diagenesis of biogenic silica.

Introduction

Glacier-influenced sedimentation dominates high-latitude continental margins of both hemispheres (Dowdeswell and O'Cofaigh, 2002). These margins have been shaped extensively by the action of grounded ice, which periodically expanded to reach the continental shelf edge. Such evolution has affected northern hemisphere margins since the late Pliocene, and Antarctic margins since the late Eocene-Oligocene. In fact, the modern high-Arctic climatic regime can be regarded as an analogue to that of Antarctica during the late Paleogene and early Neogene (Hambrey et al., 2002). For these reasons, Antarctic margins may be considered as "mature" counterparts of the younger polar and sub-polar European and American margins.

It has been known for more than a decade that debris flow deposits generated at the base of grounded ice, make up the bulk of the Northern Hemisphere glacial prograding wedges, and that these overlie earlier non-glacial continental margin sediments (Aksu and Hiscott, 1989; Laberg and Vorren, 1995). Conversely, the nature of the glacial wedges and the transition from the pre-glacial to the Antarctic glacial continental margin is still poorly documented (Cooper and O'Brien, 2004; Barker and Camerlenghi, 2002). Scientific exploration of the Antarctic margin is less intense than that of the northern hemisphere polar margins, and the pre-glacial to glacial transition within the margin wedge is at deeper stratigraphic levels in Antarctica, and therefore relatively less accessible by seismic studies. The so-called 'onset' of glaciation in Antarctica is still an open problem in terms of margin response to glacial loading, erosion and deposition. The onset of glacial conditions on the Antarctic margins has been postulated to be diachronous around the continent and different between the margins shaped by the West and East Antarctic Ice Sheets (Barker et al., 1998).

Based on this rationale, in the framework of the Reprocessing Avanzato di Dati sismici Antartici (RADA) project of the Programma Nazionale di Ricerche in Antartide (PNRA), new technologies have been tested (Diviacco et al., 2003) and applied (this paper) to original seismic reflection datasets (Figure 1) in an effort to improve the overall quality. The data were collected within the Sediment Drifts of the Antarctic Offshore (SEDANO) PNRA project as pre-site survey for Ocean Drilling Program (ODP) Leg 178 (Barker and Camerlenghi, 2002) on the Antarctic Peninsula deep-water margin.

On the continental rise of the Pacific margin of the Antarctic Peninsula, contourite drift sediments are fine grained and laminated (Pudsey and Camerlenghi, 1998; Shipboard Scientific Party, 1999a; Lucchi et al., 2002; Lucchi and Rebesco, 2005). Strata are continuous laterally over long distances and retain high porosity down to depths of 500–600 m below the seafloor (Volpi et al., 2003). The response of these sediments to multichannel seismic reflection is typically one of exceptional penetration and acoustically laminated sections characterized by relatively high-seismic frequencies. The lateral continuity of reflectors is locally interrupted only below the deep-sea channels that intervene between the large sediment drifts. Here, coarse grained beds prevent seismic energy penetration and, in place, produce a blanking effect over the strata below (see Figure 1 in Rebesco et al., 2002).

An exception to this ‘norm’ is represented by a transparent layer present at shallow depth below the deep-sea Alexander Channel, which separates sediment Drifts 6 and 7 (see Rebesco et al., 1998, 2002). Based on its lenticular shape, erosional lower boundary, hummocky upper boundary, and lack of coherent internal reflectors, we interpret this layer as a debris flow deposit buried by distal turbidites. It had been identified prior to drilling ODP Site 1095 (see Figure F2 in Shipboard Scientific Party, 1999a) among the units to be avoided when drilling the sediment drift next to the Alexander Channel system. As far as it is known this deposit is unique in the depositional history of the Pacific margin of the Antarctic Peninsula. In fact no further deposits of this kind are visible in the seismic lines available in this sector of the margin, whose oceanic crust is dated at about 40 Ma (Larter et al., 1997) on the basis of magnetic anomaly data. We envisage that this debris flow deposit is related to an important event in the evolution of this margin. In this paper we describe the seismic reflection data reprocessing directed towards improving the seismic images, and propose an interpretation of the origin of the deposit in relation to important environmental changes in Antarctica.

Original seismic sections

The multichannel seismic sections analysed in this work belong to the SEDANO ODP site survey performed by the R/V *OGS-Explora* in 1995 (Figure 1; Camerlenghi et al., 1997). The seismic lines initially processed to stack sections are illustrated in Shipboard Scientific Party (1999b), Lucchi et al. (2002), and Volpi et al. (2003). Acquisition parameters are described in Table 1.

The debris flow deposit that is the object of this study (Diviacco et al., 2003) is a lens-shaped, transparent unit over 100 ms two way travel-time (twt) thick infilling the depression between Drift 6 and 7 on the continental rise of the Antarctic Peninsula. It was identified on original sections of both Lines I95-137 (Figure 2) and I95-138 with its upper surface at about 100 ms twt below the seafloor.

A shot gather from Line I95-137, with normal move out (NMO) corrections and no gain applied (Figure 3), shows that no reflections exist in the debris flow unit (interval between 5.40 and 5.55 s twt). The amplitude plot in the same gather shows a decay of about −12 db in the transparent debris flow unit. The return of high amplitudes below the debris flow unit suggests that the amplitude decay is not due to absorption of energy, as happens with coarse-grained intervals elsewhere on this margin. Reflections from the debris flow unit are affected by velocity pull-up effects below small mounds at the seafloor (see around shot point (SP) 5800 in Line I95-137 of Figure 2). Standard velocity analysis techniques performed during original processing were not able to produce velocity models with the needed resolution to study these phenomena.

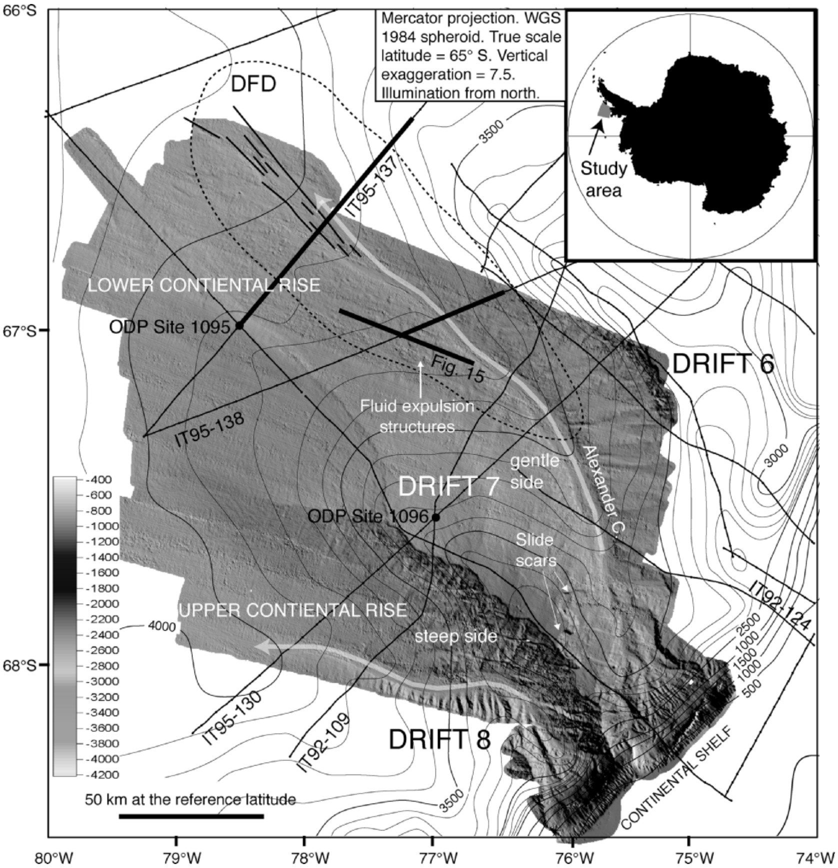

Figure 1. Location map of the SEDANO Site Survey including Lines I95-137, I95-138, and I92-109 displayed in following figures (Mercator projection, WGS 1984 spheroid, true scale latitude 65°S, vertical exaggeration = 7.5, illumination from north). The main elements of this glacial marine sedimentary system are outlined after Rebesco et al. (1998). Light grey bold lines with arrows indicate the major trunk-type deep sea channels bounding sediment Drift 7; Thin dashed line: Estimated extend of the late Pliocene Alexander Channel mega debris flow deposit (DFD). The shaded relief map is derived from the MAGICO multibeam survey conducted with the R/V OGS-Explora in 2004 (Rebesco et al., 2005).

Table 1. Acquisition parameters, multichannel seismic reflection survey, OGS-Explora, 1995, SEDANO Project.

Energy source	
Gun type	GI
Number of guns	2
Total volume	6.8 l (420 in^3)
Tow depth	6 m
Shot interval	25 m
Sensors	
Streamer length	3000
Number of traces	120
Trace interval	25
Tow depth	6–7
Coverage	60-fold
Sampling rate	2 ms
Record length	8 s

Reprocessing

Noise reduction

High levels of noise often characterize the seismic records collected in the commonly unfavourable weather conditions of the circum-Antarctic seas. In our case the raw seismic record was contaminated by cross-talk, spikes and noises in different frequency bands. While low-frequency noise and spikes can be easily corrected using band-pass and notch filters, cross-talk noise and noise within the useful frequency band can be problematic. We used spectral-shaping noise-removal techniques, by which the frequency spectra are smoothed by application of a median filter to remove

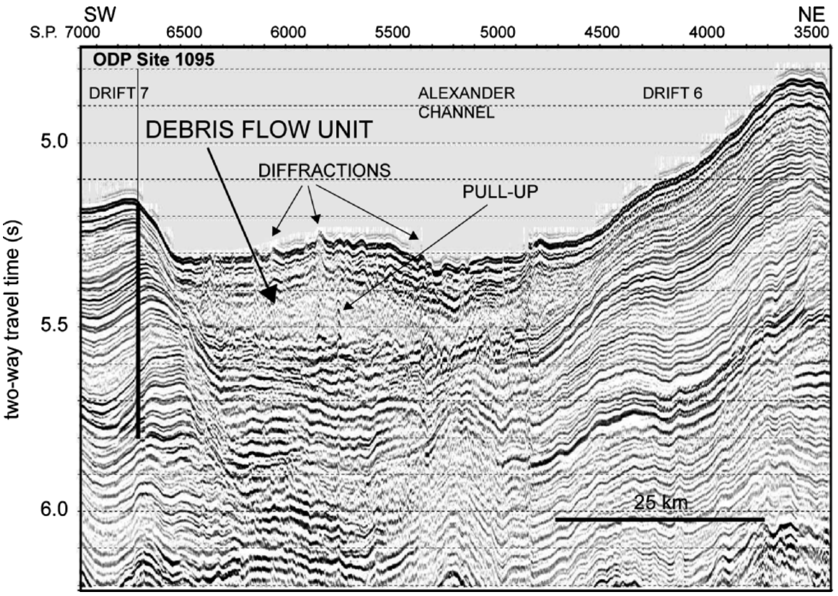

Figure 2. Portion of an original section of seismic Line I95-137 showing the transparent debris flow deposit underlying Alexander Channel (lens-shaped transparent unit from 5.40 to 5.50 s twt). Note that the section is highly vertically exaggerated (60×).

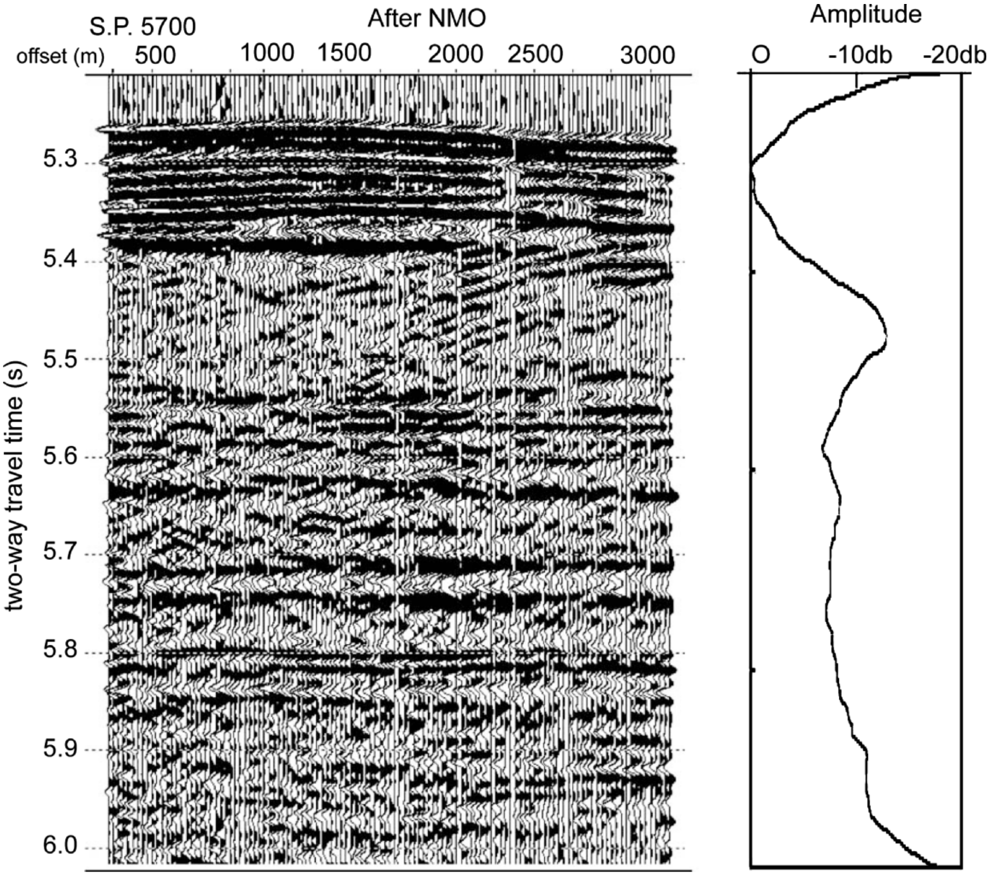

Figure 3. Left: Shot gather from Line I95-137 across the debris flow unit (interval between 5.40 and 5.55 s twt). Right: Amplitude decay across the same unit.

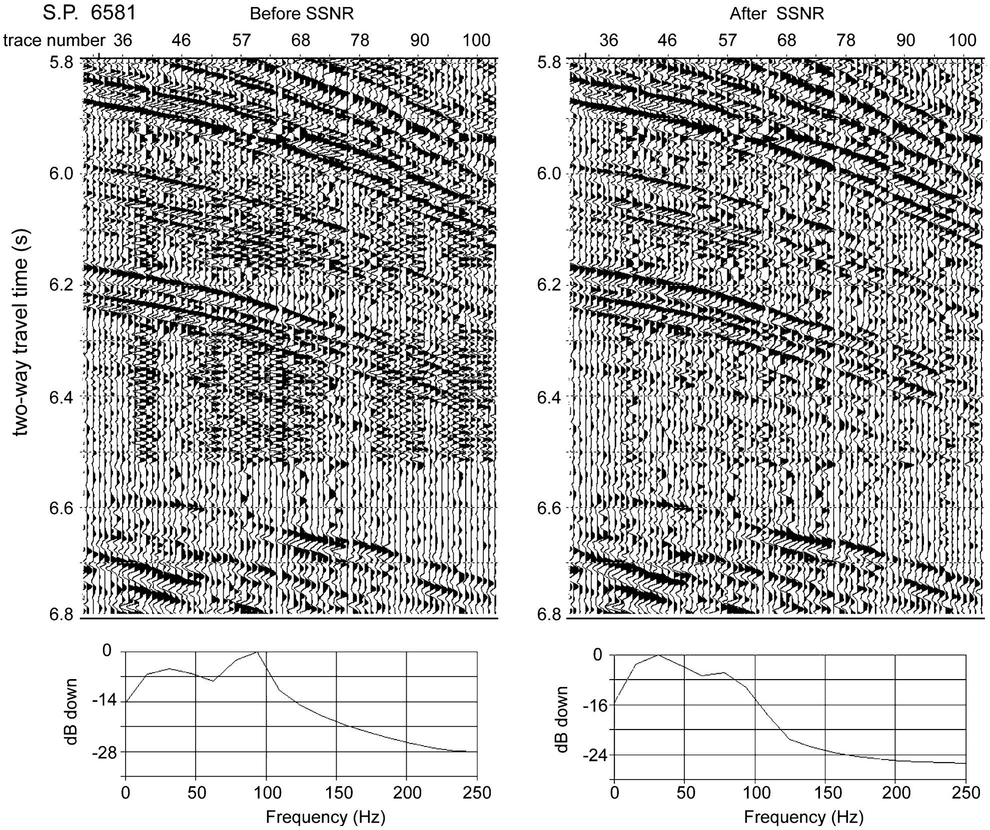

Figure 4. Spectral-shaping noise-removal (SSNR) on a shot gather of Line I95-137.

band-limited noise peaks. This technique successfully suppressed most of noise without affecting the useful signal (Figure 4).

Gain

The preservation of relative amplitudes has been one of the main concerns during this study. The gain recovery has been defined using spherical divergence functions based on the velocity model. Since the latter has been built by several iterations, starting from conventional velocity analysis and ending with acoustic tomography (see below), the spherical divergence functions were updated as new velocity models were derived.

Deconvolution

During original processing, a standard predictive deconvolution with a 160 ms operator, 4 ms prediction distance and 2% pre-whitening was used. In order to minimize the number of assumptions implied in the signal deconvolution, we applied autocorrelation functions and the Hilbert transform to estimate the shape of the source wavelet. This wavelet was then used to design an appropriate filter to deconvolve the data (Lines and Ulrych, 1977). With this method the random reflectivity assumption is rendered less relevant by summing autocorrelations and offset before NMO. At the same time the Hilbert transform diminishes the effects of filter truncation with respect to traditional predictive deconvolution. Finally, this method adapts well to varying noise levels (Treitel and Robinson, 1966).

The wavelet extraction approach enabled us to extract part of the signal that was not evident either in the original data or in the data with spiking deconvolution applied (Figure 5).

Time sections

The stacked sections, produced using the above-described techniques, show evident improvements in comparison to the original section (Figure 6). Deconvolved records better define the transparent

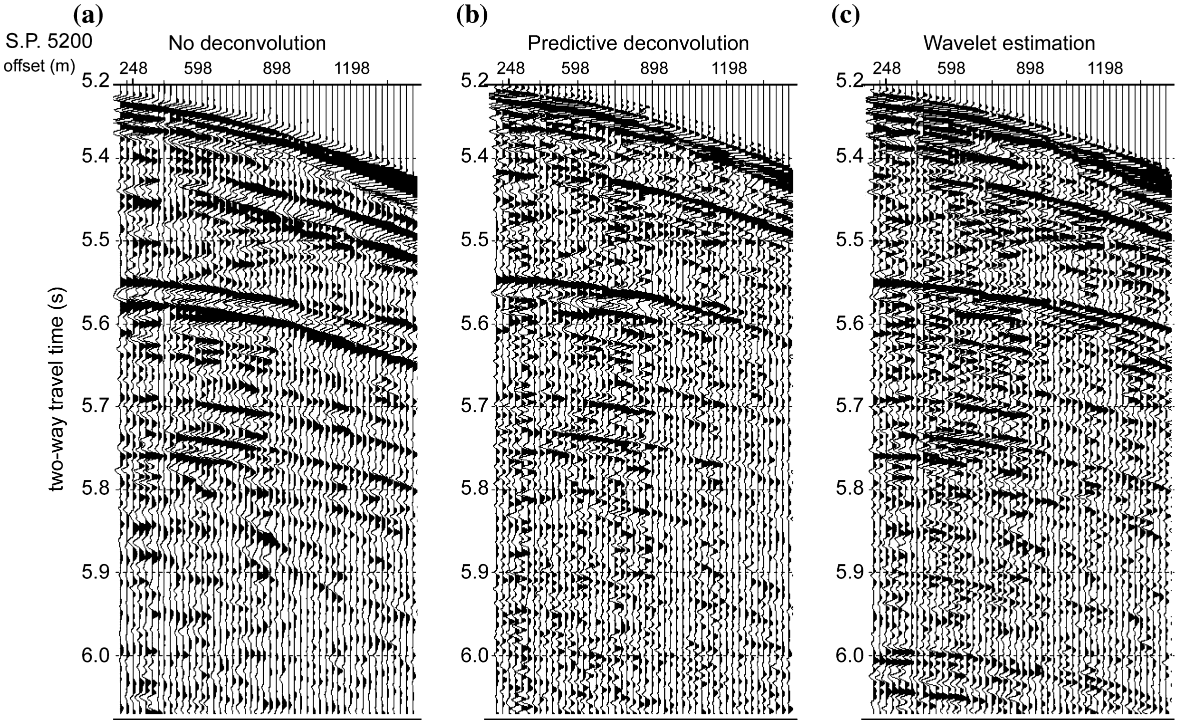

Figure 5. Effects on a single shot gather of deconvolution using the wavelet extraction approach (Line I95-137 SP 5700): (a) before deconvolution; (b) after spiking deconvolution; (c) after the wavelet extraction method. See text for details.

debris flow unit, in particular, the top and bottom transitions to reflective sediments, the lateral pinch out on the contourite drift sediments, and the contrast in amplitude with the surrounding sediments.

Positive polarity diffractions in the near-seafloor water column, in some cases associated with narrow areas of low amplitudes in the entire underlying section and pull-up effects, become even more evident after reprocessing (Figures 6 and 7). These diffractions were cut off by a crude seafloor mute during the original processing. The narrow amplitude drops and the velocity pull-ups appear differently in four sections obtained by stacking four different offset ranges of 30 available channels (Figure 7). The stacking of longer offsets produces a splitting of the low-amplitude cone below the near seafloor diffraction (see Figure 7c,d compared to Figure 7a,b). Because these anomalies are not found consistently in the seismic data set, we exclude an origin by cable or recording artefacts. Rather, we prefer to explain them as undershooting effects related to a high-velocity anomaly. Because the velocity pull-up can be seen immediately below the transparent layer, the high-velocity anomaly must be placed between the base of the debris flow unit and the seafloor.

The narrow amplitude anomaly is a shadow cone (Figure 7), and because the splitting shadow cone coincides with a splitting of the pull-up effect, it is likely to be the product of energy absorption or scattering produced by high-velocity sediments. Diffractions are undoubtedly co-responsible for this amplitude drop because the shadow cones tend to disappear as time migration algorithms are applied (Figure 8). This means that the migration process found energy along hyperbolic diffraction paths and collapsing them in its apex recovered the missing amplitudes.

Velocity analysis

The velocity analysis was performed with the purpose of improving the quality of the seismic section through depth migration and to derive information on the composition of sediments and fluids.

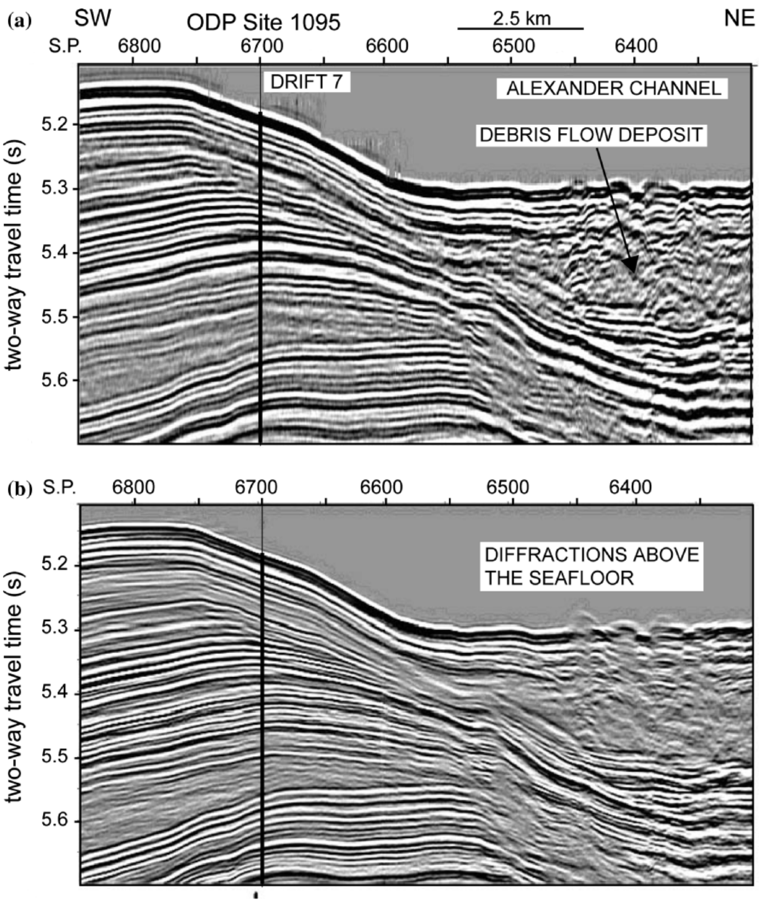

Figure 6. Effects of deconvolution using the wavelet extraction approach on Line I95-137: (a) original stacked section; (b) after the wavelet extraction deconvolution method.

Without external calibration of velocity and unit thickness, which is the case here because ODP Site 1095 was drilled in sediment types different from the debris flow unit, velocity-depth models will always be subject to ambiguity. Different combinations of the two parameters can model the same time position of a reflection (Figure 9). However, in the case of the pull-up effects observed below the debris flow unit, it is possible to resolve the velocity anomaly necessary to flatten the reflectors that have been pulled up. In order to do this, reflectors were first interpreted and picked on the time migrated stacked section to define the layer boundaries. Then, different velocity models were tested in order to verify their effect on the shape of the target horizon, and eventually, coherency inversion and tomography were used to derive a final refined velocity model.

We focused our tests to the marked pull-up of reflectors below the debris flow located at SP 2600 of Line I95-138, in order to understand the significance of a series of overlying diffractions in the water layer above the seafloor (Figure 10). Assuming that the diffractions are generated by small sedimentary mounds, we locally imposed velocities up to 400 ms^{-1} higher than that of the surrounding near-surface sediments. The tests demonstrate that positive velocity anomalies confined to the small mounds are unable by themselves to affect significantly the travel times of the deeper reflectors. In other words the deep, wide pull-ups cannot be generated by velocity anomalies within the mounds.

A second test was performed to investigate the possibility that the pull up is produced by local increases of the thickness of the debris flow

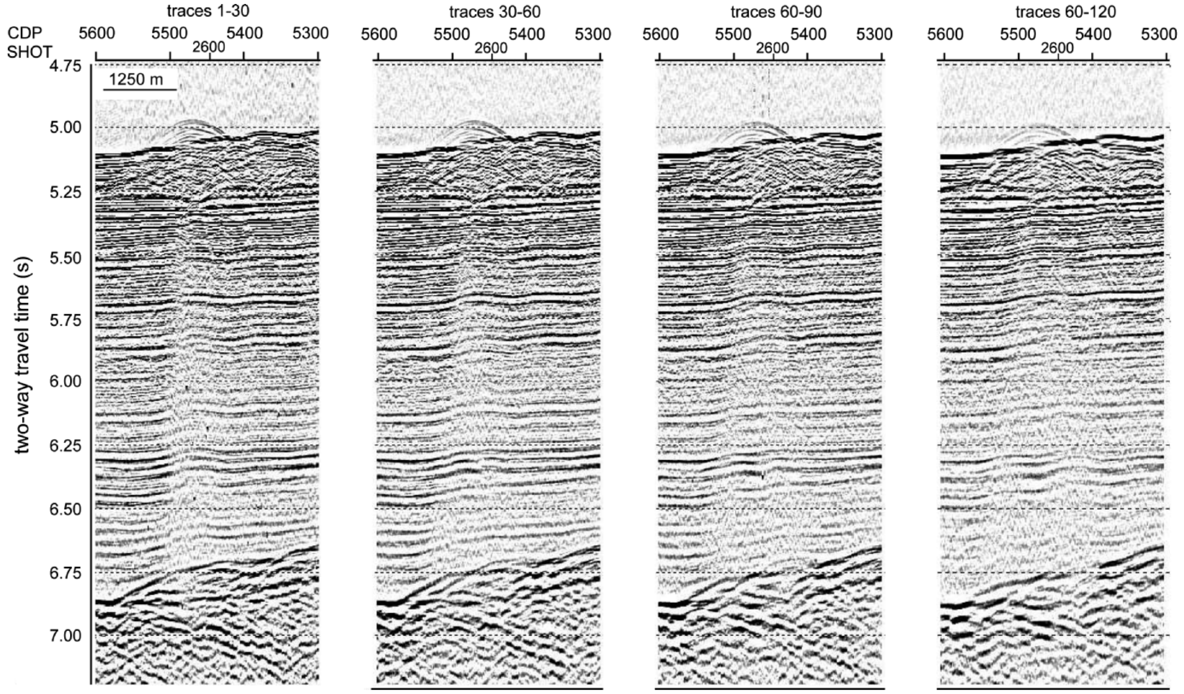

Figure 7. Stacked sections obtained for four different offsets groups, each made of 30 out of the 120 streamer channels. The sections at large offsets show a splitting of the low amplitude area and pull up. CDP = common depth point.

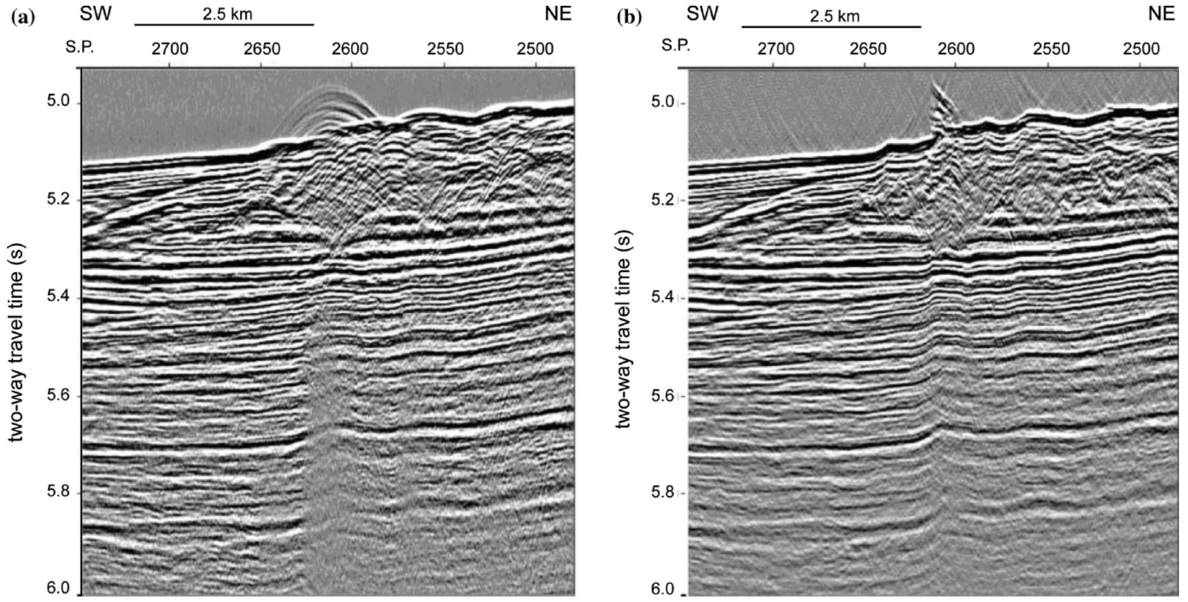

Figure 8. Stacked Line I95-138 (a) and time migration of the same section (b). The narrow amplitude anomalies (shade cone) disappear after migration.

deposit. A series of depth migration tests were performed by assigning velocities ranging between 1500 and 2000 ms^{-1} to the debris flow unit, while the velocity of the layer beneath was set to 1650 ms^{-1}, in line with the velocity information from nearby ODP Site 1095 at similar

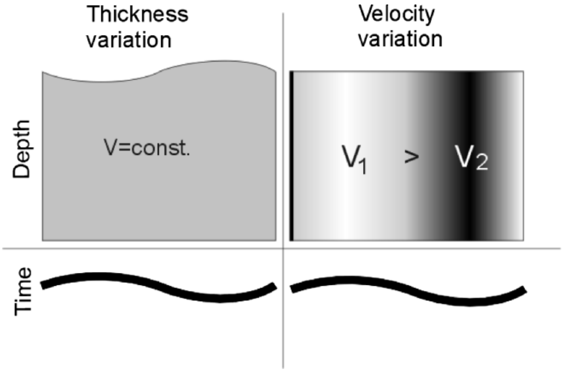

Figure 9. Schematic representation of the velocity/depth ambiguity.

sub-bottom depth (Volpi et al., 2001). The pull-up effect can be removed when an increasing thickness of the debris flow unit with velocity of 1800 ms^{-1} is considered (Figure 11).

With these results in mind, a final refined velocity model was then built by coherency inversion and tomography (Figure 12). This shows a relatively high velocity in the debris flow unit with lower velocity units above and below. The highest velocities in the debris flow unit are nearly 1750 ms^{-1}. With this model the pull-up effect is removed at shallow depth, while deeper horizons are not completely flattened, revealing possible faulting. We also observe a lateral velocity gradient in the debris flow unit, with a higher velocity in the western part.

Interpretation and discussion

The Late Pliocene Alexander Channel mega debris flow deposit

From the results of this study, the seismic appearance of the debris flow can be described as follows (Figure 13). The Alexander Channel debris flow deposit bears a lens shape in a cross section subparallel to the slope, pinching out onto the flanks of the adjacent Drifts 6 and 7 (Figure 13a). The maximum thickness is nearly 200 ms twt in Line I95-137, which translates into 175 m. In the more proximal location of Line I95-138, the maximum thickness is reduced to about 100 ms twt, equal to about 90 m.

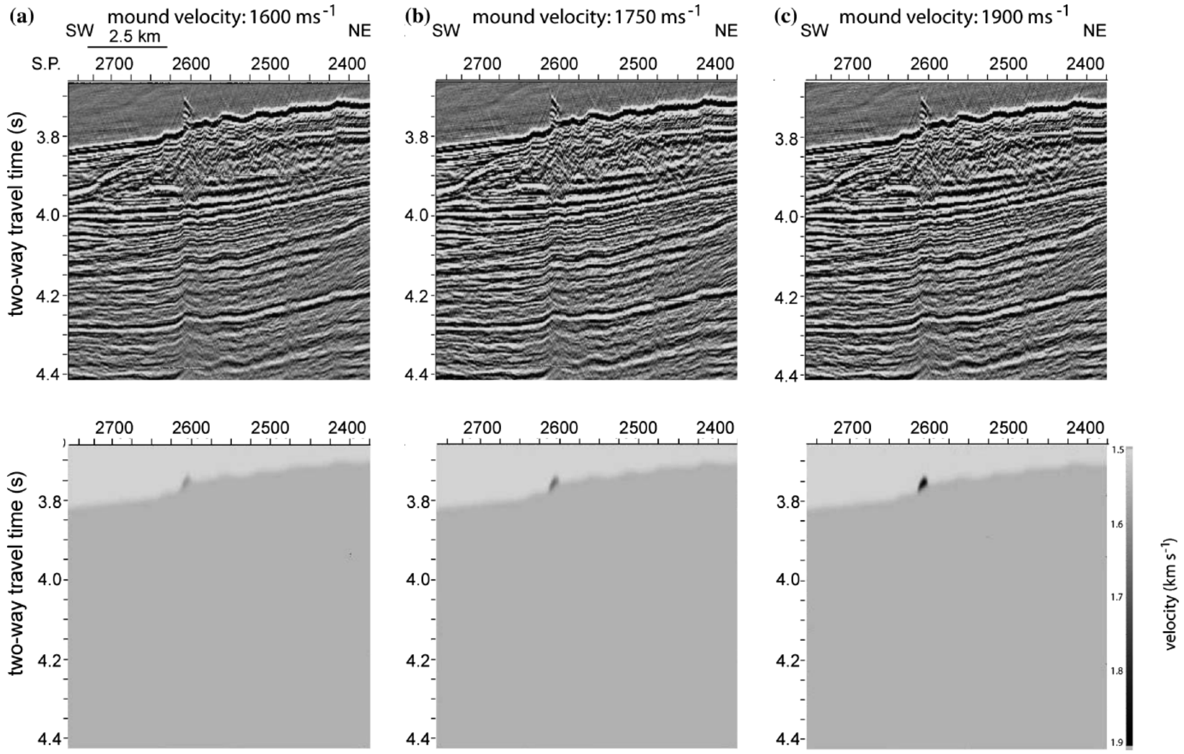

Figure 10. Line I95-138. Negligible effect on the migrated section of a high-velocity mud extrusion (three increasing velocities in a, b, and c).

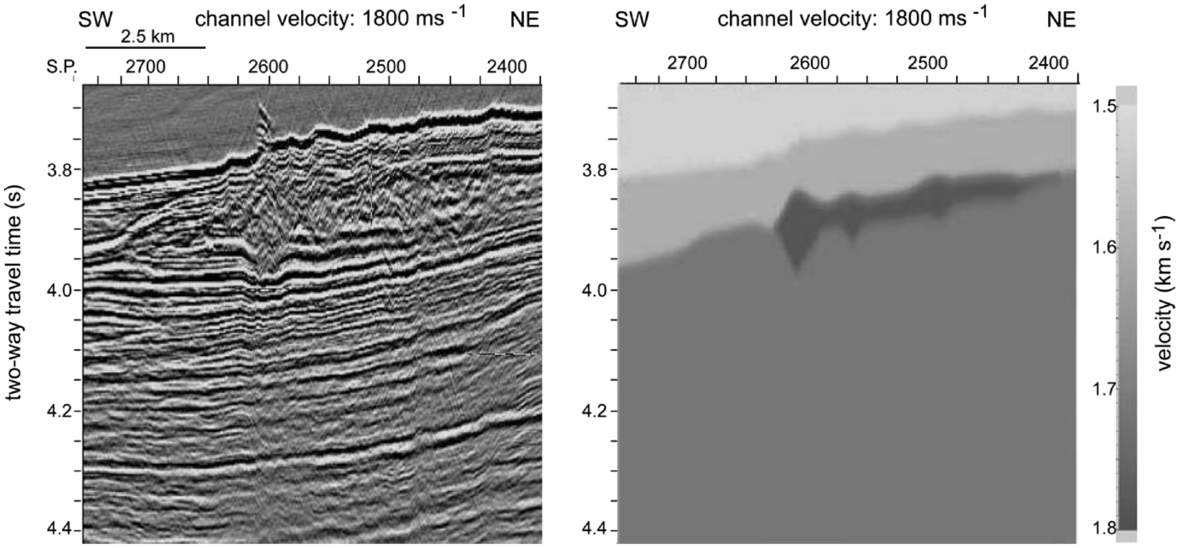

Figure 11. Removal of the pull-up effect by increasing thickness and velocity of the debris flow unit, Line I95-138.

The debris flow is a low amplitude non-reflective (transparent) seismic unit with a lower boundary coinciding with an irregular surface which we interpret as an erosional surface cutting several troughs into the underlying deposits, which consist mostly of turbidites of the paleo-Alexander Channel depositional system according to Lucchi et al. (2002) and Tucholke et al. (1976). The paleo-Alexander Channel system may have formed such a surface that was later sealed by the debris flow deposit. Alternatively, the erosion originated from the debris flow during its emplacement. The rough basal topography of the debris flow deposit might reveal the presence of chutes (Nygård et al., 2002).

The lower boundary of the debris flow appears conformable with the bounding strata at the two sides, where it pinches out on the flanks of the drifts. The correlation of the pinch out of the debris flow to ODP Site 1095 along Line IT95-137 and to ODP Site 1096 along Line IT92-109 locates the debris flow deposit close to the onset of the

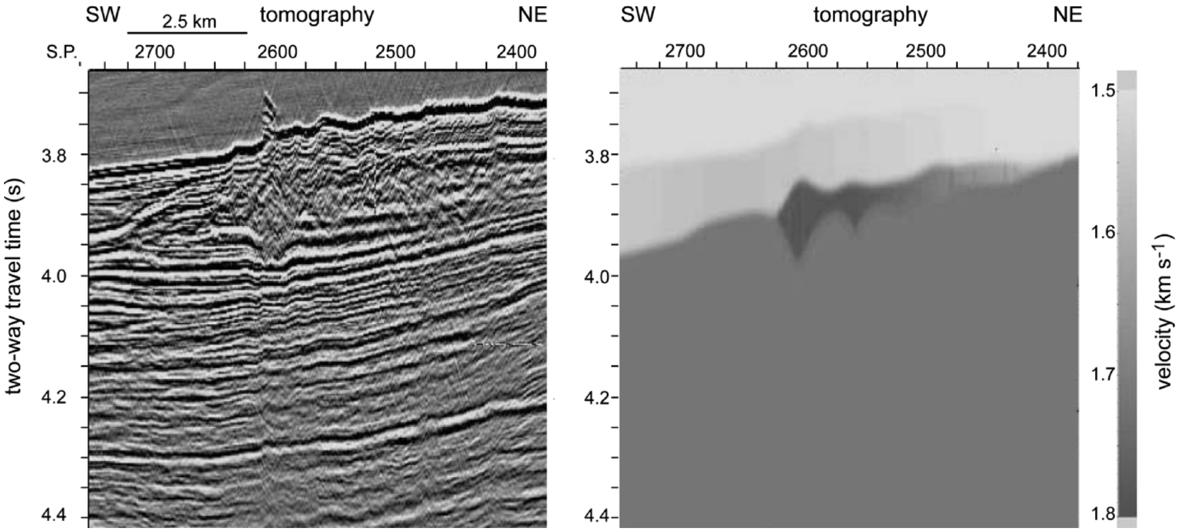

Figure 12. Final velocity model from acoustic tomography, Line I95-138.

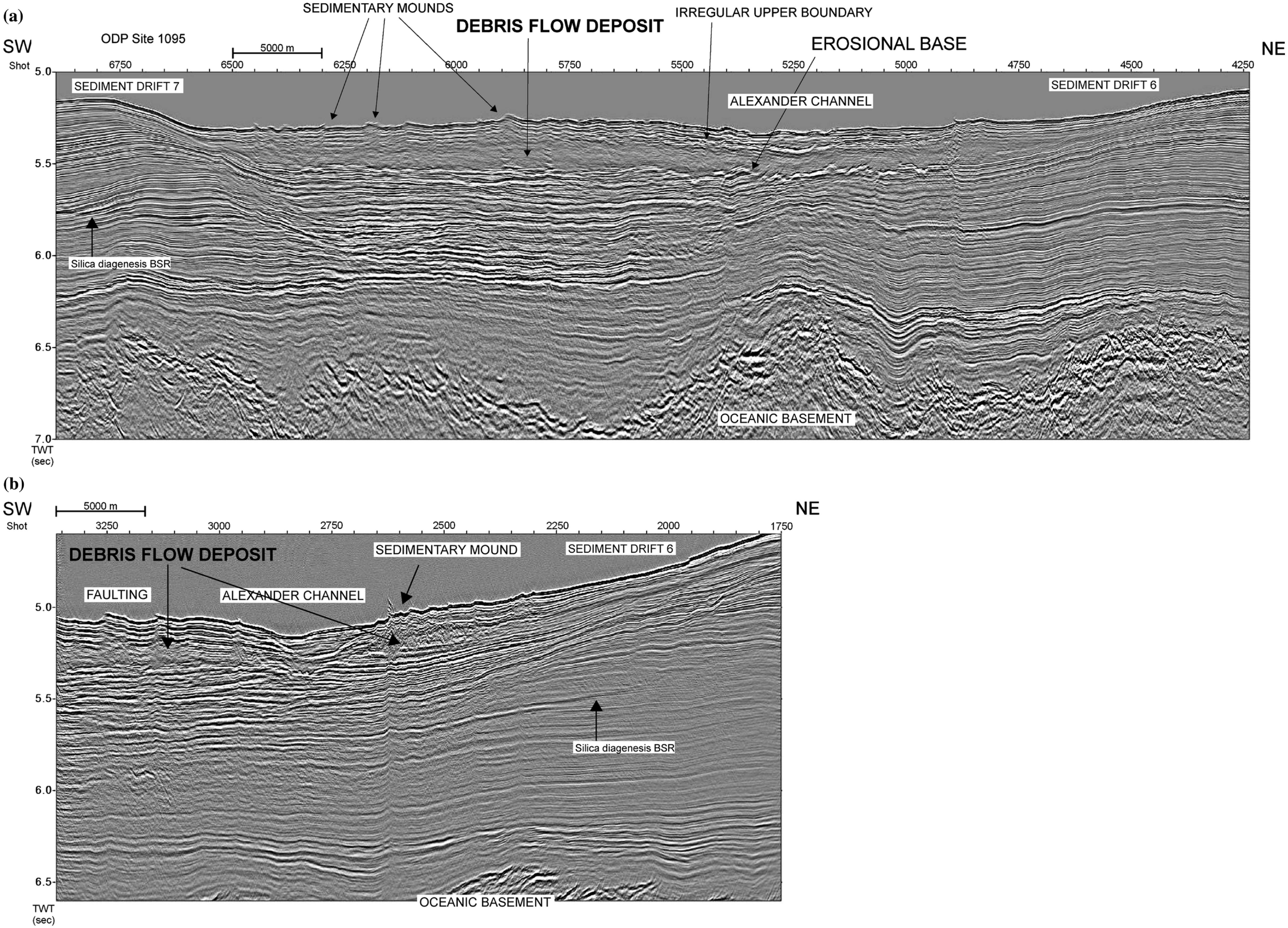

Figure 13. Time migrated sections displaying the final seismic images of the Alexander Channel debris flow deposit: (a) Line I95-137, distal location; (b) Line I95-138, proximal location.

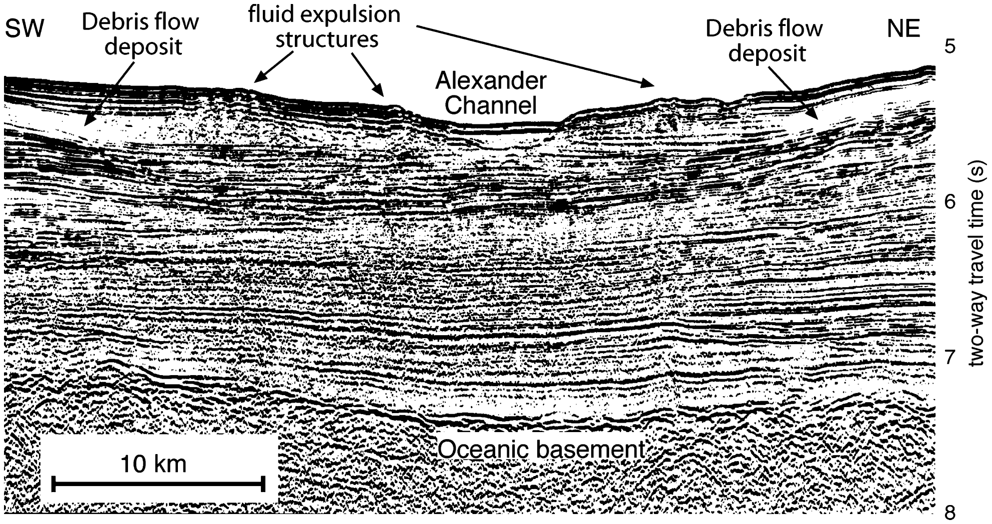

Figure 14. Original stack section of Line I92-109 (after Rebesco et al., 1996) displaying the seismic evidence of the late Pliocene Alexander Channel mega debris flow deposit in a location proximal to the margin.

Thalassiosira insigna-*T. vulnifica* zone (first occurrence of *T. vulnifica*) in the late Pliocene (2.68–3.15 Ma; Winter and Iwai, 2002). However, at ODP Site 1096 this biostratigraphic boundary falls in the oldest part of C2An.1n magnetic chron (2.58–3.04 Ma), while at ODP Site 1095 it falls in the preceding chron (3.11–3.22 Ma). Because the stratigraphic succession is more expanded and the drilling provided a more continuous section, we give more credit to the tie with ODP Site 1096, and hence we assign the debris flow an age of nearly 3.0 Ma.

The image of the debris flow from Line I95-138 (Figure 13b) shows that it is not laterally continuous. The largest part of the deposit is continuously present on the SW side of the channel, while it is not present below the channel, and on the NE side it is generally thinner and possibly discontinuous. According to Lucchi et al. (2002), the transition between confined to unconfined gravity flows along the present day Alexander Channel occurs at approximately 150 km from the base of the continental slope, at the transition between upper and lower continental rise. This is between Lines I95-137 and I95-138, which is where the Alexander Channel thalweg widens from less than 10 km to over 100 km. Turbidity flows within the channel must have eroded away parts of the debris flow deposit closer the margin, while the decreasing energy of the more distal flow has left the deposit intact at the seafloor. The missing parts of the debris flow deposits on the NE side of the proximal Alexander Channel were probably eroded also by the density flows originating on the steep and dissected side of Drift 6.

Seismic evidence for the late Pliocene Alexander Channel mega debris flow deposit exists also closer to the continental margins (e.g., seismic Line I92-109; Figure 14 and I95-130, not shown). The debris flow deposit is thinner and completely eroded below the Alexander Channel. Diffraction of acoustic energy below small seafloor relieves suggest the presence of fluid expulsion structures also in this proximal location.

With a width up to 50 km and thickness up to 175 m (both measured in Line I95-137), a maximum length of about 200 km (the distance between the two strike seismic lines where the deposit is absent), and its overall lens shape, provides volume estimate of the Alexander Channel debris flow deposit of approximately 1800 km^3. Therefore, it can be termed as mega debris flow deposit (Mienert et al., 2002; Canals et al., 2004; Hühnerbacher et al., 2004; Tappin, 2004; Issler et al., 2005). Based on the information available on large scale phenomena of sediment failure along continental margins (e.g., Haflidason et al., 2004), it is likely that this deposit results from the amalgamation of smaller debris flows which were part of a single, multiphase episode of continental margin collapse.

In this interpretation, the origin of the debris flow deposit is from continental slope failure, and the run out distance is up to 250 km. Debris flow deposits are believed to make up the bulk of the glacial prograding wedges (Vorren et al., 1998; Dowdeswell and O'Cofaigh, 2002; O'Cofaigh et al., 2003), where the diamicton delivered by the ice sheet, grounded on the continental shelf edge, generates high density flows with relatively short run-out distance compared to turbidity flows. Glacial margin accretion by debris flows, well documented in Northern Hemisphere margins, is believed to apply as well to the longer-lived glacial margins of Antarctica (Anderson et al., 1979; Larter and Cunningham, 1993; Anderson, 1999; Eyles et al., 2001; Cooper and O Brien, 2004). The resting angle of such Antarctic continental slope deposits (exceeding 13°) is indeed much higher than that of turbidites at low latitude continental margins (a few degrees or even less than one degree, see, e.g., McAdoo et al., 2000). However, when certain physical conditions are attained (visco-plastic flows of low yield strength sediments), the run-out distance of debris flows can be of hundreds of kilometers, as in the case of the debris flow deposits in front of the Bear Island trough mouth fan in the Barents Sea (Marr et al., 2002; Ilstad et al., 2004). In that context, the Alexander Channel debris flow probably belongs to this style of mass wasting, but it is an outstanding deposit in that its thickness exceeds by tens of meters that of its Northern Hemisphere counterparts.

There is no clear evidence of a source area for the debris flow deposit in the available seismic and bathymetric data from the continental slope, between Drifts 6 and 7. The slide scar, produced by the mass wasting event occurred nearly 3.0 Ma, most likely has been buried by the rapid progradation of the glacial wedge. According to Larter et al. (1997), the late Cenozoic progradation of the shelf break on the Antarctic Peninsula Pacific margin was focused in four distinct depositional wedges corresponding to four lobes in the modern morphology of the continental slope. In particular, the horizontal progradation of the margin was about 25 km in the southernmost identified lobe (lobe 4) close to Drift 6, but was minimum in inter-lobe areas of the margin (like in front of Drift 7). The high slope angle (up to 17°) of the lobes was interpreted by Larter and Barker (1989) to result from the stacking on the upper continental slope of high shear strength sediments generated by unsorted transport at the base of grounded ice. The relatively lower slope angle (lower than 13°) of the inter-lobe areas with respect to the lobe ones was interpreted by Rebesco et al. (1998) as the result of consecutive sediment failures favoured by the relatively low shear strength of the sediments transported there by fast-flowing, wet-based ice-streams. Therefore the slide scar of the Alexander Channel debris flow deposit is expected to be part of the margin, like the inter-lobe area in front of Drift 7, that has prograded less than adjacent parts of the margin as a consequence of greater failure. The persistent failure of inter-lobe sites makes it unlikely to preserve ancient slide scars. Accordingly, seismic lines do not show evidence of such expected large scars in the continental slope.

A regional erosional surface suggests that the Pacific margin of the Antarctic Peninsula underwent a major architectural change in response to the late Pliocene cooling of global climate (Lear et al., 2000). Such surface coincides with the boundary between sequences S2 and S1 of Larter and Barker (1989). Elsewhere on the Antarctic margin, similar erosional surfaces and mass wasting events exhibit late Pliocene ages (Bart et al., 1999, 2000; De Santis et al., 2003; Cooper and O'Brien, 2004) and represents the transition of the West and East Antarctic ice sheets from temperate and highly dynamic to cold, dry-based and relatively stable.

We suggest that the onset of the late Pliocene global cooling altered the dynamics of sediment transport on the Antarctic Peninsula continental margin by favoring the onset of the modern, cold, dry-base stable conditions of the Antarctic Ice Sheet. Early failure of continental slopes was due to the focused sediment load, accompanied by continental-scale erosion. The margin became steeper and more stable, with development of proximal depo-centers in correspondence of the continental slope, because the reduced melt-water occurrence at the ice-base resulted in coarser and relatively less sorted sediments with higher shear resistance. The Alexander Channel debris flow deposit may therefore be considered as distal evidence of the late Pliocene regional margin collapse. The uniqueness of this debris flow deposit in the depositional history of the Antarctic Peninsula margin supports an origin from a major event destabilizing the continental slope. This scenario allows us to establish a parallel between the Late

Pliocene Antarctic Peninsula margin and Pleistocene sub-polar northern hemisphere margins, namely the Norwegian margin (Bryn et al., 2003; Solheim et al., 2005) and the Atlantic Canadian margin (Mulder and Moran, 1995), where the role of the overpressure induced by glacial sediment overload, as well as the glacially induced change of composition and texture of continental slope sediments, are identified as key factors in the development of margin instability.

Other possible source areas for the debris flow, rather than the continental slope, are represented by the relatively gentle flanks of the adjacent drifts. The slopes of the continental rise of the Pacific margin of the Antarctic Peninsula reveal signs of mass wasting both in the distal gentle slopes with resting angle lower than 1 degree (Amblas et al., 2005) and in the steeper, dissected parts (Figure 1 and Rebesco et al., 2005). Similar failures in the deep-water continental rise of divergent continental margins are relatively common features (e.g., Jacobi, 1976; Piper and McCall, 2003) . However, the possibility that portions of the adjacent sediment drifts collapsed into the Alexander Channel thalweg to generate the debris flow, is discarded because: (1) the symmetry of the deposit in the distal, laterally continuous part, with respect to the channel, and (2) because sediment failure evidence from these drift slopes indicates small, disseminated and likely frequent failure episodes rather than a single failure event such as the late Pliocene one we find here (Figure 1 and Rebesco et al., 2002). Two multi-step scars are visible in the most landward part of the eastern flank of Drift 7, facing the Alexander Channel (Figure 1). These scars are considered too small to have generated the late Pliocene Alexander Channel Debris flow deposits. In addition, in spite of the low sedimentation rate in this part of the margin (5 mm kyr^{-1} since the late Pliocene, Barker and Camerlenghi, 2002), the morphological evidence of the two scars seems too sharp to be nearly 3 million years old.

We finally introduce a concept that deserves attention in the framework of the major events occurred in the Southern Ocean in the late Pliocene. A 1 to 4-km-sized asteroid impacted into the deep ocean in the Bellingshausen Sea about 1000 km west of Cape Horn (Kyte et al., 1981, 1988; Kyte and Brownlee, 1985; Margolis et al., 1991) producing seafloor morphological evidence, sedimentological evidence and geochemical evidence in the form of an iridium anomaly in the ejecta deposit. From stratigraphic analyses of deep sea cores collected in the impact area, Gersonde et al. (1997) identified the age of the deposit at 2.15–2.14 Ma because of its location into the *Thalassiosira kolbei–Fragilariopsis matuyamae* diatom zone directly below the magnetostratigraphic Réunion Event (C2r.1n) and in oxygen isotope Stage 82One of the objectives of ODP Leg 178 drilling on the continental margin was to identify ejecta deposits as well as a sedimentological evidence of the supposed mega tsunami generated by the asteroid impact in the ocean (Barker and Camerlenghi, 1999). No geochemical nor sedimentological evidence were found in that stratigraphic interval (Kyte, 2002; Barker and Camerlenghi, 2002). We therefore conclude that although on a conceptual basis a mega tsunami may have triggered a unique slumping in the continental margin only 1300 km away from the impact zone, and a consequent mega debris flow deposit, the existing stratigraphic discrepancy prevents to establish a link between the two phenomena. The age of the Eltanin asteroid impact is presently being revised (see the recent abstract by Gersonde et al., 2005) and placed to 2.5 Ma. If this new age will be confirmed, then the age difference between the two

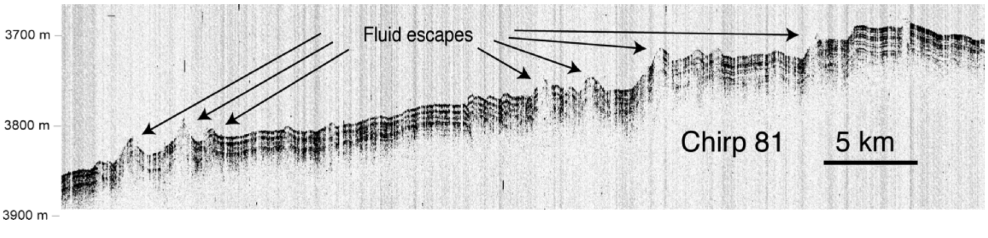

Figure 15. Hull-mounted CHIRP sonar profile collected with the RV *OGS-Explora* in 2004 above the rough seafloor overlying the late Pliocene Alexander Channel mega debris flow deposit. Such mounds correspond to the high-velocity anomalies analyzed in this study, and are interpreted as evidences for fluid expulsion (see also Rebesco et al., 2005a, b).

events would be greatly reduced, and the possibility that the late Pliocene Alexander Channel mega debris flow deposit is the result of the tsunami produced by the Eltanin asteroid impact should be re-considered.

Seismic energy diffraction as indicator of rough topography of the buried debris flow deposit and fluid expulsion

The seismic energy diffractions generated at the upper boundary of the transparent debris flow unit (Line I95-138 SP 2500–2550 in Figure 8a) are produced by the irregular, rough (horizontal dimension smaller that the Fresnell zone) surface of the debris flow deposit. This surface roughness may occur when single large blocks (olistoliths) or agglomerates of smaller sediment blocks are preserved in the upper part of the flow (e.g., Dowdeswell et al., 1997; Canals et al., 2004). Flow structures such as flutes, furrows, or pressure ridges may also contribute to the roughness of the upper boundary of the debris flow deposit (Masson et al., 1998; Lastras et al., 2002; Nygård et al., 2002). In addition, a rough topography may result from intrusion of diapirs or from fluid/mud expulsion structures (Carter, 2001).

The energy diffraction generated at, or above the average seafloor, and its association with narrow energy shadow cones and reflector pull-up, suggest fluid migration structures from the buried debris flow deposit to the seafloor. The positive polarity of the diffractions indicates that they are formed by sediment (density and/or velocity higher than that of seawater) projecting up to 70 m above the seafloor, most likely in the form of isolated mounds or ridges (Rebesco et al., 2004). Because the low amplitudes of the shadow cones are largely recovered in the migrated sections (see Figure 8b), at least part of the energy dispersion was originated by terminations of reflectors along vertical, or sub-vertical features. These can be produced by faults that generate a small offset of strata, or by fluid conduits that interrupt the lateral continuity of reflectors. The high-velocity anomaly along these vertical zones, responsible for the reflector pull-up, is inconsistent with the presence of fluids, especially if overpressured (Carcione and Gangi, 2000; Tinivella, 2002). A high-velocity anomaly in this context can only be produced by carbonate cementation following the activity of methanotrophic bacteria (Hovland and Judd, 1988; Paull et al., 1992; von Rad et al., 1996), or by formation of methane clathrates (Chand and Minshull, 2003; Gei and Carcione, 2003). Both explanations may equally apply in this deep (high pressure), near surface (cold) sub-surface environment. The possibility that the mounds are coral bio-herms is discarded because of the persistent cold water temperatures (e.g., Freiwald, 2002). In addition, stacked and migrated sections (see SP 4800–5350 in Line I95-137 in Figure 2 and SP 2420 and 2470 in Line I95-138 in Figure 12) show that the sediment draping the debris flow deposit is affected by low-offset sub-vertical faulting. A high-resolution acoustic profile from such rough topography is displayed in Figure 15.

The fluids generating the mounds are likely to have been expelled from underlying sediments overloaded by the debris flow deposit at the time of its deposition. In addition, a contribution to fluid expulsion may have come from dewatering of the debris flow deposit itself, which probably had a high water content in order to achieve the appropriate low viscosity for the observed long run-out. With typical values of sediment permeability, the overpressures generated by the instantaneous emplacement of the debris flow deposit would have dissipated in much less than 3.0 m.y. We have calculated, using the simplified equation describing the elastic linear consolidation of a homogeneous soil layer (Terzaghi, 1943), the time necessary to achieve 95% of average consolidation (Um) of a 175 m thick layer draining only upwards with a consolidation coefficient (Cv) ranging from 10^{-8} to 10^{-7} m^2 s^{-1} (average values in shales). The resulting time ranges from 0.1 to 0.01 m.y. respectively. Because the inferred draining of excess pore pressure from the Alexander Channel debris flow deposit is expected to occur not only as diffuse flow through the sediment pore space, but also as focussed flow along conduits leading to venting sites, the time for dissipation of pore pressure will be shorter than the calculated ones. Therefore, if this was the only origin of the fluids, the escape structures observed (mounds and conduits) would be inactive. However, widespread presence of an upward fluid flow within the sedimentary column of the sediment drifts was postulated by Volpi et al. (2003) as a consequence of the transformation of opal-A to opal-CT, which implies a reduction of porosity and generation of excess fluid pressure. A secondary source of overpressured fluids from silica diagenesis might therefore maintain activity of the fluids vents above the debris flow deposit.

Conclusions

Improved seismic images of the Alexander Channel mega debris flow has been obtained by the re-processing of multichannel seismic reflection data focusing on the reduction of noise, the recovery of relative amplitudes and deconvolution before stack, and velocity analysis.

The mega debris flow deposit is defined as a lens-shaped low amplitude seismic unit with an erosional lower boundary and an irregular upper surface confined between Drifts 6 and 7, in the area presently incised by the Alexander Channel. In the more proximal part, the deposit has been eroded by subsequent turbidity flows. The deposit has a maximum observed thickness of 175 m, width up to 50 km and length up to 200 km The estimated total volume is of about 1800 km^3 while the inferred provenance from the continental slope implies a run-out distance exceeding 250 km.

The uniqueness of the deposit in the sedimentary history of this margin and its late Pliocene age (nearly 3.0 Ma) obtained by correlation to ODP Sites 1095 and 1096 allows us to define a major mass wasting event that coincided with the margin-wide erosion that accompanied a change in the dynamic behaviour of the Antarctic ice sheet during the latest major response to global cooling.

Isolated sedimentary mounds at the seafloor above the debris flow deposit underlie narrow high-velocity zones. We interpret the mounds as the surface expression of fluid and mud expulsion from subvertical conduits that include methane hydrates or authigenic carbonates. If the origin of the fluids is only from the excess pore pressure induced by the rapid emplacement of the debris flow deposit, then the fluid expulsion conduits would be expected to be inactive. However, the regional deep-seated excess pore-fluid pressure induced by the diagenesis of biogenic silica may have contributed to the continuing activity of the vents until today.

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