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SEISMIC SURVEY OF THE ANTARCTIC PENINSULA PACIFIC MARGIN: RESULTS OF THE 1989-92 CRUISES OF THE R/V OGS-EXPLORA

Abstract. This paper presents a preliminary interpretation of the multichannel seismic reflection data set collected by the Osservatorio Geofisico Sperimentale (OGS) within the Programma Nazionale di Ricerche in Antartide (PNRA) on the Antarctic Peninsula Pacific Margin south of the Hero Fracture Zone. The profiles have been correlated with those collected by the British Antarctic Survey in the northeastern part of the margin. We identified four seismic sequences on the continental shelf and slope, and previously unknown large sedimentary bodies on the continental rise. We describe the data set on three different settings of the margin: continental shelf, outer shelf and slope, and continental rise. We outline the two principal results, which correspond to thematic objectives of the Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT) program:

1) The identification of a prograding wedge of sediments on the continental shelf and slope with different characteristics along the margin supports the observation that the sedimentary regime of the Antarctic Peninsula Pacific Margin is controlled by synchronous glacial/interglacial processes and diachronous ridge crest-trench collisions.

2) The large sedimentary bodies identified on the continental rise show indications of bottom-current control on the depositional processes affecting the margin. External shape and internal characteristics, together with general considerations on deep circulation in the Southern Ocean, allow us to interpret these bodies as sediment drifts.

INTRODUCTION

The geology of the Antarctic Peninsula bears many similarities to that of the Andes. The subduction complexes of the two areas belong to a continuous magmatic arc corresponding to the Western margin of Gondwanaland, active at least from the Triassic (De Wit, 1977; Dalziel, 1983; Lower and Scotese, 1987, Grunow et al., 1992). They separated during the Late Oligocene (magnetic anomaly 8) with onset of the oceanic expansion that led to the opening of the Drake Passage (Barker and Burrel, 1977) and formation of the Scotia oceanic plate. The Scotia Plate is moving left-laterally with respect to the Antarctic Plate along the South Scotia Ridge, which is characterised by eastward migration of continental blocks of the Gondwanaland margin (South Orkney micro-continent and the Elephant Island Group). Subduction of the Phoenix oceanic plate at the South Shetland Trench is seen at the Antarctic Peninsula Pacific Margin between the Shackleton and the Hero Fracture Zones. The Antarctic-Phoenix spreading axis, almost parallel to the margin, became inactive, or drastically reduced its activity, at about 4 Ma (Barker, 1982).

Subduction along the Antarctic Peninsula Pacific Margin south of the Hero Fracture Zone stopped after collision between segments of the Phoenix ridge and the trench. Fracture zones almost perpendicular to the margin separated these segments. These fracture zones now divide sections of oceanic crust characterised by magnetic anomalies that become younger towards

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the continent (Herron and Tucholke, 1976; Barker, 1982). The fracture zones dissected the ridge crest before collision into at least nine segments. Timing of collision, as calculated by Larter and Barker (1991a) varied from 50 to 4 Ma, with progression from southwest to northeast (Fig. 1). After collision at each segment, the trench topography dispersed and the margin became passive (Tucholke and Houtz, 1976; Larter and Barker, 1991a). Analogy with other similar cases (DeLong and Fox, 1977; DeLong et al., 1978 and 1979) suggests that after ridge crest-trench collision the fore-arc underwent thermal uplift, followed by a long period of subsidence.

Glacial and interglacial cycles influenced the pattern of sediment transport and deposition on the margin. Larter and Barker (1989) proposed a model for the Pliocene-Pleistocene evolution of a high-latitude passive margin (Fig. 2):

1) During an interglacial stage, the deposition of glacial marine and pelagic sediments on shelf and slope generates the intergrounded sequence (Fig. 2a).

2) During the successive glacial stage, a grounded ice-sheet erodes the former sediments or deposits a thin layer of basal till on the continental shelf. It also transports a large quantity of unsorted sediment to the shelf-edge and dumps it on the upper slope, generating the grounding sequence (Fig. 2b). This model is based mainly on interpretation of the multichannel seismic reflection profiles collected by the British Antarctic Survey on the Antarctic Peninsula Pacific Margin (Larteter and Barker, 1989).

The surveys of the Antarctic Peninsula Pacific Margin and the South Scotia Ridge were the targets for three consecutive cruises of the R/V OGS-Explora of the Osservatorio Geofisico Sperimentale (OGS) within the Programma Nazionale di Ricerche in Antartide (PNRA). The vessel recorded a total length of nearly 10,500 km of multichannel seismic reflection lines, magnetic and gravimetric profiles during the 1989-90,1990-91 and 1991-92 austral summers (Fig. 1).

This paper focuses on the 17 seismic profiles (3,300 km) collected during the first and third cruises on the Antarctic Peninsula Pacific Margin south of the Hero Fracture Zone. The aim of this paper is to present an interpretation of the stack versions to illustrate the main characteristics of the margin and to outline the main points of interest within the thematic objectives of the Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT) program endorsed by the Scientific Committee on Antarctic Research (SCAR).

MULTICHANNEL SEISMIC DATA

All profiles discussed in this paper were acquired with a 3,000 m-long analogic streamer (120 channels). The seismic source (towed at a depth of six metres) consisted of an array of 28 airguns (total capacity of 45.16 litres) during the 1989-90 cruise, while during the 1991-92 cruise the total capacity was 71.96 litres employing an array of 40 airguns. Shot spacing was 100 metres and the hydrophone group spacing was 50 metres. The resulting fold coverage was 3,000 %.

The data processing centre of the Osservatorio Geofisico Sperimentale applied to all profiles a standard processing sequence consisting of the following steps: summation of pairs of adjacent traces in each shot gather (resulting in an effective group spacing of 100 m), spherical divergence correction, common depth point sort, predictive deconvolution, normal move-out correction using velocities picked from semblance plots, far-trace mute, common depth point stack, running trace mix (3 traces) with time variant trace weighting, space and time filtering, automatic gain control using a 300 ms window.

The core of the multichannel seismic survey was done between 64°S and 69° S, in a part of the Antarctic Peninsula Pacific Margin that was largely unknown. Nine of the profiles cross the margin, five lie on the shelf and three on the continental rise. The nine profiles orthogonal to the margin (Fig. 3) are oriented differently within the different collision zones:

- profiles IT92-124, -108 and -106 lie in the southern part, between the Heezen and Tula Fracture Zones where collision occurred at about 32 Ma;

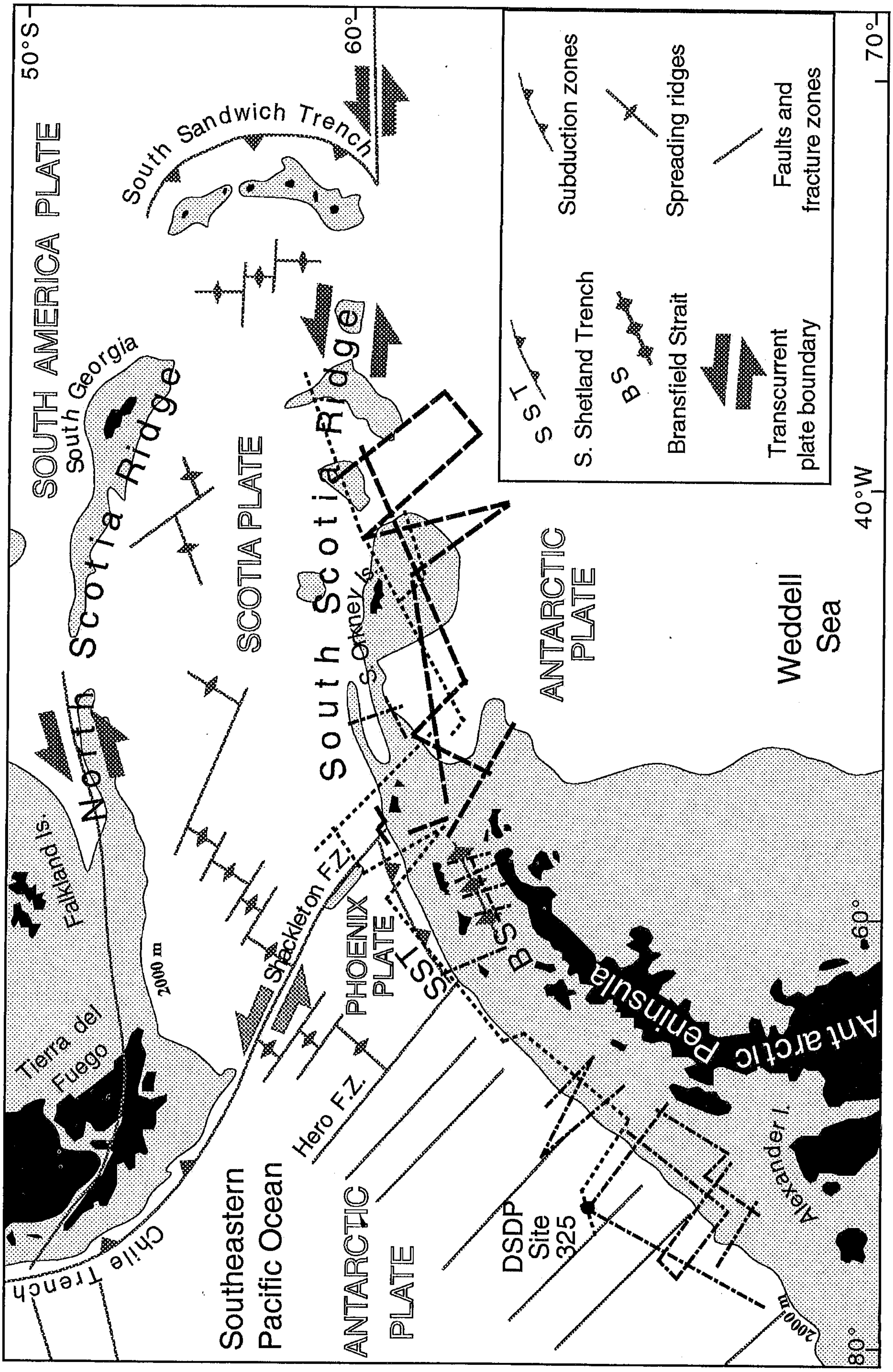

Fig. 1 — Sketch map of the main tectonic boundaries of the Scotia Arc Region (after Dalziel, 1983). Fracture zones and spreading ridge positions after Barker et al. (1991). Profiles collected by Osservatorio Geofisico Sperimentale on the Antarctic Penisula Pacific Margin and South Scotia Ridge also shown. Dotted lines: 1989-90 Cruise; thick dashed lines: 1990-91 Cruise; thin dashed/dotted lines: 1991-92 Cruise.

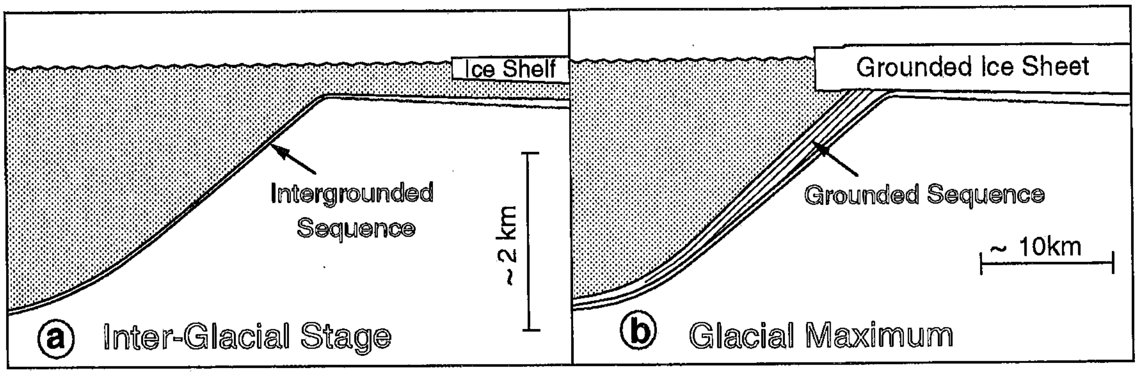

Fig. 2 — Glacial/interglacial depositional model for outer shelf and slope (after Larter and Barker, 1989). a) Interglacial stage with deposition of the intergrounded sequence on continental shelf and slope. b) Glacial stage with deposition of the grounded sequence on the continental slope.

- profiles IT92-110 and IT89-48 lie near Deep Sea Drilling Project Site 325, between the Adelaide and Biscoe Fracture Zones (collision at 16.5 Ma);

- profiles IT92-113, -114 and -115 come from near the Biscoe Fracture Zone; one of them lies south of the fracture zone (collision at 16.5 Ma) and two lie to the north, where collision occurred at 14.5 Ma.

- profile IT89-46 lies north of the South Anvers Fracture Zone, where collision occurred at 10 Ma.

The remaining profiles, collected in a direction parallel to the margin, both on the continental shelf and on the continental rise, provide a means of correlation between orthogonal profiles.

We describe three groups of profiles according to the main physiographic provinces that identify three main sedimentation environments on the margin:

1) Mid-Shelf High and Mid-Shelf Basin (the elements recording the ridge crest-trench collision);

2) outer shelf and continental slope (the record of margin progradation);

3) continental rise (sediment drifts and bottom-current-controlled sedimentation).

Mid-Shelf High and Mid-shelf Basin

The sub-parallel continuous reflectors of the uppermost sedimentary sequences of the outer continental shelf, conformable with the seafloor, onlap a seismic unit without any clear pattern of coherent reflections (Fig. 4). The unconformity consists of a rough surface, whose western flank gently dips toward the continental slope without any major morphologic step. This unit sometimes outcrops on the seafloor. The unit occurs in the middle part of the shelf, approximately 60 km landwards of the shelf-break in the northeastern part of the margin, and more than 100 km in the southwest. This buried morphologic high corresponds to the Mid-Shelf High (MSH) of Larter and Barker (1991b), sequence S4 (pre and syn-tectonic deposits) of Anderson (1991) and to the "paleo-island arc" of Kimura (1982). In this presentation we adopt the terminology of Larter and Barker (1991b).

A thick sedimentary sequence overlies the Mid-Shelf High towards the inner shelf (Fig. 5). This sequence, characterised by coherent reflections lacking lateral continuity, identifies a sedimentary basin corresponding to the Mid-Shelf Basin of Larter and Barker (1991b). The basin contains several seismic sequences: the deepest and thickest sequence is the least reflective and does not show a clear relationship with the transparent unit of the Mid-Shelf High. Three younger units show frequent lateral terminations of reflectors, often indicating onlap unconformities. The reflectors of the sedimentary basin near the Mid-Shelf High are truncated by the seafloor. The shape of the basin is asymmetrical, with the outer flank steeper than the inner one. Fig. 6 shows a general picture of the margin. The Mid-Shelf Basin is at least 30

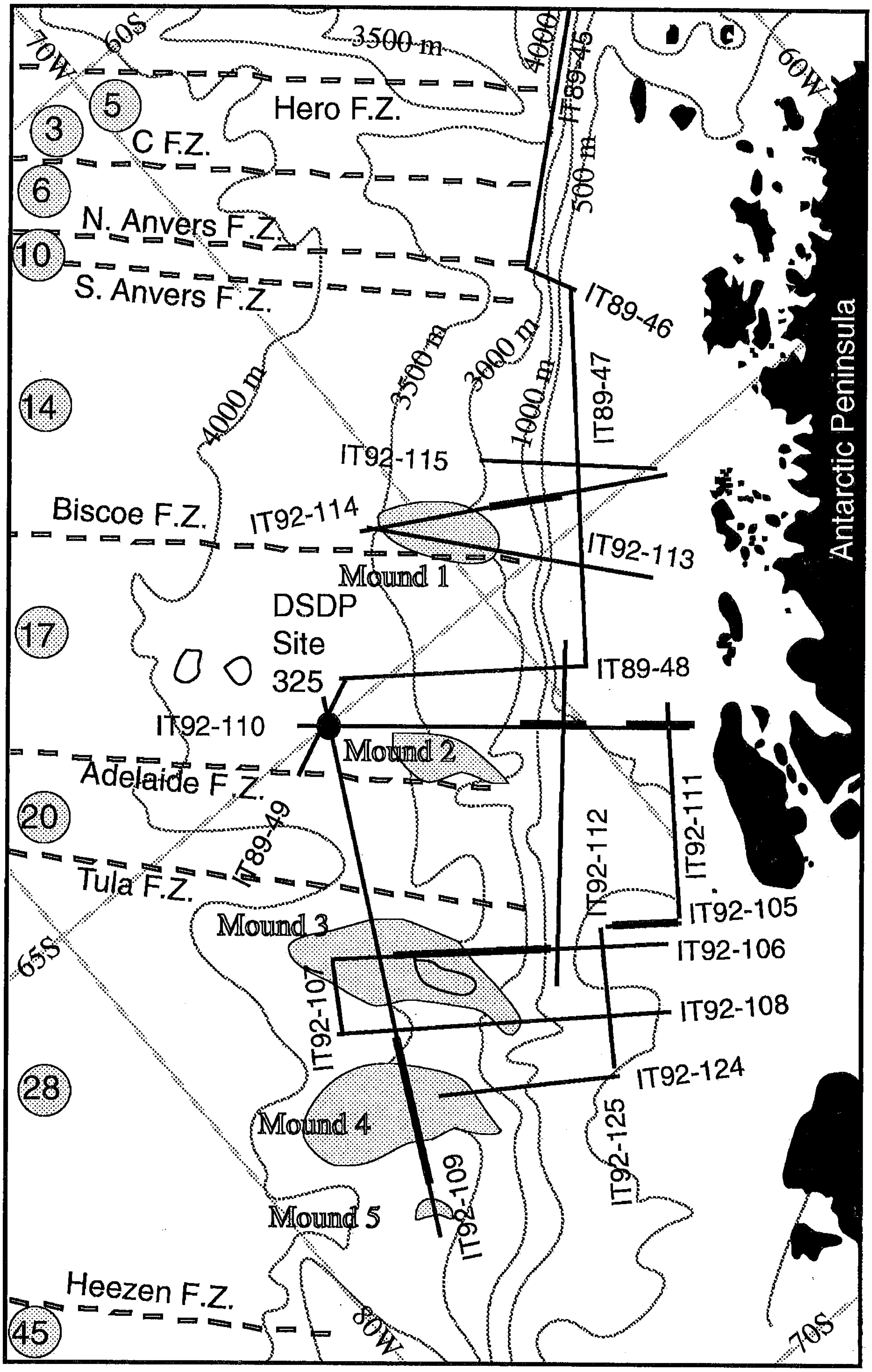

Fig. 3 — Track map of the profiles collected by Osservatorio Geofisico Sperimentale on the Antarctic Penisula Pacific Margin south of the Hero Fracture Zone. Fracture zone locations after Tomlison et al. (1992). Age of collisions, after Larter and Barker (1991a), are indicated in Ma. within circles. Thicker segments indicate the parts of seismic lines shown in figures. Position of the mounds identified on the continental rise are also shown.

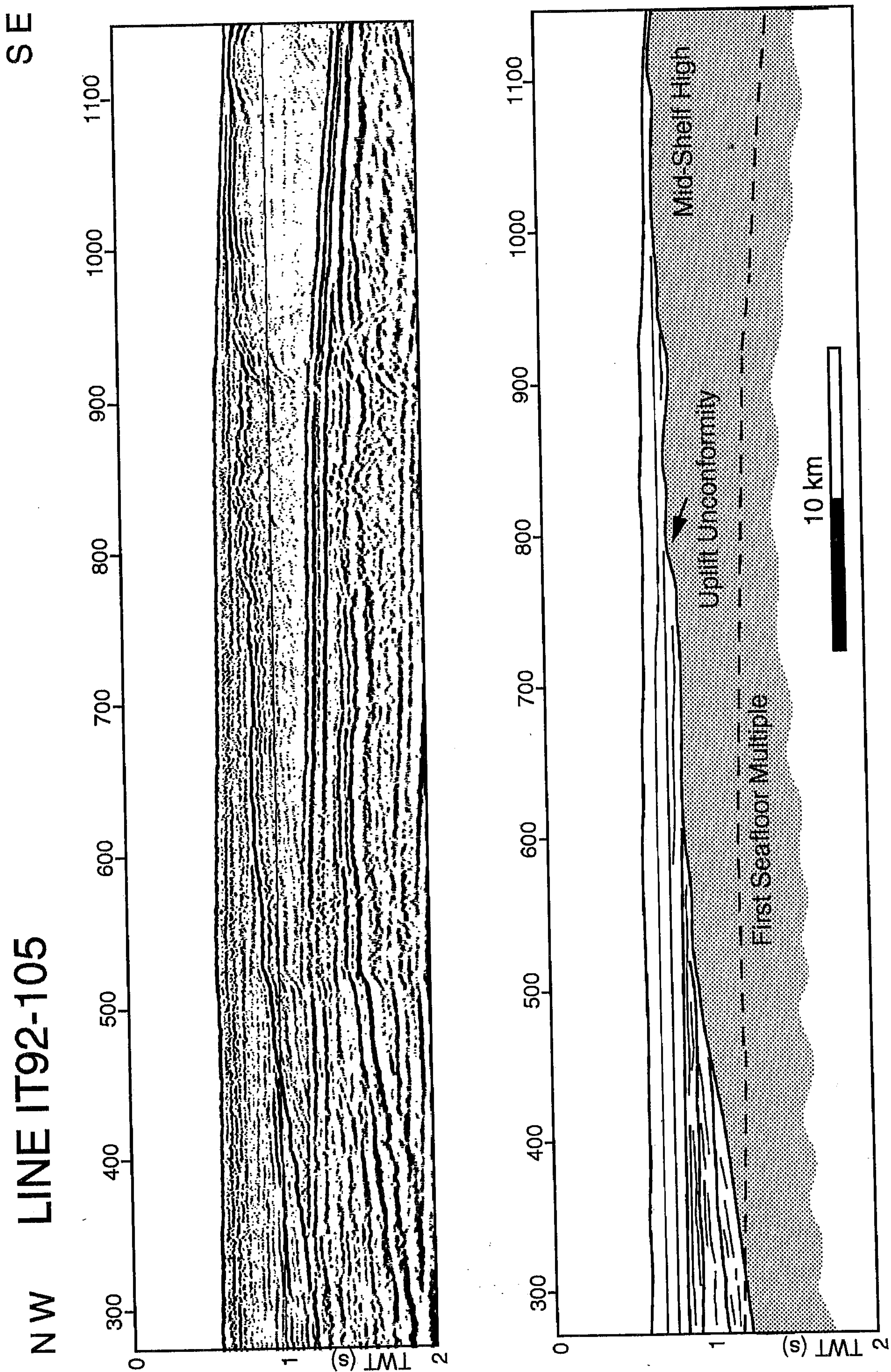

Fig. 4 — Stack version and interpretation of southeasternmost part of line IT92-105. Location in Fig. 3. The sub-parallel reflectors of the outer continental shelf sedimentary sequences onlap the rough surface of a transparent seismic unit that appears to be a buried morphologic high corresponding to the Mid-Shelf High (MSH) of Larter and Barker (1991b).

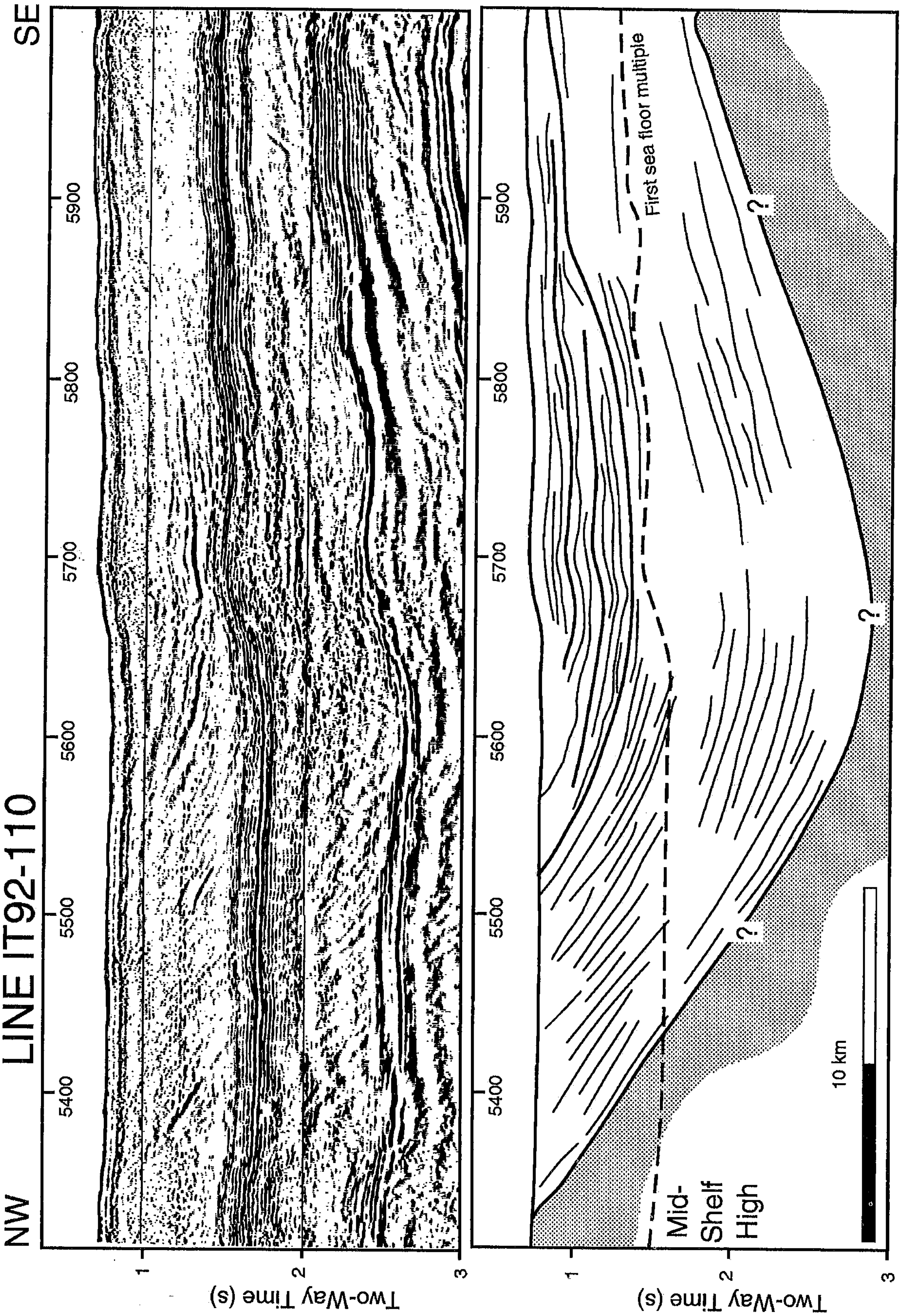

Fig. 5 — Stack version and interpretation of the southeasternmost part of line IT92-110. Location in Figs. 3 and 6. An asymmetric sedimentary basin (Mid-Shelf Basin of Larter and Barker, 1991b) overlies the inner flank of the Mid-Shelf High. Reflectors of the steeper side are truncated at the seafloor. Different seismic sequences are identified.

km wide and about 2 seconds (two-way travel time) thick at its depocentre. Profile IT92-111 lies along the axis of the basin, demonstrating the longitudinal continuity of this feature for at least 150 km.

Outer shelf and continental slope

The seafloor of the outer shelf and shelf-break of the Antarctic Peninsula Pacific Margin is deeper than that of continental shelves of low latitudes. The mean depth of the shelf-edge is around 450 m, and the seafloor of the continental shelf gently dips landwards to the Mid-Shelf High.

Seismic profiles perpendicular to the margin image a rather smooth seafloor profile on the outer shelf. Profile IT89-48 (not in figures), showing three asymmetric crests (vertical relief up to 60 m) is the only exception. Strike profiles outline the uneven and irregular seafloor character of the outer shelf, showing differences in relief of up to 200 ms (two-way time) within some tens of kilometres. Abrupt steps and gentler slopes are present, with either convex or concave profiles. It is not clear whether these are erosive or depositional features. The action of ice moving over the shelf in a direction approximately orthogonal to the margin was probably the cause of such features.

The shelf-edge is generally quite sharp, and the continental slope is very steep, with measured angles up to 17°. This is common to Antarctic margins (Figs. 6, 7, 8, and 9). On most of the profiles a Mid-Slope Bulge is present, which gives a convex appearance to the slope profile (Figs. 7 and 8). The bulge is absent only on profiles IT89-46 and IT92-106 (Fig. 9) where the slope profile is concave.

A strong seafloor multiple reflection, produced by the high acoustic impedance contrast, disturbs those parts of seismic-reflection profiles lying on the continental shelf of the Antarctic Peninsula Pacific Margin. Grounded ice shelves covered the Antarctic continental shelf sediments during glacial stages, over-consolidating them and thus giving them a relatively high seismic velocity (see also Larter and Barker, 1989).

We have distinguished four seismic sequences, whose characteristics are shown in Fig. 7. The lower sequence (4) is the least defined, since seafloor multiples strongly obscure it on the continental shelf. Its lower boundary is not visible, while a strong, discontinuous high-amplitude reflection characterises the upper boundary. On the continental slope and on the shelf near the Mid-Shelf High it represents one of the most prominent seismic events of the Antarctic Peninsula Pacific Margin. Seafloor multiple reflections hide this boundary between the shelf-break and the Mid-Shelf High, where it is sub-parallel to the seafloor (see also Fig. 6). Disrupted chaotic reflections identify this sequence. On the continental slope, reflections suggest seaward-dipping bedding not conformable to the upper boundary.

Sequence (3) is generally restricted on the outer shelf and absent or poorly represented on the continental slope. The basal reflectors exhibit downlap terminations toward the shelf-edge on sequence (4), thus defining the unconformity between sequences (3) and (4) on the outer shelf as a downlap surface. The basal reflectors of this sequence exhibit an onlap contact towards the Mid-Shelf High (see also Figs. 4 and 6). Relatively higher frequency and high amplitude reflector, even and sub-parallel, and dipping towards the slope characterise the internal configuration of sequence (3) on the outer shelf. This sequence shows no shelf-edge progradation. The upper boundary of the sequence is sub-parallelel to the seafloor and conformable with the reflectors, while on the upper continental slope erosional truncations of reflectors occur at the upper boundary. On the lower continental slope the internal configuration becomes chaotic, not allowing an accurate definition of the boundaries. The main characteristic of the two overlying sequences, (2) and (1), is the presence on the outer shelf of dipping foresets that indicate a prograding shelf-edge. The upper part of most foreset beds is eroded and overlain by sub-horizontal, continuous topset beds. Basal reflections of sequence (2) are conformable to the boundary with sequence (3) on the continental shelf, and downlap on the lower sequence, either (3) or (4), on the lower part of the continental slope. A major erosional surface, which causes significant truncation of foresets, defines the boundary between sequences (2) and (1) on the outer shelf.

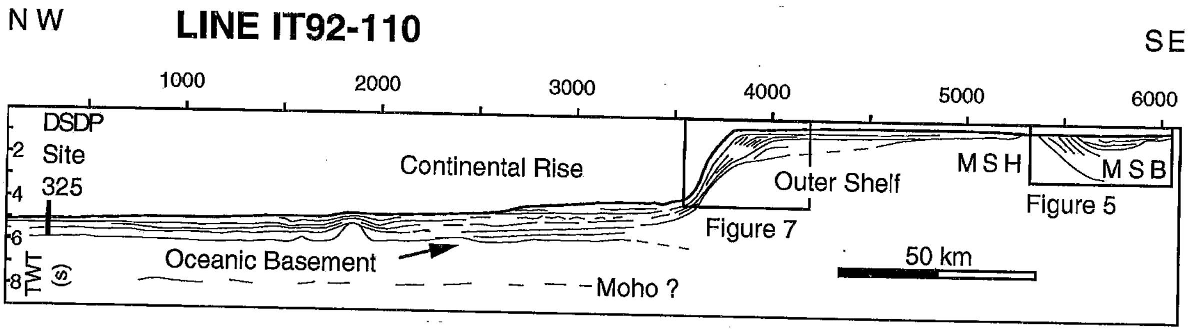

Fig. 6 — Schematic line drawing of profile IT92-110 showing a general picture of the margin. Location in Fig. 3. The main physiographic provinces are indicated (see text). The parts of the profile shown in figures are squared. A prominent intra-basement reflector present nearly 2 seconds below the top of the oceanic basement has been interpreted as the Moho discontinuity, similarly to that reported by Ashcroft (1972) north of the Hero Fracture Zone.

Sequences (1), (2) and (3) form a prograding wedge of sediments. Downlap terminations of basal reflections characterise them all. In profiles across the margin, a prominent downlap unconformity is always present on the lower slope (see Figs. 8 and 9). To the southwest of the margin (profiles IT92-124, -106 and -108; Fig. 9) the downlap unconformity seems to be deeper in the sediment section, more than 700 ms (two-way time) at the base of the slope, while to the northeast of the margin (profiles IT92-114 and -115; Fig. 8) it occurs at much shallower depths (as shallow as 200 ms two-way time).

Continental rise

Between 64.5°S and 69.0°S, on the continental rise of the Antarctic Peninsula Pacific Margin, we identified two areas where large sedimentary bodies (mounds) occur (Fig. 3). Profiles IT92-113 and -114 show one mound (called Mound 1) in the northeastern area. Two mounds (called Mounds 4 and 3, the latter subdivided into 3a and 3b) occur in the southwestern area on profiles IT92-106, -107, -108 and -109 (Figs. 9 and 10).

The elevation of the largest of these sedimentary bodies above the surrounding seafloor is more than 1 km. The sedimentary thickness above the oceanic basement beneath the top of the mounds is about 2.5 s (two-way time), which is equivalent to nearly 3 km. They are at least 150 km in length, at right angle to the continental margin, and tens of km (up to more than 50 km) in width.

The external shape of these mounds is always asymmetric: northeastern Mounds 1 and 3a (Fig. 9) show a steeper, rough slope facing the continental slope. A sedimentary gap corresponding to a seafloor depression separates them from the base of the continental slope. A flat very gently dipping surface is present on the outer flank, which fades into the abyssal sediments of the lower continental rise and oceanic basin. The southwestern Mound 3b shows an outer slope that appears steep and rough, while the gentler surface facing the margin merges with the outer slope of Mound 3a (Fig. 10). The multichannel seismic data set collected during the R/V Maurice Ewing Cruise EW91-01 came upon Mound 2 (Robert Larter, personal communication). Profile IT92-109 collected by the Osservatorio Geofisico Sperimentale strikes parallel to the margin, about 100 km off the base of the slope. It offers the best seismic expression of Mounds 3a, 3b, and 4 and is the only one to intersect Mound 4 (Fig. 10). Mound 5 is a small feature located on the southwesternmost part of profile IT92-109, which has seismic characteristics very similar to those of the larger mounds.

At present, the spacing of the seismic grid does not allow us to precisely identify the geometry and lateral extent of the mounds. However, these sedimentary bodies correlate with positive anomalies in the gravity field (McAdoo and Marks, 1992, plate 5). Mounds 4 and 3, which we were able to trace on the gravity map, appear very sinuously elongated in a direction approximately orthogonal to the margin. The shape of the anomaly in plan view is sigmoidal, with a wider (presumably thicker) central body and two narrow tips, one facing the margin and the other pointing to the open ocean. The shape of Mound 3 appears to follow a change

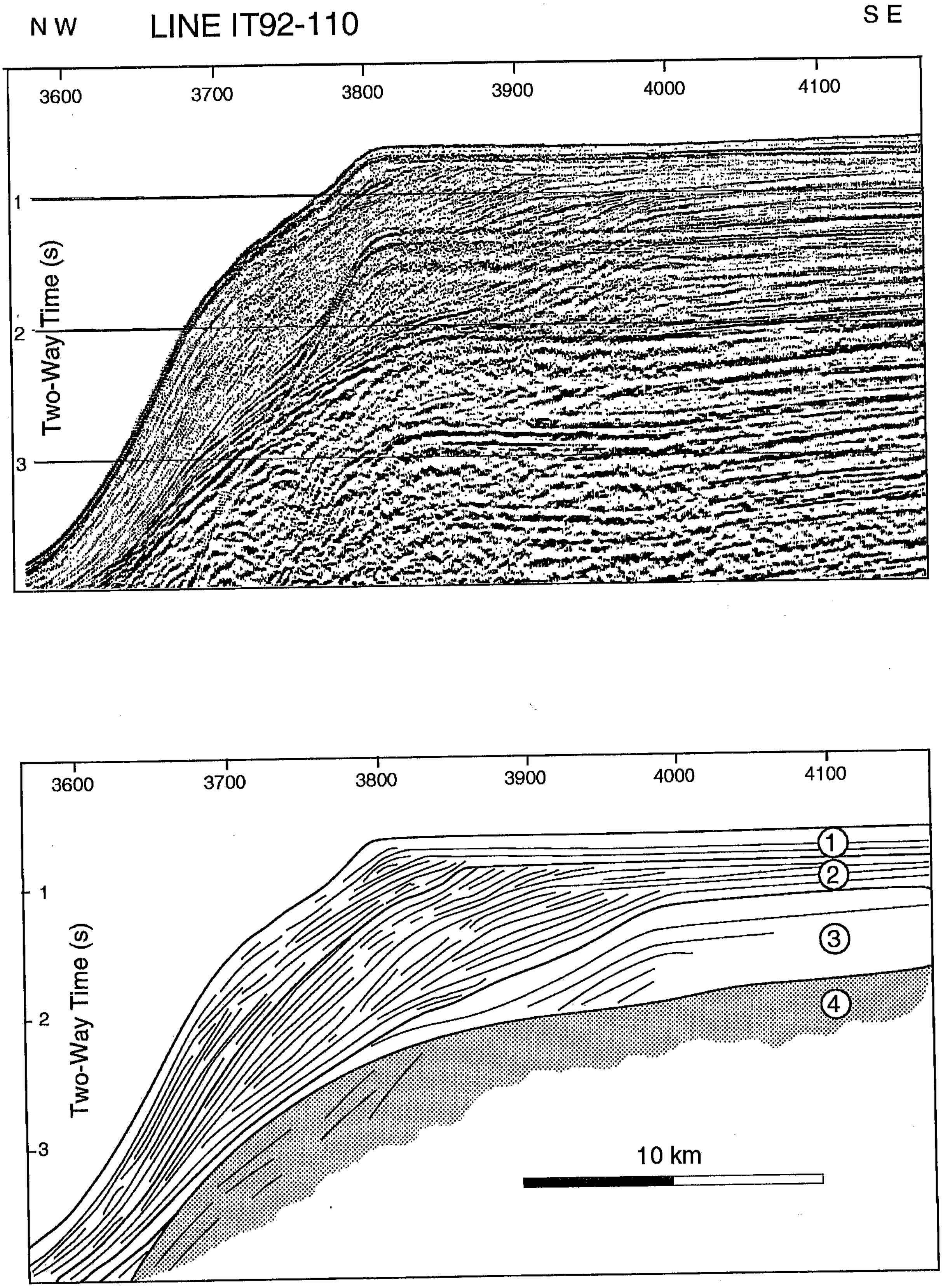

Fig. 7 — Stack version and interpretation of part of line IT92-110. Location in Figs. 3 and 6. Four seismic sequences numbered from 1 to 4 are identified on the outer shelf and continental slope. See text for details.

in direction of the continental margin. We point out here that this shape is not that characteristic of a deep-sea fan. The gravimetric evidence of Mound 1 is almost comparable in magnitude and shape to the ones just described.

The internal structure of the mounds differs on the gentler and the steeper sides (figure 9 and 10). Highly reflective sequences, with linear, parallel or sub-parallel reflectors conformable to the seafloor characterise the gentler side. Lateral continuity of reflectors is typical. Evidence of small channels is extremely rare. The lateral continuity of the reflectors is interrupted approximately below the crest of the mounds. Truncation of reflectors at the seafloor (interpreted as either erosional or due to sediment non-deposition) characterises the steeper slope. Present day channelling, documented on Mound 1 by the GLORIA images (Tomlinson et al., 1992) generate diffractions and irregular seafloor surfaces. High reflectivity is characteristic also of the steepest side, but lateral terminations of reflectors and undulating reflectors (sediment waves) are common.

We recognise these characteristics from the seafloor reflection down to a regional high amplitude horizon (X) located at 5.5 s (two-way time) from the sea surface below the crest of Mound 4 in Fig. 10, which should appear sub-horizontal in a depth section. Horizon X thus divides the sediment sequence below the mounds into two parts. Below horizon X (about one third of the sequence) reflections have low amplitude and are mostly continuous and sub-parallel, thus denoting a lower energy of sediment deposition. Above horizon X we interpret the sedimentary sequence as a sediment drift that has progressively migrated from the southwest to the northeast in profile IT92-109 of Fig. 10. The mounds appear to be built by progressive downlapping on both sides. On the side that develops as the steeper and more irregular one, the occurrence of sediment waves of about 3 km wavelength suggests upslope migration of sediment, under the action of strong bottom-currents, and aggradation on the crest of the mound. On the gentler side (NE) reflector downlap creates a divergent pattern towards the crest. After the mound attains a markedly asymmetric shape, the crest appears to drift to the northeast with deposition of sub-parallel sedimentary layers on the gentler side, and with erosion or non deposition on the steeper side. The distributary system that transfers sediments from the shelf and slope to the oceanic basin by turbidity currents and local slope instability phenomena produces the channels and gullies observed on the steeper sides. The morphologic gap between the mounds and the continental slope that coincides with lateral termination of reflectors of the mounds themselves (erosion and/or non-deposition) is further evidence of bottom currents along the margin.

A high amplitude reflector, corresponding to an abrupt change in acoustic impedance, is evident in most of the profiles. The reflector occurs at a nearly constant depth of 700-800 ms (two-way time) below the seafloor, sometimes crosses other reflectors of different dip, such as between shot points 2900 and 3300 of profile IT92-106 depicted in Fig. 9, and separates a more transparent seismic sequence (below) from a reflective sequence (above). By analogy with the high-amplitude reflector recognised at 500-800 ms (two-way time) below seafloor on the South Orkney Microcontinent margin (Lonsdale, 1990), we propose to interpret this reflector as a bottom-simulating reflector, possibly produced by a silica diagenetic front.

DISCUSSION

Correlation and significance of seismic sequences on continental shelf and slope

We correlated the seismic sequences described on the continental shelf and slope of the Antarctic Peninsula Pacific Margin with those already identified by Larter and Barker (1989, 1991b). Within the ANTOSTRAT program, the Osservatorio Geofisico Sperimentale (OGS) and the British Antarctic Survey (BAS) exchanged parts of their seismic data sets. The two institutes employed digital recording systems with comparable characteristics and similar acquisition parameters.

Intersections of profiles from the two surveys provide direct correlation in the northernmost part of the margin (between the North and South Anvers Fracture Zones). Four profiles allow direct correlation in the area of Deep Sea Drilling Project Site 325 (north of the Adelaide Fracture

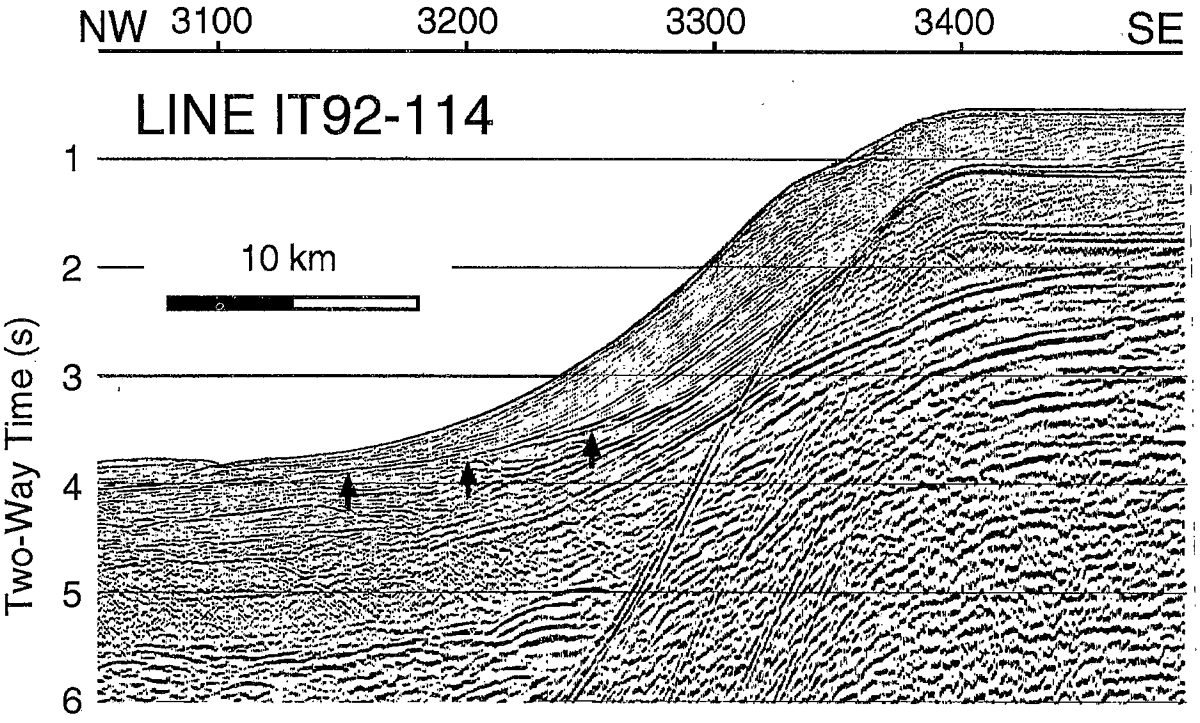

Fig. 8 — Stack version of part of line IT89-114. Location in Fig. 3. The outermost part of the continental shelf and slope is shown. Arrows indicate a prominent downlap unconformity present at the base of the continental slope as shallow as 200 ms below the sea bottom.

Zone). Strike profiles of the Osservatorio Geofisico Sperimentale survey generally allowed extrapolation to the southwest.

Identification of sequences where direct correlation is possible is straightforward. In particular, the interpretation of profile IT92-110 (Figs. 6 and 7) matches profile AMG878-19 (collected by the British Antarctic Survey), located slightly to the northeast.

According to the proposed interpretation, the upper boundary of sequence (4), probably the most prominent unconformity on the margin, is an "uplift" unconformity caused either by erosion or by a long period of sediment starvation following a thermal uplift of the continental margin, due to ridge crest-trench collision at each crustal segment. Thermal uplift, predicted by theoretical models and supported by thermal metamorphic rocks found on-shore on the continuation of the Mid-Shelf High (Smith Island, Larter and Barker 1991b), caused the formation of the mid-shelf structural high. The uplift of the Mid-Shelf High created a barrier to the sediment flow from land to sea that caused the renewed deposition in a probably pre-existing fore-arc basin (Mid-Shelf Basin), which rests on the inner side of the Mid-Shelf High.

The prograding sediment wedge formed by sequences (1), (2), and (3) would have started to grow with the first sediment by-passing of the Mid-Shelf High. Glacial/interglacial cycles controlled the sedimentary regime responsible for the deposition of Sequences (1) and (2). Repeated advances and retreats of grounded ice-sheets caused rapid progradation of the shelf-break and steepening of the continental slope. Subsequent ice-sheet advances eroded the upper part of the foresets, while interglacial periods produced the topset layers. Sequence (3) does not show shelf progradation and steepening of the slope. For this reason, a pre-glacial regime rather than glacial-interglacial cyclicity is more likely appropriate to explain its origin.

This general reconstruction of events originates mainly from seismic sequence interpretation of profile IT92-110, which lies between the Biscoe and Adelaide fracture zones, where correlation with Deep Sea Drilling Project Site 325 is available. Two events evidently control the sedimentary regime on the Antarctic Peninsula Pacific Margin: 1) The onset of glaciation and alternations

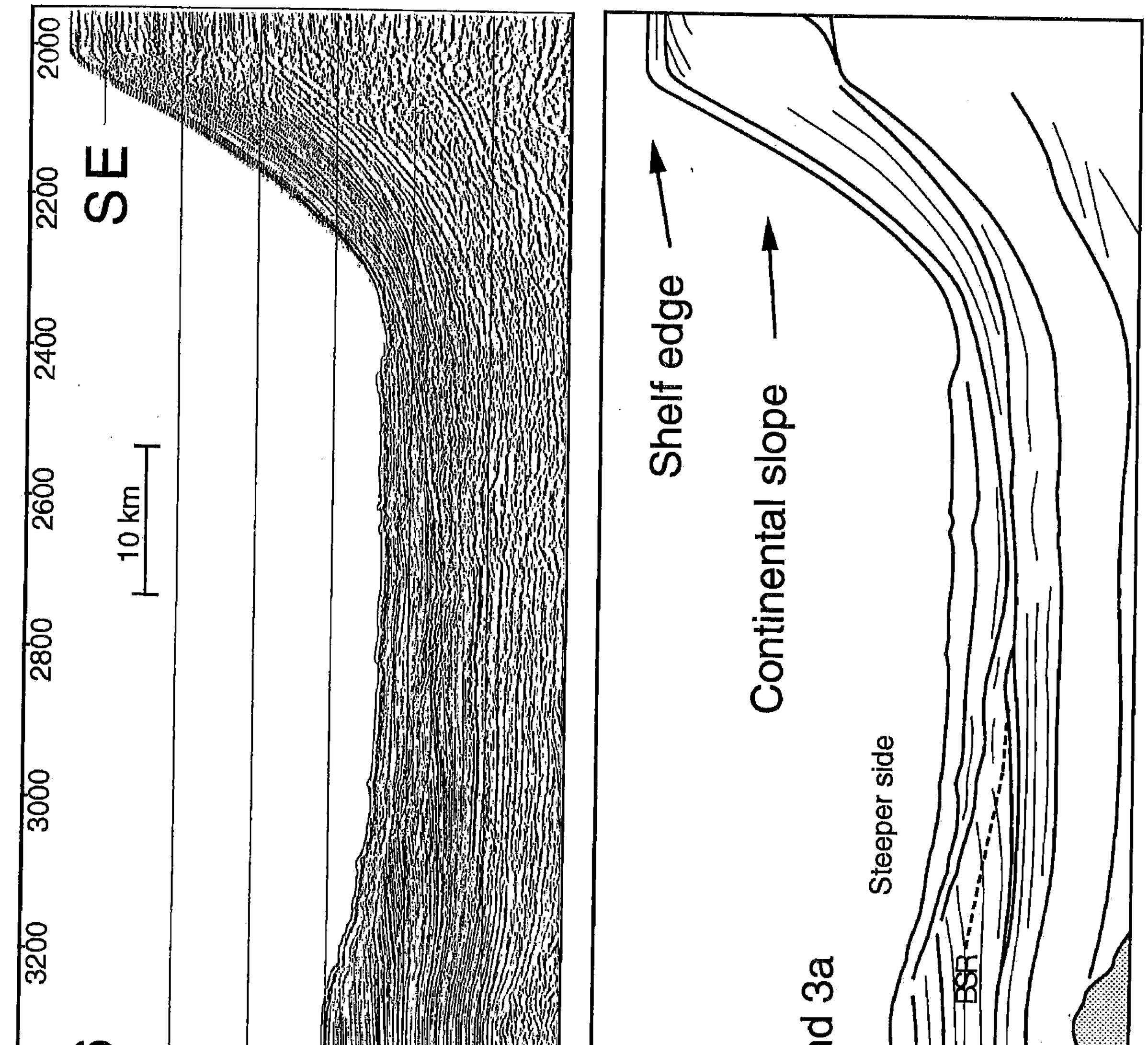

Fig. 9 — Migrated version and interpretation of part of line IT92-106. Location in Fig. 3. Mound 3a, one of the 5 asymmetric mounds identified, is shown. The Bottom Simulating Reflector (BSR) crossing the other reflectors at a nearly constant depth of 7-800 ms (two-way time) is marked with a dotted line.

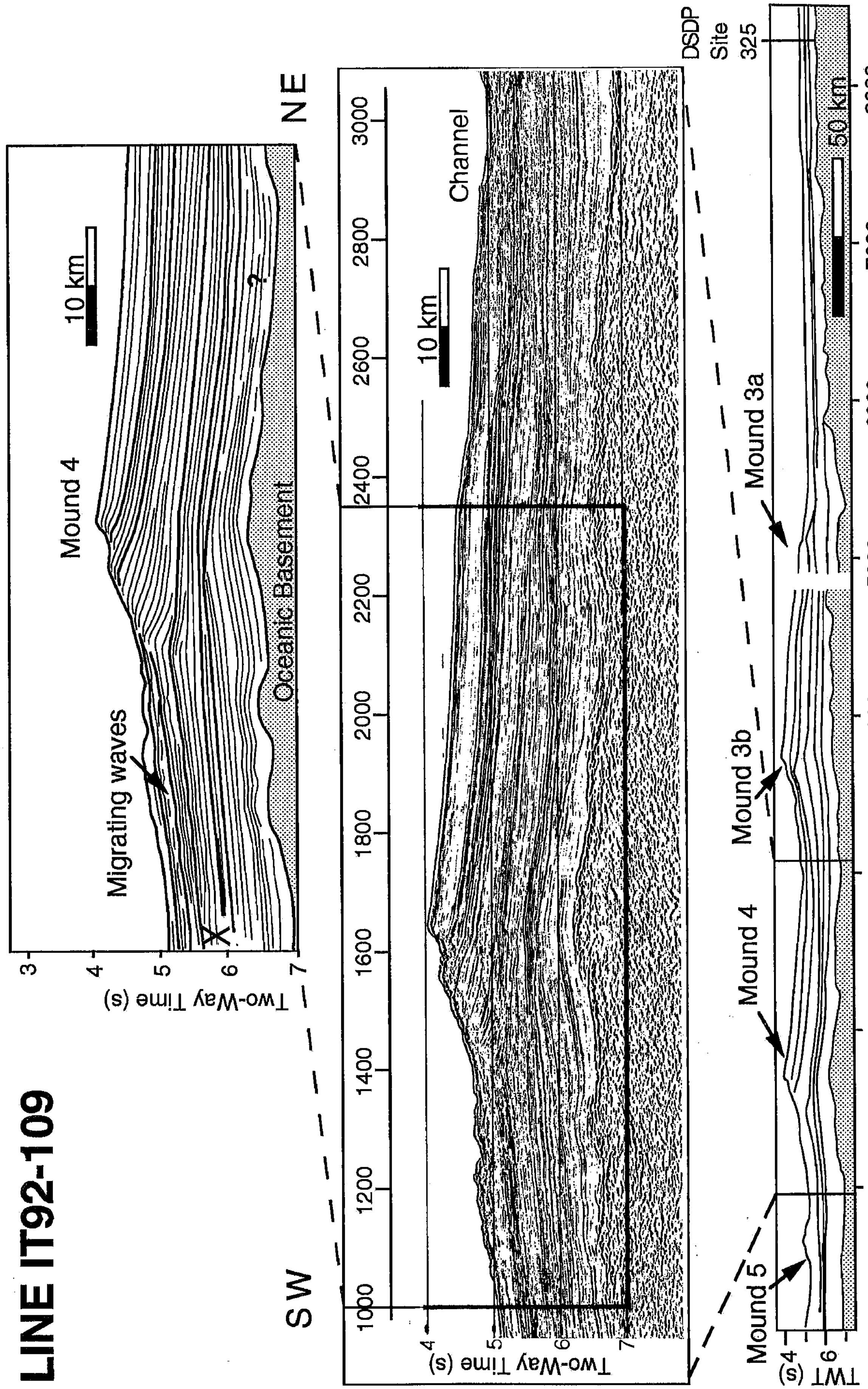

Fig. 10 — Migrated version of part of line IT92-109. Its position within the entire line is indicated in a schematic line drawing in the lower part of the figure. A detailed line drawing of the internal characteristics of Mound 4 is shown in the upper part of the figure. Horizon (X) marks the onset of developement of sediment drift.

of glacial-interglacial periods, expected to be synchronous on the margin. 2) Ridge crest-trench collision, and subsequent thermal uplift of the fore-arc, which is diachronous on the margin. For this reason we should not expect a close correlation between sequences across fracture zones. In our data set, we have noted that the downlap surface at the base of the continental slope is present at different depths in the sediment column. It appears shallower in the northeastern part of the margin. This could be evidence of time-progressive tectonic control on sedimentation.

Deep Sea Drilling Project Site 325 (Hollister, Craddok et al., 1976) aids interpretation of this part of the margin's sedimentary history. The site lies on the continental rise between the Biscoe and Adelaide fracture zones. Penetration of Oligocene to Early Miocene age sediments reached 718 m below the seafloor.

Turbiditic and ice-rafted terrigenous sediments are the essential components of the recovered sequence. The curve of the accumulation rate reveals a hiatus, or starvation period, between 15 and 8 Ma (Tucholke et al., 1976). This Middle Miocene event may correspond to changes in deep-water circulation or reduction in the terrigenous sediment supply. Larter and Barker (1991b) correlated this event with the "uplift" unconformity found on the margin to mark the upper boundary of sequence (4).

Bottom-current-controlled sedimentation on the continental rise

Supporting evidence for sediment drifts.

Sediment drifts are a common feature in the deep oceanic basins and continental rises. At least a dozen drifts are present in the North Atlantic Ocean (McCave and Tucholke, 1986; Stow and Holbrook, 1984). Their characterisations both in terms of seismic reflection (Pickering et al., 1989) and sedimentation (Kidd and Hill, 1986) are fairly well known, although the variability of geometry, internal structure and lithology can be considered itself a diagnostic character.

According to Johnson and Schneider (1969), sediment (or contourite) drifts are "large sedimentary bodies with lengths of up to hundreds of kilometres, widths of tens of kilometres, and reliefs of 200-2000 m".

McCave and Tucholke (1986) define the large scale characteristics of sediment drifts thus:

- surface and internal reflectors do not conform to deeper surfaces;
- thickness exceeds that of adjacent sedimentary cover;
- bedding thickens at the drift axis and thins either at both drift margins or on one side of the drift where the bottom-current flow is fastest;
- internal reflectors are often very weak, especially if the drift contains only fine-grained sediments deposited far from the source area;
- mud waves and/or undulating reflectors that indicate the earlier development of mud waves commonly mantle the drifts (Faugères and Stow, 1993).

Marked erosional surfaces are also very characteristic of contourite drift deposits, and may supply prominent internal reflectors (Faugères and Stow, 1993). Tucholke and Mountain (1986) related erosional surfaces to bottom-current activity or main hydrologic events, such as the growth of the Antarctic ice and ice-sheet formation. The detailed acoustic character generally depends on the seismic investigation parameters, the grain size, and the sedimentary structures. Transparency or absence of structures is a frequent characteristic because of fine-grained, homogeneous sediments. Variations of sediment grain size caused by changes in bottom-current velocity can produce high amplitude reflections (Faugères and Stow, 1993). Both acoustically transparent and well-laminated sediment drifts have been widely described in oceanic basins (Scrutton and Stow, 1984).

The peculiar geostrophic oceanographic conditions of the Southern Ocean are favourable to strong bottom-currents. Hollister (1993) identified the interaction between strong surface circulation, eddy fields, and low frequency variability in the watermass as the cause of benthic storms. The sea-surface variability map obtained from Seasat data (Cheney et al., 1983) shows high variability off the Antarctic Peninsula Pacific Margin. Faugères et al. (1993) identified the seafloor topographic control (steep slope of a continental margin) and the availability of biogenic and terrigenous sediment (highly productive passive margin) as factors controlling contourite accumulation. We identified in the surveyed area of the Antarctic Peninsula Pacific Margin all the above mentioned characteristics of sediment drifts and the boundary conditions for the formation of strong bottom water currents.

The strongest evidence for bottom-current influence on the sedimentation on the continental rise comes from the sediments of the Antarctic Peninsula Pacific Margin themselves. Direct evidence of the action of bottom-currents on sediments (contourites) is present in the sediment cores of Sites 322, 323, 324, and 325 of Deep Sea Drilling Project Leg 35 (Hollister, Craddock et al., 1976) in the Bellingshausen Basin (Southwest Pacific Ocean). Well-sorted quartz-silt and sandy-silt layers with sharp upper and lower boundaries and lack of internal sedimentary structures beside faint lamination, occur in the sediments recovered from the lower continental rise and abyssal plain (Tucholke et al., 1976). The contourites have been correlated to the flow of the Antarctic Circumpolar Current, which reaches the seafloor in this region. Ewing et al. (1969) have noted reduction in sediment thickness in this area, due to the erosion or non-deposition caused by the Antarctic Circumpolar Current. Because turbiditic sedimentation is common in this area, turbidity currents are probably the main source for terrigenous sediment. Bottom currents then "pirate" the sediment put into suspension in the nepheloid layer and re-distribute it in the form of contourites.

Seismic reflection profiles collected by institutes other than the Osservatorio Geofisico Sperimentale show evidence also for bottom-current influence on sedimentation. On the continental rise of the Antarctic Peninsula Pacific Margin, large abyssal sediment-waves occur in the Challenger profile 35 of the Deep Sea Drilling Project Leg 35 (Tucholke and Houtz, 1976; Tucholke, 1977). They are on the continental rise northeast of Site 325, in a position close to Mound 1. Sediment dunes, with identification of the contour current direction have been outlined several tens of km from the basinward prosecution of Mound 3 and near Site 324, Leg 35 (see fold-out A in Hollister, Craddock et al., 1976), in close association with deep-sea-fan acoustic facies. Larter and Cunningham (1993) analysed the British Antarctic Survey seismic data-set, located to the northeast of the Deep Sea Drilling Project Site 325. They took into consideration the action of bottom-currents as a paleo-oceanographic factor affecting sedimentation on the Antarctic Peninsula Pacific Margin. However, they placed the emphasis of their interpretation on the continental margin sedimentary regime, and thus on the action of turbidity currents.

Outline of deep-water circulation.

The Southern Ocean has long been known for its intense and complicated pattern of oceanic circulation, since there are no major latitudinal physical barriers to watermass movements. At the surface, there is a zone of convergence called the Antarctic Polar Front Zone permanently between 60°S in the Pacific Ocean and 50°S in the Indian and Atlantic oceans. Elevated instability, with formation of current jets, meanders, and cold (cyclonic) eddies characterise this zone (Pickard and Emery, 1982). Inward from the Antarctic Polar Front Zone, very close to the Antarctic coast, the surface circulation is in a westward direction (East Wind Drift). Further north, up to the 40°S parallel, the Antarctic Circumpolar Current (ACC), or West Wind Drift, flows in an eastward direction. The Antarctic Circumpolar Current is generally a slow current (about 4 cm/s) with increasing velocity at the Antarctic Polar Front Zone (up to 100 cm/s have been measured in jet currents) and in the narrow Drake Passage. It is worth noting that the Antarctic Circumpolar Current is very deep (down to 3,000 m). The transport is thus 110 Sverdrup on average (Pickard and Emery, 1982).

Antarctic Bottom Waters originate mainly in the Weddell and Ross seas (Gordon, 1966). They flow northwards and eastwards to spread into the adjacent oceans, but the pattern of deep and bottom water circulation still lacks detail.

80% of the Antarctic Bottom Water forms in the Weddell Sea. There the constraints are enough to define the circulation pattern rather well. Foldvik and Gammelsrφd (1988) reported velocities at the bottom as high as 100 cm/s, due to the meandering outflow of cold and dense ice-shelf water. Heezen and Hollister (1968), based on the evidence of ripple marks from bottom photographs, postulated velocities as high as 50 cm/s in the Drake Passage.

In this area of the Antarctic Peninsula Pacific Margin, there are very few studies on bottom circulation. A branch of the Antarctic Bottom Water formed in the Weddell Sea is believed to flow westwards along the continental rise of the Antarctic Peninsula Pacific Margin (Hollister and Elder, 1969; Nowlin and Zenk, 1988). On the other hand, a tongue of Ross Sea cold water flows to the east reaching 105°W (Bellingshausen Basin) and then weakens and turns northwards (Gordon, 1966), probably right in the area where we identified the mounds. A loop of strong bottom-currents coming from the southwest Pacific Basin bounds this tongue. Although commonly "sluggish conditions" define bottom water circulation in the southwest Pacific Basin, there are not many station points in the area to reach definitive conclusions.

Alternative hypothesis.

Larter and Cunningham (1993) noted a distinct upward facies change in the sediments of the Antarctic Peninsula continental rise, which appears to correlate with the onset of glacial progradation on the shelf. They proposed that this transition corresponds to a sedimentation dominated by margin-derived turbidites. Therefore we can expect the existence of deep-sea fans. Both sediment drifts and deep-sea fans are deep-water sedimentary deposits with a mounded shape in transverse section occurring along continental margins. According to Mitchum (1985), we can use the following diagnostic criteria to distinguish sediment drifts from deep sea fans: internal reflections are very continous even in longitudinal section; mounds are internally asymmetric, with a long gentle and a short steep flank; mounds are larger than most fans; the elongate map shape of the mounds is at least 1 to 3; mounds are physically isolated from continental sources of coarse sediment.

The above characteristics are all present in the mounds identified on the continental rise of the Antarctic Peninsula Pacific Margin, leading the authors to prefer the sediment drift hypothesis rather than the other obvious explanation by deep-sea fans:

1) The lateral continuity of the internal reflectors is notable both in Figs. 9 and 10.

2) The mounds are always asymmetric. The largest ones (3 and 4) have a long gentle northeastern flank and a short steep southwestern flank. This geometry is the reverse of that expected in the case of turbidites flowing down the continental slope and deflected leftwards by the Coriolis force. In the case of Coriolis-force-controlled levees of turbidites, the expected geometry would be a rough steep northeastern slope and a southwestern gentler slope produced by overbank deposition.

3) The elevations above the surrounding seafloor of the larger of these bodies (about 1 km) are impressive. Turbidites are unlikely to climb upslope for 1 km in elevation to reach the top of the mounds.

4) In map view, the shape of mound 3 (the largest and best defined on the gravity field of McAdoo and Marks, 1992) seems very sinuously elongated in a direction approximately orthogonal to the margin. Lateral physical barriers, like basement ridges or hardrock escarpments, do not appear to constrain such a shape. This is not the characteristic shape of a deep-sea fan.

5) A sedimentary gap corresponding to a seafloor depression separates the mounds from the continental slope. No evidence of a canyon is present on the continental slope. Turbidite channels, relatively small compared to the sedimentary bodies, occur only in the deep areas between the mounds (Fig. 10).

CONCLUSIONS

The vessel OGS/Explora collected 17 multichannel seismic reflection profiles on the Antarctic Peninsula Pacific Margin south of the Hero Fracture Zone. The Osservatorio Geofisico Sperimentale undertook this survey between 1990 and 1992 with two cruises within the Programma Nazionale di Ricerche in Antartide (PNRA). Interpretation of the fully processed data set (stack versions and two migrations) has allowed us to outline the main characteristics of this margin.

We identify three provinces in agreement with previous studies in adjacent areas:

1) On the continental shelf, a sedimentary basin and a structural high correspond respectively to the Mid-Shelf Basin (MSB) and the Mid-Shelf High (MSH) of Larter and Barker (1991b).

2) On the outer shelf and slope, we identified a prograding wedge of sediment downlapping towards the continental rise. Four seismic sequences correspond, where direct correlation is possible, to those described in the northeastern part of the margin by Larter and Barker (1989). The upper two sequences bear characteristics suggesting deposition under a glacial/interglacial sedimentary regime (rapidly prograding shelf-edge, steep continental slope, foresets eroded at the top and overlain by topsets). The lowest sedimentary sequence of the prograding wedge is present mainly on the continental shelf. Its deposition may have occurred before, or during, the onset of glaciation. The downlapping surface appears to be shallower in the sedimentary section of the northeastern profiles, located where ridge crest-trench collision is younger.

3) On the continental rise, two main areas of large sedimentary bodies more than 1 km in elevation above the surrounding seafloor, tens of km wide, and more than 150 km long have been identified.

Results from the preliminary interpretation of the profiles collected by the Osservatorio Geofisico Sperimentale allow us to identify two points of interest within the thematic objectives of the ANTOSTRAT program.

1) Two factors control the sedimentary regime of the Antarctic Peninsula Pacific Margin: glacial and tectonic processes. We expect the former to be synchronous on the margin, while the latter are diachronous. The downlap surfaces in different parts of the Antarctic Peninsula Pacific Margin have different depths in the sedimentary column of the continental slope. We present this fact as evidence of time-progressive tectonic control on sedimentation.

2) The presence of the large sedimentary bodies on the continental rise is one of the most relevant features for better understanding the sedimentation history of the Antarctic Peninsula Pacific Margin. The external shape and the internal characteristics of the mounds of the Antarctic Peninsula Pacific Margin show evidence of bottom-current control on the depositional processes on the continental rise. We interpret the sedimentary sequences below these bodies down to a regional high amplitude relfector (X) as sediment drifts. Supporting evidence of bottom-current activity comes from seismic profiles and samplings from the Deep Sea Drilling Project Leg 35 in the Bellingshausen Basin.

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