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SEA BOTTOM MORPHOLOGIES OF THE ROSS SEA AREA (ANTARCTICA)

Abstract. During the 1987-88, 1988-89, 1989-90 and 1990-91 Austral summers, multichannel seismic reflection, gravity and magnetic surveys in the Ross Sea were recorded and then processed by the Osservatorio Geofisico Sperimentale (OGS) of Trieste. Some of the most evident morphological features of the sea bottom in the Ross Sea and their spatial distribution are identified and investigated in this paper, together with an analysis of the general glacial, morphological and sedimentary patterns of the area. Data collected by other investigators using sparkers, side-scan sonars and sub-bottom profilers are also considered. The classification of the features is based on an assemblage of morphogenetically related elements and their geometric relationships.

INTRODUCTION

The Ross Sea is bordered by Victoria Land to the east and Marie Byrd to the west; southward the Ross Sea is limited by the Ross Ice Shelf and northward by the Ross slope.

From the geophysical point of view, the Ross Sea is one of the most interesting objectives in Antarctic explorations, both for the relatively good operating conditions and for its key position between East and West Antarctic.

Many geophysical surveys have been carried out in the Ross Sea in the past; the U.S.G.S. (United State Geological Survey), B.G. R. (Bundesanstalt fur Geowissenschaften und Rohstoffe), I.F.P. (Istitut Francais du Petrole), M.A.G.E. (Marine Artic Geological Expedition), in particular have performed multichannel seismic surveys (see Hinz and Kristoffersen, 1987).

During the O.G.S. geophysical surveys, multichannel seismic, gravity and magnetic data were collected along sixty profiles totalling more than 9640 km.

The location map of the seismic lines is given in Fig 1.

Direct information about the geology of the area comes from surface surveys and from wells, both onshore and offshore: DSDP, MSSTS, CIROS and DVDP.

MAIN GLACIAL FEATURES OF THE ROSS SEA AREA

The continental shelf of the Ross Sea and adjacent lands shows clear evidence of glacial modelling. As is known, the Ross ice sheet and the glaciers in the Transantarctic Mountains

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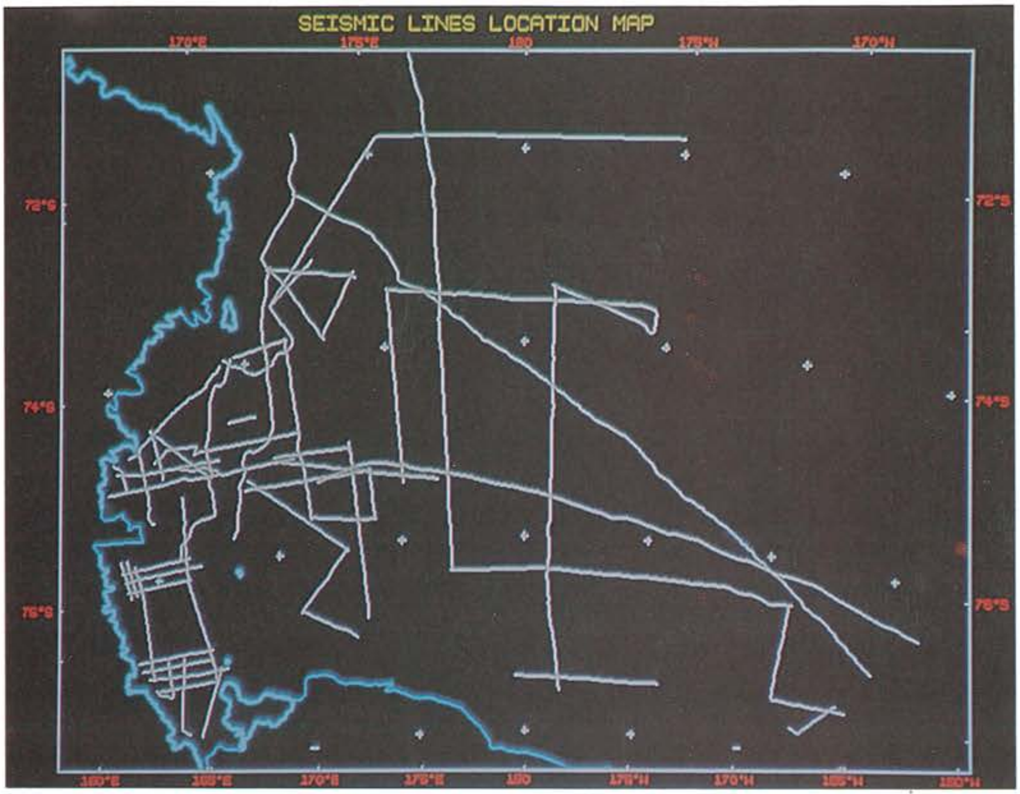

Fig. 1 - Seismic Lines Location Map.

Fig. 2 - Priestley Outlet Glacier. The troughs occupied by this kind of glaciers are typical "fiords" stretching over the continental platform.

Fig. 3 - Boomerang Glacier, Terra Nova Bay. The Alpine morphology developed in the area between the main valleys and characterized by cirques crests and horns.

extended in the past down to the bottom of the present Ross Sea. Scott (1905) supposed that, during the phases of maximum glacial extension, an ice sheet stretched up to the edge of the continental shelf.

Stuiver et al. (1981) proposed an ice sheet model based on these assumptions and supported by a number of data. This model has since been modified by Denton et al. (1989).

In Northern Victoria Land the Transantarctic Mountains are characterized by an Alpine type morphology, with branched glaciers, cirques and peaks. South of the Priestley Glacier (Fig. 2), the Transantarctic Mountains are crossed by outlet glaciers fed by the East Antarctic Ice Sheet.

The main geomorphologic features of the region are quite old and go back at least to the Miocene. In particular, the following main morphologic types can be separated out:

1) **Glacial troughs**. These are wide and extended valleys, of glacial origin, which, in the down stream sections form typical "fiords". These features are among the oldest, and were modelled, at least partly, in Miocene time.

2) **Alpine morphology** developed in the areas between the main valleys and characterized by cirques, crests and horns (Fig. 3).

3) **Residual ancient morphology**. These are residual features not yet effaced by the progressing morphology. They are tabular reliefs ("Mesas") whose edges are dented by the glacial cirques giving a typical nibbled aspect. Their upper part consists of subhorizontal layers of the Beacon Supergroup (Permian-Triassic), of the Ferrar Dolerite (Jurassic) or of exhumed Kukri Peneplain modelling the underlying crystalline rocks of Paleozoic age.

4) **Coastal reliefs**. The rounded reliefs of the coastal area can also be considered as residual morphologic features of glacial origin, later cut at their edges by typical cirque erosion

Fig. 4 - Northern Foothills. The roundish reliefs are residual morphologic features of glacial origin, later cut by typical cirque erosion forms and by tectonic deformation.

forms. These surfaces are cut by tectonic deformations (Fig. 4).

In Victoria Land, traces of drifts related to several glaciations, at least as old as Mio-Pliocene can be seen. The last Quaternary glaciation (Late Wisconsinian) is well known while information about previous glaciations remains scarce and confined to limited areas.

The last glacial maximum (LGM) is evidenced by glacial drifts correlatable from the Beardmore Glacier to Terra Nova Bay (Orombelli et al., 1992). They consist of coarse glacial till, of modest thickness, little- or unaltered, with striated pebbles, perched stones and ice-covered moraines. The erosive activity of the Antarctic glaciers, in both this phase and the previous ones, has been modest on the whole, as proven by the preservation of ancient alteration forms in the area crossed by the glaciers. During the LGM, in the eastern sector of the Ross Sea the outlet glaciers and the platforms gradually thickned, reaching, at Terra Nova, an elevation of about 400 m above present sea level, with a notable advance of the ground line and the development of a marine-based ice sheet, whose configuration and extension still remains an open question. The evidence so far shows that the Ross ice sheet had to advance northward, incorporating the minor glaciers of Victoria Land. A similar model is valid also for the Quaternary glaciations. On the basis of recent investigations of marine geology (Reid, 1989), the grounding line should have extended, during the LGM, up to the north of Coulman Island. Beyond this zone, in fact, organisms collected in the marine sediments show an age of about 18,000 yr ago (C14), and so are contemporaneous with the IGM.

MAIN SEDIMENTARY FEATURES OF THE ROSS SEA AREA

The Antarctic continental margin must be considered a unique sedimentary environment because terrigenous sediment deposition is due almost entirely to ice activity.

Glacial sedimentation probably occurs over relatively short intervals of geologic time and is followed by long periods of extensive reworking and redeposition of sediments by normal marine agents; this reworking of glacial marine deposits is largely controlled by the position of the floating ice shelf and perennial ice-pack front which affects shelf circulation.

Sediment cores collected on the continental shelves of the Ross Sea consist primarily of diamictons (unstratified, unsorted, clastic debris consisting of sand and larger particles in a muddy matrix). These sediments are dark gray or black, generally devoid of fossils, with low water content and are typically overcompacted.

These sediments, consisting primarily of basal tills (Anderson et al., 1980), are not reworked by bottom currents and this is supported by the fact that they are unsorted, unstratified and generally devoid of fossils, suggesting a rapid deposition directly from ice; moreover they appear to be confined to those continental shelves which adjoin large ice shelves; for them, Harland et al. (1966) used the term "orthotills".

Orthotills are presently exposed on the seas floor in a few scattered locations only, and may represent eroded, or non-depositional, surfaces.

For the sediments reworked by marine currents (Circumpolar Deep Water, contour currents, thermoaline currents) Harland et al. (1966) used the term "paratills", classifying as "compound paratills" those enriched in current-derived silt and clay, and as "residual paratills" those which had their muddy matrix depleted of their silt-clay content.

The paratills are distinguishable from orthotills because benthic foraminifera are present in the former and an incipient stratification is characteristic of the compound paratills. A well developed horizontal parallelism of elongated pebbles is also present in the compound paratills.

The concentration of ice-rafted debris (IRD) in Antarctic marine sediments (Anderson et al., 1980) decreases abruptly beyond the shelf break, and continental rise deposits are frequently devoid of IRD. This is because the vast majority of sediments rafted out to sea by ice shelves are carried to, or near the ice-rock interface. This material is deposited during basal melting seaward of, but near to, the buoyancy line (Boulton, 1972), and this buoyancy line should, in a normal floating ice shelf, be located well inland of the calving line. Tabular bergs calved from large floating ice shelves contain therefore only a lesser amount of debris, probably mainly concentrated within shear zones. The quantity of material transported in this manner is controlled by complex and poorly understood ice-sheet processes.

Icebergs calved from valleys and piedmont glaciers are capable of transporting large quantities of sediments (Ovenshine, 1970), and the rate of supply of glacial sediments by this agent is probably greater than by large ice shelves. Hence, it is possible that a larger quantity of IRD is transported to the deep sea floor during glacial minima, when valley and piedmont glaciers play a greater role in supplying sediments to the sea.

Redeposition of glacial sediments by bottom currents, slumping, mass flow, debris flow, grain flow and turbidite mechanisms is actively occurring today over much of the West Antarctic continental margin. As expected, there is a strong correlation between the duration of seasonal ice production, which controls shelf circulation, and the degree of resedimentation by bottom currents.

Mass flow deposits are probably widespread over the Antarctic continental slope and rise, and in depressions of the continental shelf. Debris flow deposits are most prevalent on those continental slopes where muddy sediments mantle the adjacent shelf.

In contrast, turbidites, and probably grain flow deposits, are more common on those parts of the continental slope and rise where continental shelf sediments are winnowed by bottom currents. In any case, debris flows are apparently the most active mechanisms in these areas.

The erosional activity of the ice sheets during their fluctuations in advance and retreats over the continental shelf caused the asportation of large quantities of sediments, contributing to the overdeepening of the shelf itself. The record of the erosional activities is also present in the seismic sections as unconformities. One of these especially - known as the Ross Sea Unconformity (RSU) - characterizes the shallowest part of the sedimentary sequences.

This discontinuity, usually lying between 2 and 40 metres below the sea floor, is most likely due to an abrasion of several hundred metres of sediments. The RSU is underlain by a scarcely stratified diamictite level, which is interpreted as a basal till, and it is covered with a thin layer of Holocene sediments, largely formed by ice-rafted clasts, and composed of sand and clay with associated biogenic silica.

The RSU is assumed to belong to the Pliocene or Pleistocene, even if there are large margins of uncertainty about its age.

Seismic and sedimentological evidence seems to favour the hypothesis that the RSU is due to the erosion of the ice over the sea floor during the first advance of the ice sheet in West Antarctica. The basal till was therefore formed by erosional phenomena when the ice sheet was still in direct contact with the sea floor. The glacio-marine and pelagic sediments overlying this till were deposited after the ice retreated.

Alley et al. (1989) refer this erosional event to the maximum advance of the West Antarctic ice sheet during the Wisconsin, when the ice reached the Ross shelf edge; this phenomenon is paralleled by a sea level lowering long enough to allow the ice sheet to reach the edge; Drewry (1979) estimates this lowering to be possibly of the order of dozens of metres.

MAIN MORPHOLOGICAL FEATURES OF THE ROSS SEA AREA

Most of the morphology of the Ross Sea is due to the depositional and erosional phenomena related to the advance and retreats of the ice shelf.

Ross Sea bathymetry does not show any strict relation to the structural elements of the basement, as evidenced by the seismic lines. The average water depth - over 400 metres -of the shelf, is much higher than others around the world (about 200 meters or slightly more), which has been explained to be due to the load of the ice sheet, which is some thousand metres thick.

The Antarctic continental margin is engraved into a large sedimentary sequence, reaching in some areas (Victoria Land Basin) the thickness of 10-14 kilometers. The upper part consists of glacio-marine Cenozoic sequences prograding toward the shelf edge.

The wells drilled in the Ross Sea (refer to sites DSDP and CIROS) only reached the Oligocene, and therefore we lack direct information on the older formations.

These prograding sequences are well evidenced by an analysis of the seismic lines, especially in the eastern part of the Ross Sea, and the evolution seems to be strictly due to the fluctuation of the ice and thus to the sea level variations over the shelf. Therefore they outline the history of the glacial evolution, starting from the late Eocene (40 My ago), when the Ross ice shelf appeared for the first time, as is shown by offshore samplings.

The whole Antarctic continental shelf displays glacial activity; off Wilkes Land for example - on the continental margin - side scan sonar (SSS) image (Eittreim and Smith, 1987) show bottom scars engraved by large, tabular icebergs, in water depths exceeding 500 metres. These scars consist of parallel grooves a few metres deep and up to some dozens of metres wide. Similar SSS imagery has been reported by Stefanon (1989) for the puzzling, possible presence of outcropping metamorphites off Cape Russel. The SSS imagery (Fig. 5) could easily be due to the presence of metamorphites, like the ones outcropping on the nearest land, in the M. Abbott area (Fig. 6). This imagery is hardly referable to floating iceberg scouring, due to the excessive parallelism of all the "tracks". Furthermore, the SSS record suggests a very hard bottom, and no loose sediment cover. The strong relief exhibited by the surface could be due to selective icesheet abrasion during a sea level low stand.

The shelf plain facing the Pennel Coast shows evidence of glacial activity as well; in this area, the plain has a mean depth of about 250 meters, and is deeply cut by canyons trending to the north (Anderson et al., 1980). Each canyon corresponds to the progression into the sea of the larger glacial valleys, some of them deeper than 1,000 metres, and showing a certain flattening where they cross the continental excarpment (the shelf break?). Northward of Cape

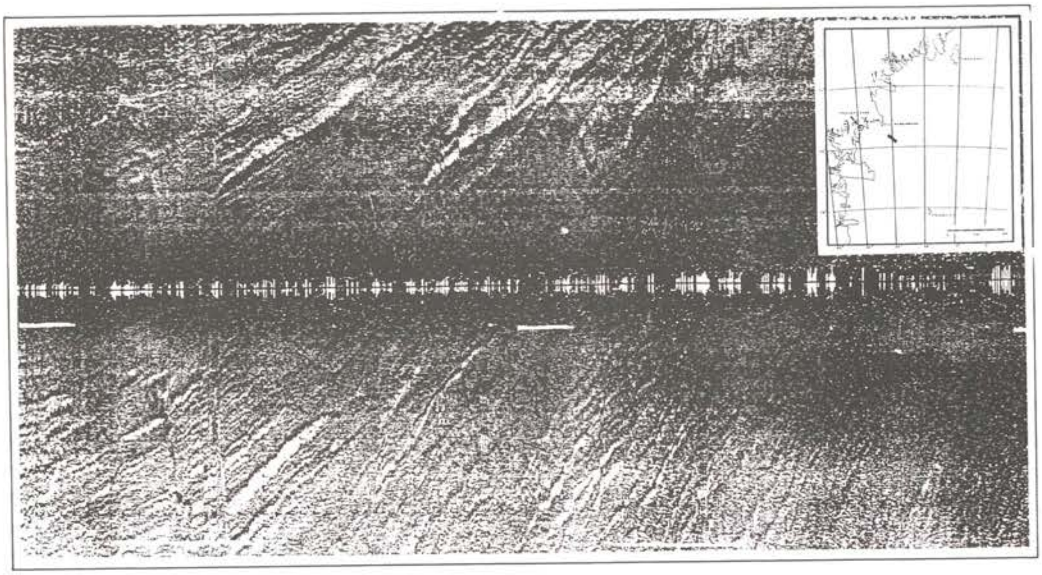

Fig. 5 - The SSS imagery (Terra Nova Bay). Sloping signals are interpreted as due to metamorphites, as confirmed by those outcropping on the nearby land. The image covers an area of 1.100x1.800 m, at about 600 m depth.

Fig. 6 - Metamorphite outcrops in the M. Abbott area.

Adare the bathymetry is rather rough, with several NW-SE oriented depressions. Terra Nova and its surroundings is characterized instead by NW-SE oriented bottom features, which reach the area below the Drygalski Ice Tongue, and proceed almost parallel to the coast (NNW-SSE oriented) toward Ross Island. The area from Cape Washington and Cape Russel is extremely rough in its northern part, showing at least two main (but faint) orientations of the features:

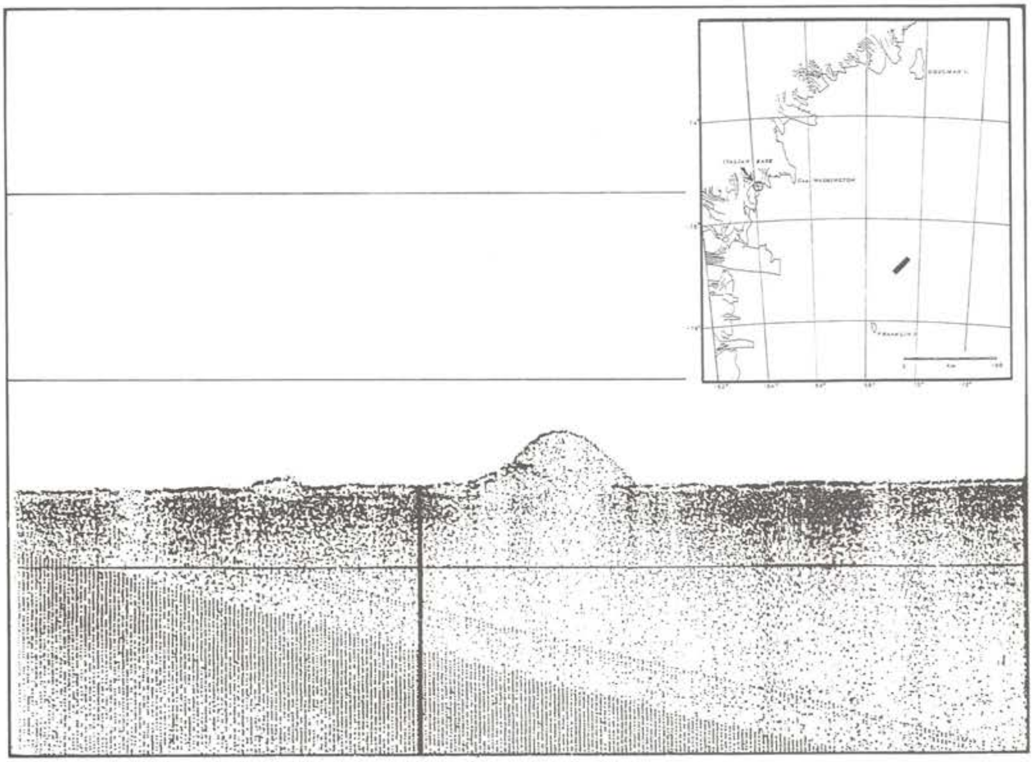

Fig. 7 - Example of "Buiaces", rare small mounds up to a few metres high.

N-S and NE-SW. The Southern part is smoother, and gently dips into the Drygalski basin. The latter feature separates the offshore continental shelf (very flat and sometimes smooth), covered with a very thin layer of recent sediments, from the rough area closer to the shore, where no recent sediment cover seems to be present.

TRANSPARENT SEDIMENTS

The layer of fine and very transparent sediments (a few decimeters thick) described by Stefanon (1989) is rather hard to explain. It locally inflates (Fig. 7) to form rare small mounds - up to a few metres high - named "buiaces", which may be rolled up into dentate profiles (Fig. 8). These sediments are a mixture of plankton skeletons and rock debris (Merlin et al., 1991; Lenardon, 1989) and cover a rather large area just east off the Drygalski basin. Another very peculiar feature is the great eveness both of the hard substratum and the cover; at least in one area both can be followed for over 30 km with a thickness (of the cover) within 10-20 cm and a water depth variation within a couple of meters (Fig. 9).

Apart from the "organic fraction", no simple explanation can be given for the presence of such sediments in the middle of the Ross Sea only, and not - as far as we have seen - close to the shore. The presence of rather strong density currents has been reported close to the shore (Anderson et al., 1983a; Anderson et al., 1984; Jacobs et al., 1970), but none of them is expected to have any effect so far offshore where, in summer only, the broken ice shelf leaving the shore is driven slowly into northern, warmer areas by a light current (during winter the area is frozen).

A working hypothesis to explain this phenomenon is as follows:

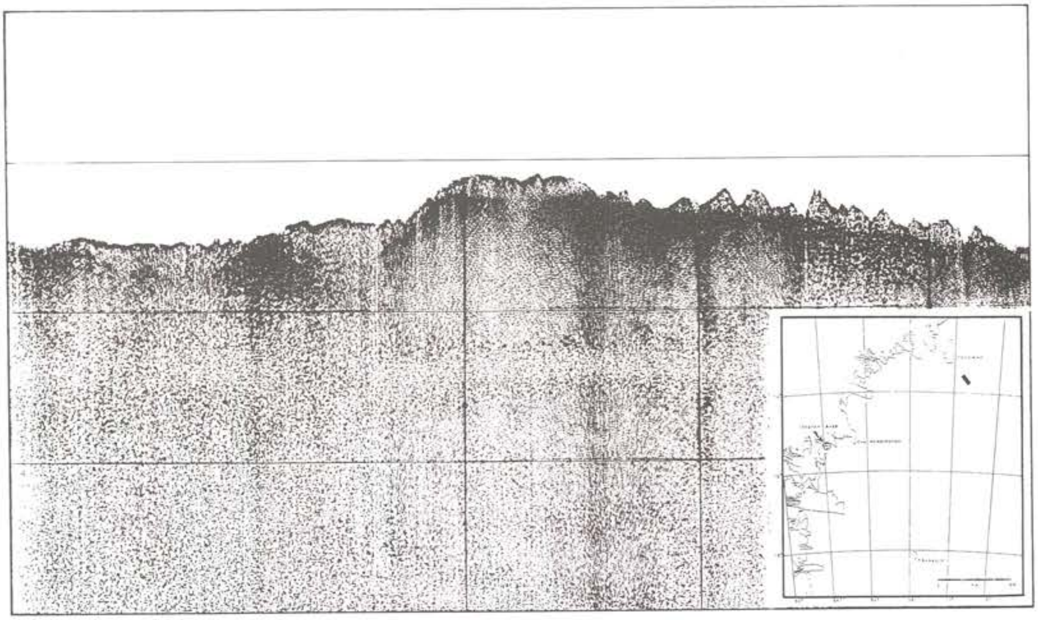

Fig. 8 - "Buiaces" rolled up into a dentate profile.

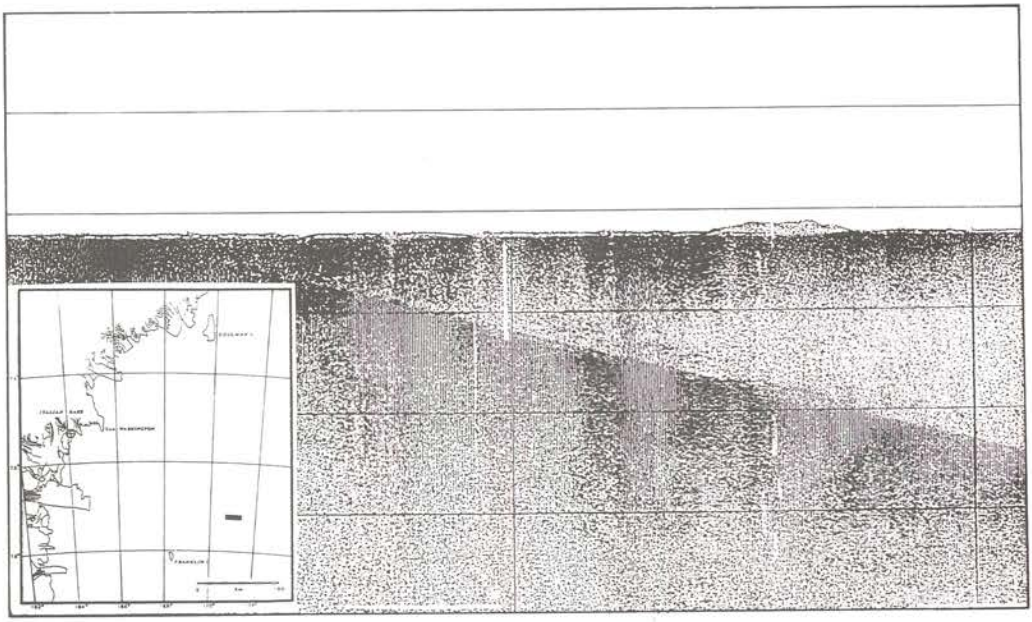

Fig. 9 - Transparent sediments. The cover has a constant very small thickness.

in Antarctica the catabathic winds are known to blow with tremendous force, up to about 200 km/h, mostly from land toward the sea. On the borders of the Ross Sea, the Transantarctic Mountains show the largest concentration in Antarctica of terrains free from ice and snow cover, a few hundreds of km (Elliot, 1985). Winds of such force must clear out all the loose sediments that are fine enough to be blown off, and the collected grains will be deposited where the wind slows down, that is, on the ice pack, up to a few miles offshore. Thus, the ice should contain a certain amount of "eolian" sediments, which are discharged where the ice melts.

The Ross Sea is characterized in summer by a strip of floating ice in slow motion from south to north. The ice comes from the decay of the pack from the McMurdo Sound area and from northern coasts (in winter time the area is frozen) and it is driven offshore and to the north by the combined effect of the current and prevailing winds. This moving ice strip melts on its way and passes right over the terrace, dropping land-driven sediments for more than a month a year.

The data on the dust load carried out to the ice-pack or to the sea are not yet sufficient to prove or to reject such an explanation. The absence of the fine cover close to the shore, even at the bottom of Drygalski, could be attributed to density induced currents, which could have prevented any sedimentation.

The hard substratum is discussed in the following chapters.

TERRACES

The terraces represent the most evident example of glacial erosion that can be seen on the seismic sections, and their study should provide useful information on the location and orientation of the valleys due to ice flow erosion. The identified terraces appear as a sequence of gentle slopes, cutting the underlying sedimentary sequence (Figs. 10, 11, 12 and 13). The maximum height of the terraces recognized so far is 40 metres. The thickness of the eroded sediments from the sea floor to the unconformity marked U4 on the seismic sections, which can be followed over almost all the Ross Sea, is about 200-250 metres (Fig. 14).

According to Hall and Buhmann (1989), the total thickness of the eroded sediments is estimated, in some zones, like McMurdo Sound, to be up to 1 km.

ROUGH SURFACES

Several areas where the sea bed exhibits great roughness have been recognized. Furthermore the majority of the seismic lines crossing rough surface areas frequently show very superficial diffraction phenomena (Figs. 15 and 16), especially in the profiles close to volcanic bodies.

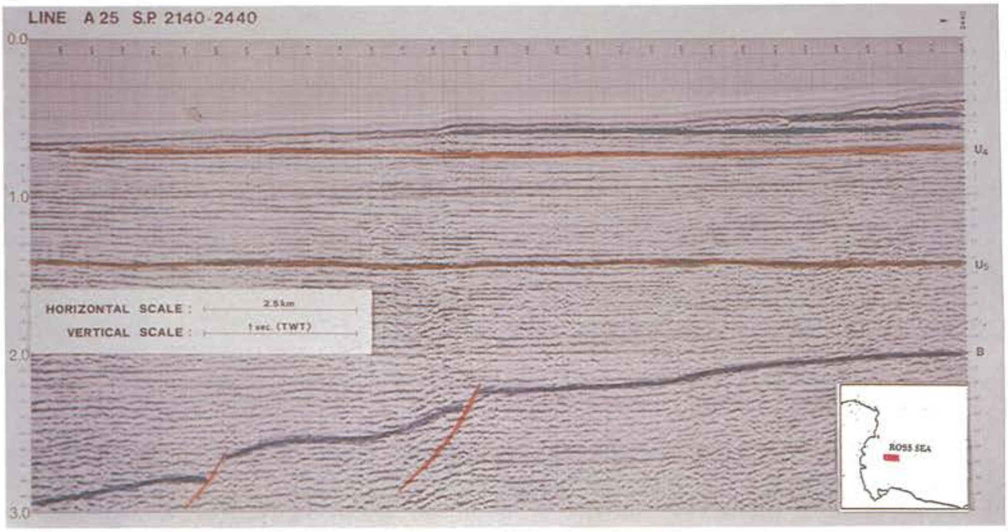

Fig. 10 - Line IT_25 is an east-west line running over the Coulman High. The sea bottom is characterized by a "Terraces" morphology that testify to a recent advance of the Ross Ice Sheet over the Ross Shelf. The scales shown in this Figure are valid for all the following seismic sections presented.

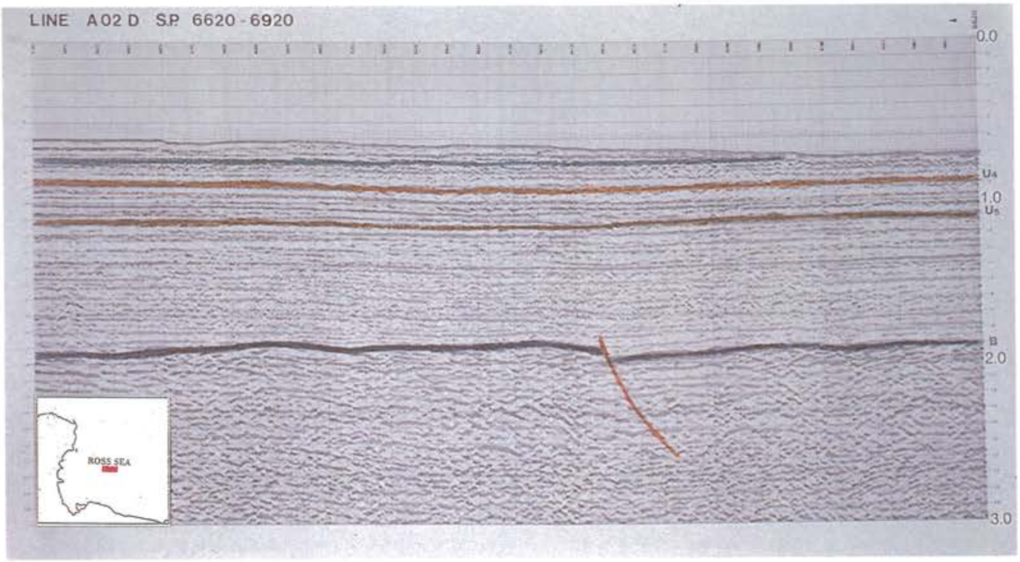

Fig. 11 - Example of "terraces".

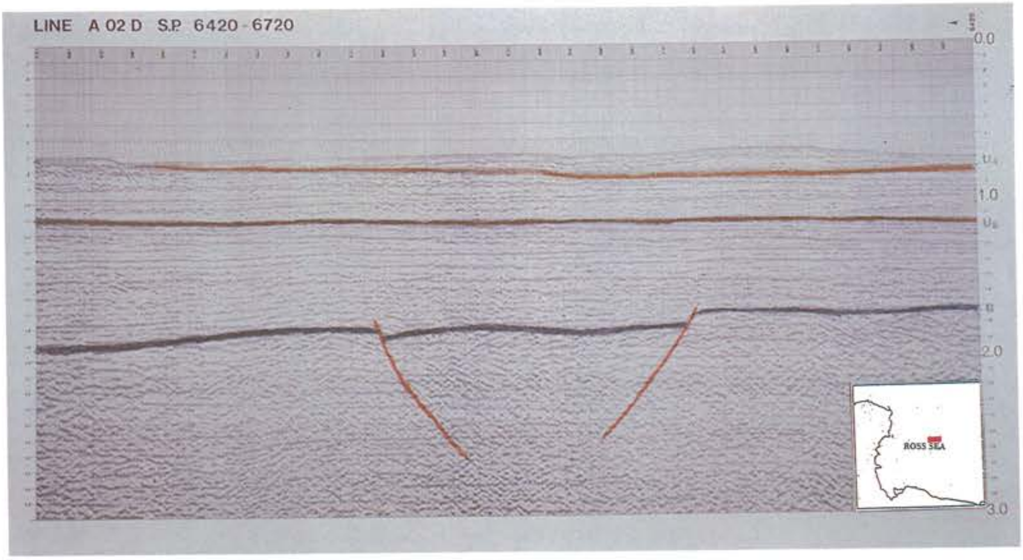

Fig. 12 - Example of "terraces". Erosion involves unconformity U4.

An unequivocal interpretation of this phenomenon is impossible without specific data on the lithology of the sea bed within these areas, and without further investigation.

We can offer three working hypothesis on the sea-bottom nature of these areas:

1) Basal eruptions (basaltic lava flows or pillow lavas), especially where Cenozoic magmatic intrusions and diffraction phenomena are evident, as in the profiles crossing the Victoria Land Basin and in the Coulman Island area.

2) Very coarse glacio-marine sediments.

3) Furrows of glacial origin.

Perhaps all these hypothesis are valid in different geographical locations.

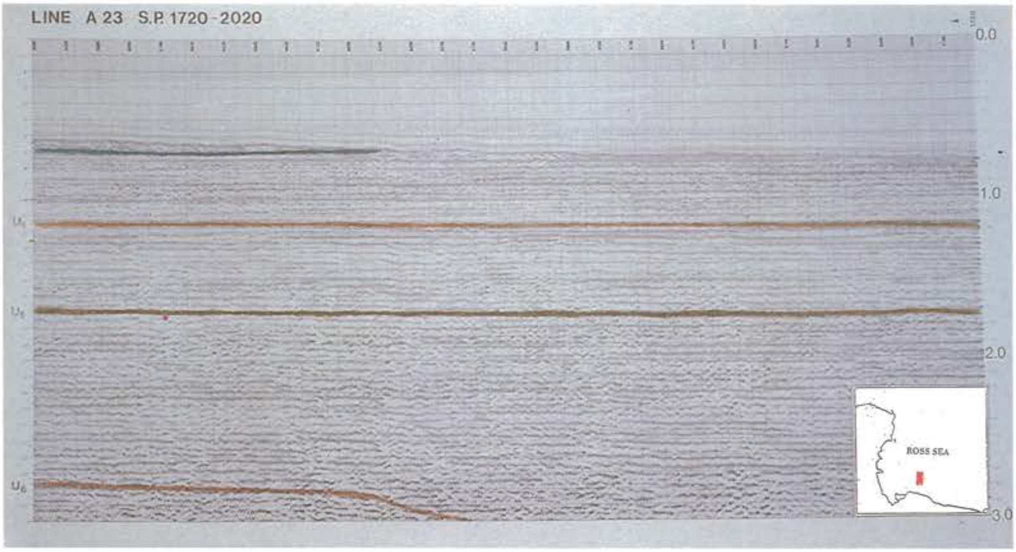

Fig. 13 - Example of "terraces".

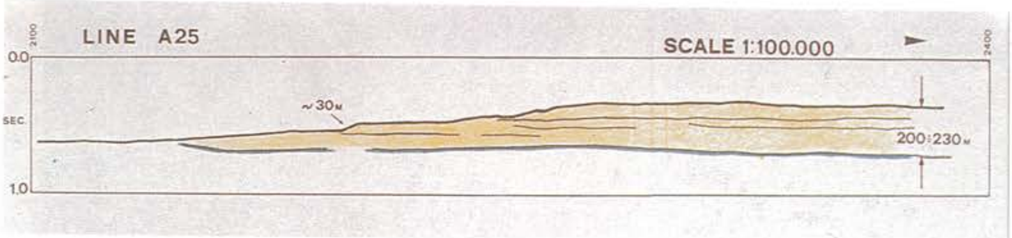

Fig. 14 - Terrace section reconstucted from Line IT_25. More than 200 m of sediments have been eroded by the ice shelf.

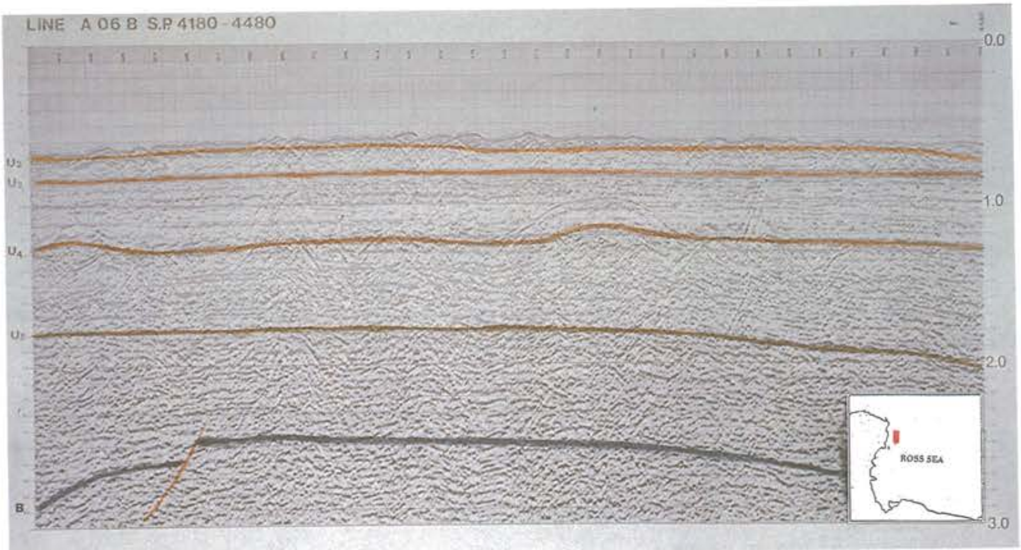

Fig. 15 - Example of very rough sea floor morphology.

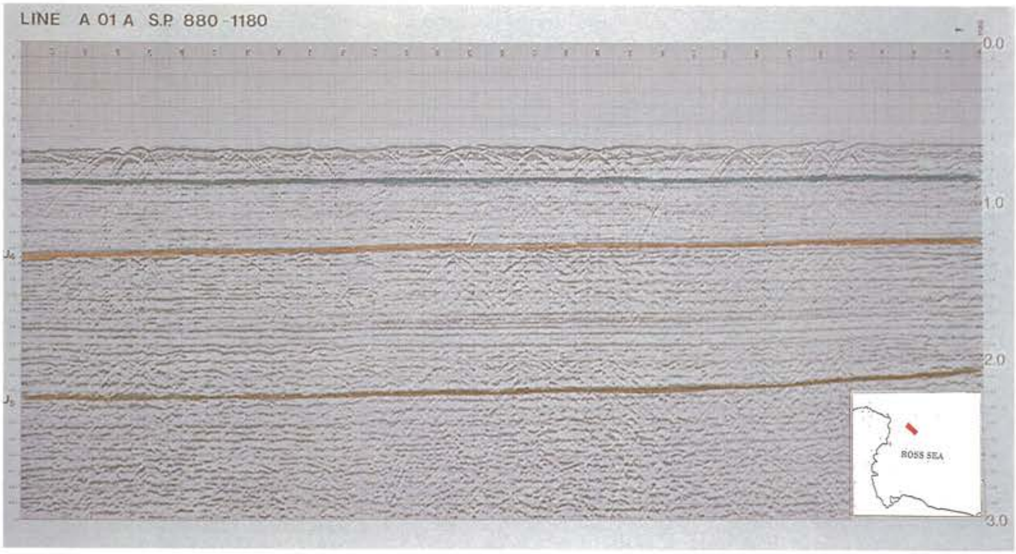

Fig. 16 - Example of rough sea floor surface. In this section very superficial diffraction phenomena are present.

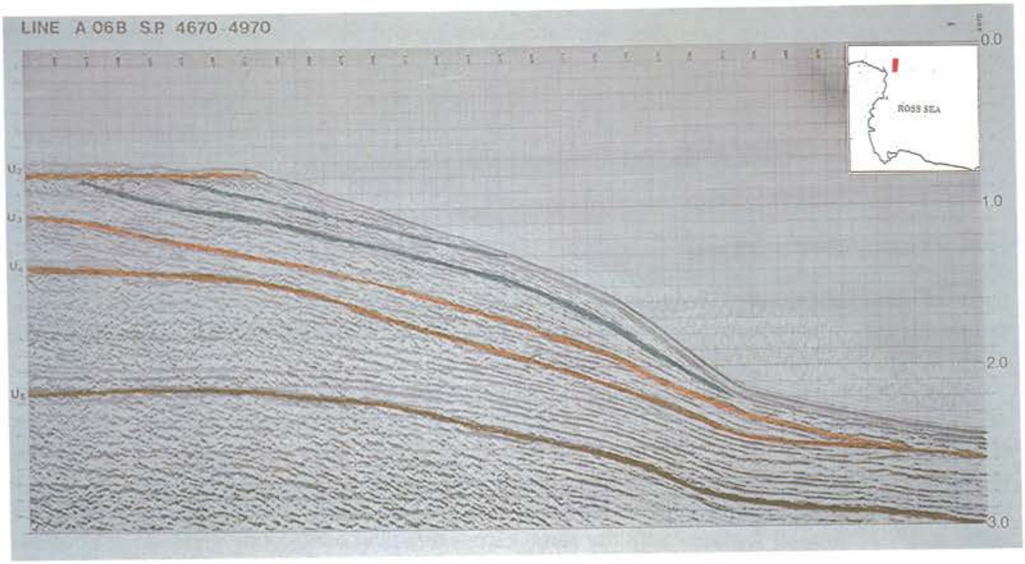

Fig. 17 - Continental slope (Line IT_06C). Two distinct clinoform depositional cycles are evident.

SLOPES

The margin of the western part of the Ross Sea is crossed by the seismic line IT_06C bearing normal to the continental slope offshore Cape Adare. Here the slop is characterized by a well preserved prograding reflection pattern which shows two distinct clinoform depositional cycles in which the uppermost prograding sequence presents a typical slant-wise pattern interpreted as a depositional unit originated in a low standing of the sea level (regression) (Fig. 17).

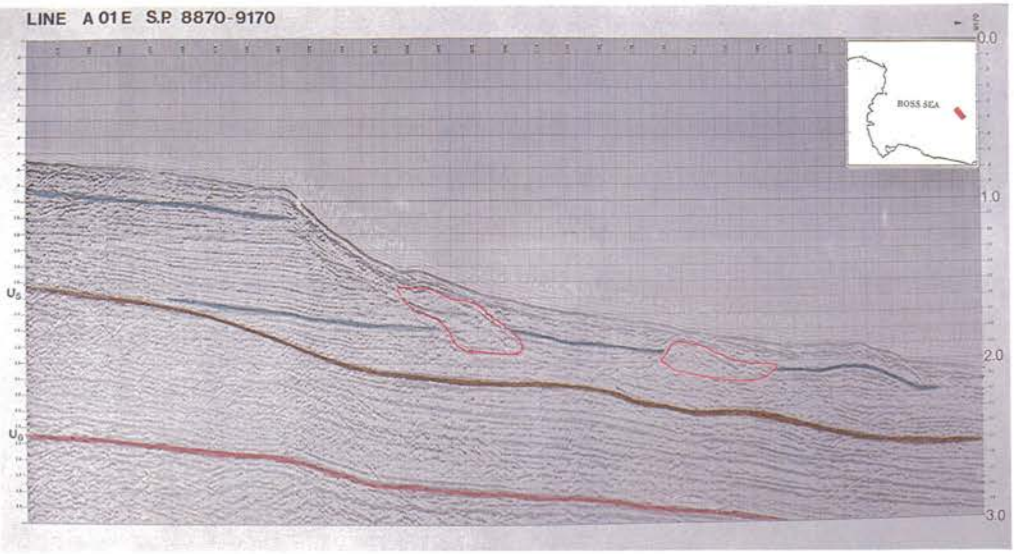

Fig. 18 - Continental slope (Line IT_01C). Gravitative depositional bodies at its base are evident.

The second section (line IT_01G) does not show evidence of prograding, and the slope is generally unstable with gravitative deposits, slumping and sliding at its base. The slope profile is probably controlled by a local erosional feature (a canyon ?) (Fig. 18).

VOLCANIC OR PSEUDO-VOLCANIC INTRUSIONS

A peculiar feature (see Fig. 19) worth mentioning has been found in the line IT_01. It appears as a "mesa" shaped hill, having a section of about 1.5 km and rising about 150 meters above the level of the surrounding sea floor. Its core appears to consist of an ellipsoidal body of amorphous material about 500 m thick, overlaid by layers of superficial sea bottom sediments which cover the top and the flanks of the hill in continuity with the uppermost layers of the adjacent plain.

Apparently, this feature suggests the presence of a volcanic body, such as the remnant of a more extended coverage of larger flows which were later eroded, and then covered by recent sediments. However, this body shows lower gravity (after subtraction of the regional trend) and corresponds to a portion of pronounced lowering in the magnetic anomaly profile: these characteristics are typical of a salt diapir and are not consistent with the presence of volcanic material. Similar features with the same characteristics, completely embedded by the recent sedimentation, have also been detected in other sections (e.g. line IT_06B) (Fig. 20).

The hypothesis of a salt diapir cannot be confirmed, as no suggestion of evaporated sedimentation has been found in the general area; features of this kind should therefore be subject to further investigation (drilling, near-bottom magnetometric and gravimetric profiling, etc.).

CONCLUSIONS

The depositional and erosional phenomena, and consequently, the morphology of the Ross Sea bottom, are essentially controlled by the advances and retreats of the Ross Ice Sheet, and by the Transantarctic Glaciers. Magmatic features of local extension have also been detected.

Erosional processes, accompanied by low rate depositional periods are prevalent in the

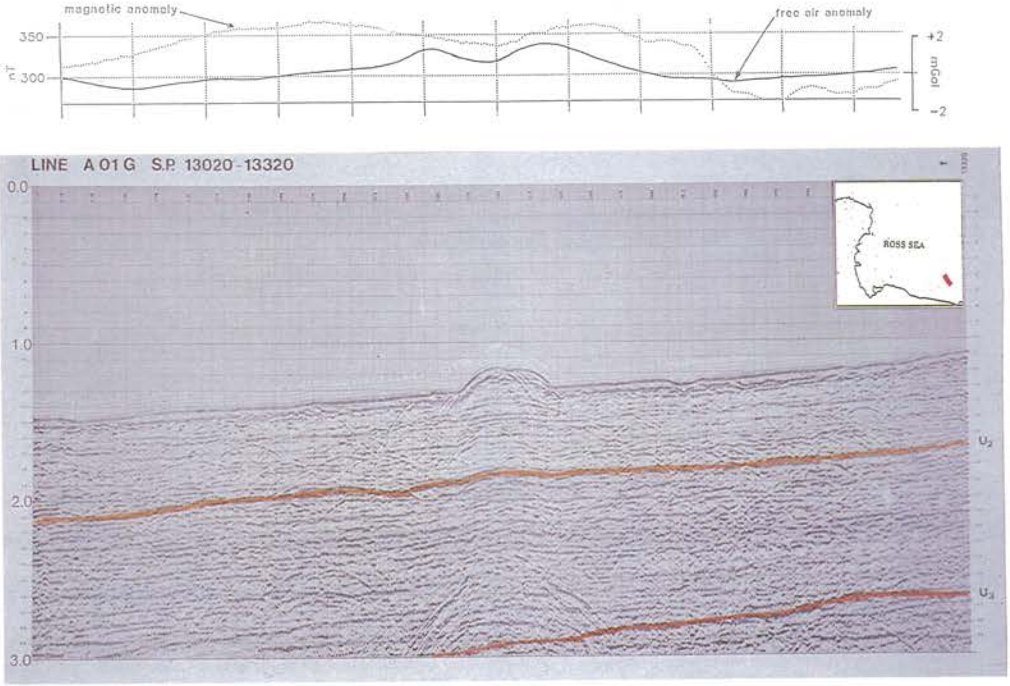

Fig. 19 - Volcanic or pseudo-volcanic body (Line IT_01G). See text for details.

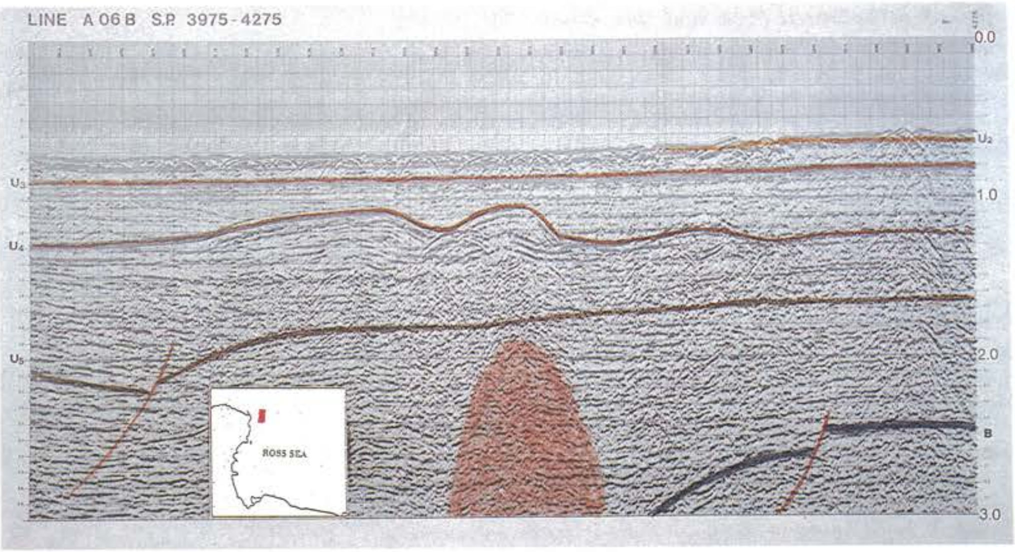

Fig. 20 - Features similar to that showed in Fig. 19 covered by recent sediments.

recent (post- Miocene) Ross Shelf history, corresponding to a general increase of glacial conditions in Antarctica. The sea bottom erosion increases moving from east to west, and is more relevant over the basement high.

While the higher erosion rate in the Victoria Land Basin can be easily explained by the action of the glaciers descending from the Transantarctic Mountains into the western part of the Ross Sea, the erosion of the basement high is still not understood.

However, the influence of climatic variations on the morphological and sedimentary environments in terms of stability and transport, up to the present, has been demonstrated.

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