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Debate
Preliminary results of seismic reflection investigations and associated geophysical studies in the area of the Antarctic Peninsula

Discussion

ROB D. LARTER

British Antarctic Survey, Natural Environment Research Council,High Cross, Madingley Road, Cambridge CB3 0ET, UK

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The South Shetland Trench

In their recent paper, the GRAPE team (1990) described the South Shetland Trench as a 'recently de-activated trench'. The evidence presented in support of this statement was:

(1) the undisturbed character of the trench-fill sediments; and

(2) marine magnetic anomaly identifications which show that spreading has ceased on the Antarctic-Phoenix (ANT-PHO) Ridge (referred to by the GRAPE team as the 'Aluk' Ridge).

In fact, neither of these observations supports the hypothesis that convergence has ceased, and all available evidence suggests that the South Shetland Trench is an active subduction zone.

Trench-fill sediments are normally undisturbed because, by definition, they are ahead of the frontal thrust of the accretionary complex (e.g. Westbrook *et al.* 1988). However, configuration of the trench-fill sediments in relation to the toe of the accretionary complex does have a bearing on the possibility of continued convergence. If convergence had ceased, the trench sediments would be expected to onlap onto the toe of the accretionary complex. The single GRAPE profile across the trench (profile 1, figs. 4a & d; GRAPE Team 1990) is not migrated, making the true disposition of the trench-fill sediments more difficult to interpret. In fact, a migrated 24-fold seismic reflection profile across the front of the accretionary complex (Fig. 1) clearly shows that the frontal thrust overrides the youngest trench sediments. This demonstrates that convergence has taken place since the deposition of the youngest trench sediments. There remains the possibility that the strong bottom currents which sweep the present-day South Shetland Trench (Nowlin & Zenk 1988) may have reduced the rate of sedimentation, so the observed stratigraphical and structural configurations may not represent present-day tectonics. However, the same multichannel seismic profile also shows high amplitude reflections from a décollement and ramp beneath the accretionary complex. A likely explanation for such reflections near the toe of an accretionary wedge is localized dilatancy in the thrust zones caused by overpressured water flowing through them (Westbrook & Smith 1983, Westbrook *et al.* 1988). If this is correct, thrust zone reflections would not be preserved long after convergence ceased.

The GRAPE team did not present any magnetic profiles from the area of the ANT-PHO Ridge, so I presume their knowledge of the magnetic anomaly pattern in this area is taken from the primary literature. The name 'Aluk', favoured by the GRAPE team, was first used by Herron & Tucholke (1976) to refer to a remnant of the once much larger Phoenix plate (Larson & Chase 1972). It is recommended here that use of the name 'Aluk' be discontinued to avoid confusion. Barker (1982) presented two magnetic profiles crossing the ridge and compared these to a synthetic magnetic anomaly profile to show that spreading ceased, or decreased to a very slow rate, about 4 m.y. ago. However, cessation of spreading on the ANT-PHO Ridge does not necessarily mean that subduction ceased at the South Shetland Trench, as implied by the GRAPE team.

When ANT-PHO spreading ceased, the Phoenix plate remnant became part of the Antarctic plate. Thus, if previous subduction at the South Shetland Trench represented Phoenix-Antarctic motion, that motion also ceased. However, the matter is complicated by extension in Bransfield Strait (Ashcroft 1972, Davey 1972, Barker 1976, 1982, Barker & Dalziel 1983), which has transformed the South Shetland arc and forearc into a separate microplate, converging on the Antarctic (previously Phoenix) plate across the South Shetland Trench. It has been suggested that extension in Bransfield Strait was probably a consequence of the slowing and eventual cessation of ANT-PHO spreading, due to continued sinking of the subducting slab, and roll-back of the hinge of subduction (Barker 1982, Barker & Dalziel 1983). Thus subduction, and possibly also horizontal convergence, would have been continuous. The timing of the start of Bransfield Strait extension is not well constrained (Barton 1965, Barker 1976, Roach 1978, Barker & Dalziel 1983), but an onset at about the time of cessation of ANT-PHO spreading is plausible. Whatever the time of onset, the existence of active extension in Bransfield Strait at present means that convergence at the South Shetland trench is required.

A well-developed outer rise, which can be accurately

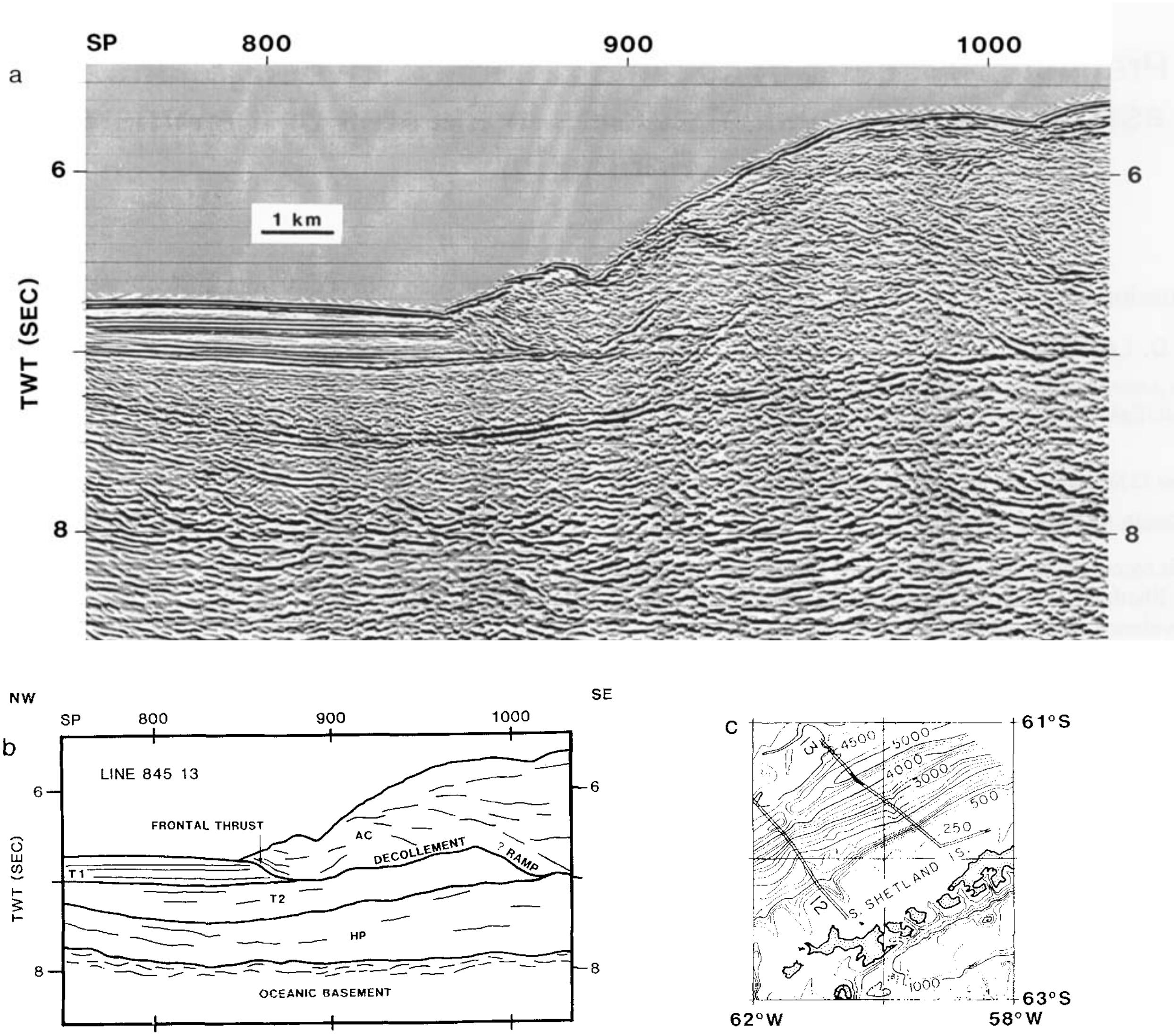

Fig. 1. a. Migrated, 24-fold seismic reflection profile (AMG 845-13) across the front of the South Shetland accretionary complex, with interpretive line drawing. **b.** Vertical exaggeration in water is 3.3:1. On line drawing: AC = accretionary complex, T1 = upper trench-fill sequence, T2 = lower trench-fill sequence, HP = pelagic and hemipelagic sediments. **c.** map to show location of University of Birmingham/BAS multichannel seismic Lines AMG 845-12 and AMG 845-13 (solid line indicates section illustrated in **a**) with bathymetric contours at 250 m intervals.

modelled using the universal deflection equation of Caldwell *et al.* (1976), is present to the north-west of the South Shetland Trench (Fig. 2). Outer rises on ocean floor adjacent to subduction zones are maintained by lithospheric flexure in response to the vertical shear force and bending moment acting on the subducted slab (Caldwell *et al.* 1976), so the existence of an outer rise in association with the South Shetland Trench indicates the presence of cold, rigid, subducted oceanic lithosphere beneath the South Shetland Islands. This does not prove that subduction is currently active, but does indicate that forces normally associated with subduction are still acting on the subducted slab.

The GRAPE team observed extensional faulting on the ocean floor to the north-west of the trench. Extensional faulting is a common feature on ocean floor approaching a trench and is thought to occur in response to flexure (see review by Dickinson & Seely 1979). A shallow earthquake on the trench outer slope with an extensional first motion was reported by Dziewonski *et al.* (1983). The epicentre and implied stress direction for this earthquake are shown on the Tectonic map of the Scotia arc (1985).

The reported earthquakes from this area do not clearly define a Benioff zone beneath the South Shetland Islands. Pelayo & Wiens (1989) pointed out that the relatively low level of seismicity associated with the South Shetland Trench (compared to other active margins) may be explained by the

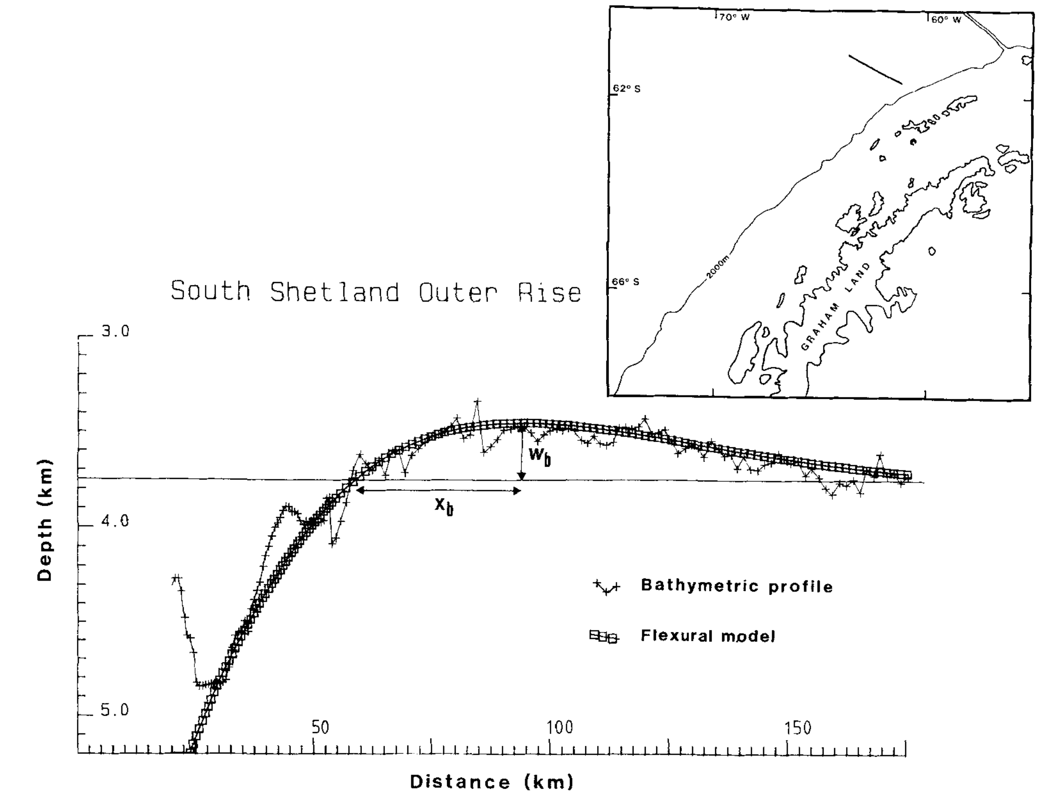

Fig. 2. Bathymetric profile (RRS *Shackleton* 1976) across the South Shetland Outer Rise, compared to a flexural model produced using the universal deflection equation of Caldwell *et al.* (1976) with shape parameters X_b = 35 km and W_b = 300 m. Zero deflection depth for the flexural model was set to 3750 m. The bathymetric profile is resolved onto 325° (location shown on inset map).

young age of the subducting lithosphere, the slow rate of convergence, and the decoupled nature of subduction associated with back-arc extension. They interpreted two large earthquakes from this area to have been located within the subducted slab. However, if this is correct, the source depths they obtained for these events suggest a very shallow angle of subduction.

Contrary to a statement made by the GRAPE team, that the continental slope is much steeper near King George Island than it is near Smith Island, numerous bathymetric profiles show that the slope becomes steeper from north-east to south-west (Barker 1982, Tectonic map of the Scotia Arc 1985).

Current-controlled sedimentation

The GRAPE team suggest that the non-horizontal layering of sediments in a trough 70 km north of the South Shetland Trench on GRAPE Profile 1 is evidence of recent deformation. The trough itself is crescent-shaped in plan view, and occurs in oceanic basement about 20 m.y. old (Tectonic map of the Scotia arc 1985). Its origin is enigmatic. However, the impression of structural disturbance in the trough-fill sediments is probably a consequence of the large vertical exaggeration used to display the seismic lines (10 : 1 at the sea floor). The sediment disposition and reflection configurations observed are typical of deep-water, current-controlled sedimentation (e.g. Barker & Burrell 1977). Moored current meter measurements indicate the presence of strong bottom currents in this region (Nowlin & Zenk 1988), so deposition under the influence of bottom currents is a more likely explanation for the observed features than intra-plate deformation. Bottom current activity probably also explains the thin sediment cover on the flanks of this trough. Elsewhere on this and other GRAPE profiles the sediments show rapid lateral variation, involving thinning or absence on elevations and the creation of moats around them, characteristics usually attributed to bottom current activity.

Bransfield Strait

The GRAPE team ascribed 'continental' and 'oceanic' structure to different areas of Bransfield Strait solely on the basis of the reflection character of the top of acoustic basement. This is not a reliable method of determining the nature of the crust. Oceanic crustal structure can only be conclusively demonstrated either by determination of the detailed velocity structure using seismic refraction techniques, or by the recognition of marine magnetic anomalies. There is general agreement that Bransfield Strait has extended by several tens of kilometres and that new crust is presently being formed along the Deception Island–Bridgeman Island volcanic line (Barker 1976, Weaver *et al.* 1979, Pelayo & Wiens 1989). However, the evidence from both seismic refraction and magnetic data is ambiguous concerning the precise nature of the crust in the central part of Bransfield Strait

(Ashcroft 1972, Barker 1976, Roach 1978, Guterch *et al.* 1985). Geochemical evidence is similarly ambiguous, with recently-erupted lavas displaying a mixture of mid-ocean ridge and calc-alkaline characteristics, as might be anticipated for magma generated in an extensional environment above a long-lived subduction zone (Weaver *et al.* 1979, Barker & Dalziel 1983). Although there are some inconsistencies between the seismic refraction data interpretations of Ashcroft (1972) and Guterch *et al.* (1985), both studies show that the crust in the central part of Bransfield Strait is thicker than standard oceanic crust. This is, however, consistent with the interpretation of Bransfield Strait as a young oceanic back-arc basin (i.e. having passed the rift-drift transition). According to Roots *et al.* (1979) the new crust formed after break-up at a divergent margin is thicker than normal oceanic crust and thins exponentially away from the margin to a steady state thickness, which is achieved about 40 m.y. after break-up.

The Miocene ridge crest-trench collision margin

On a reflection profile across the continental rise to the west of Anvers Island (GRAPE Team 1990, profile 3, figs. 4a & b) the GRAPE Team observed a small landward dip on the top of oceanic basement, despite the fact that basement ages decrease toward the margin in this area (Herron & Tucholke 1976, Barker 1982, Larter & Barker, in press). It was implied that this landward dip was due to relict downwarping of the oceanic basement towards the palaeotrench. However, seismic reflection profiles across the continental margin in this region reveal rapid Pliocene-Pleistocene progradation (Larter & Barker 1989, in press) Lithospheric flexure resulting from this sedimentary loading can explain the landward dip of oceanic basement and decrease in free-air anomaly towards the margin in the same way as flexure caused by progradation at rifted margins enhances the continental margin edge anomaly (e.g. Beaumont *et al.* 1982) Relict downwarping of oceanic basement towards the palaeotrench is implausible because basement in this area was formed on the trailing flank of the ridge during ridge crest-trench convergence, and flexural stress could not have been transmitted across the ridge crest.

Acknowledgement

The seismic data in Fig. 1 were acquired on RRS *Discovery* Cruise 154 in 1985 and processed under contract by GECO (UK). Fig. 2 was produced using Fortran programme 'ORFLEX', written by Ian Hamilton. I would like to thank Dr. P.F. Barker and Professsor G.K. Westbrook for their comments.

Reply

J.P. HENRIET[1], J. BIALAS[2] and R. MEISSNER[2] FOR THE GRAPE TEAM

[1]Renard Centre of Marine Geology, Krijgslaan 28 88, 8-9000 Gent, Belgium
[2]Christian-Albrechts-Universität zu Kiel, Olshausenstrasse 40, D-2300 Kiel 1, Germany

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We have read with great interest the comments by Larter on our recent paper (GRAPE Team 1990). In our opinion Larter's contribution deserves the status of a stand-alone short paper for the interesting new data it contains, and we appreciate that our paper encouraged him to release these data. His comments on our original contribution appear to focus on one fundamental question, and a few arguments about interpretations. We believe our statements were in general cautious, often proposing alternative views, but we do, however, acknowledge one justified correction.

The fundamental point questioned by Larter is the existence at present of active subduction along the South Shetland Trench. He will probably agree that at the South Shetland Trench subduction is on the wane, not much space being left for more subduction due to the surrounding constraints within the Antarctic Plate. While we have put the emphasis on the decreased activity (the "de-activation"), Larter puts the emphasis on the still existing (residual) convergence. We do not believe there is a fundamental contradiction between these positions.

We have stated that the cessation of convergence is supported by the magnetic anomaly pattern along the Aluk Ridge and by the undisturbed character of the young trench-fill sediments on our profile 1. The first part of the sentence might be inappropriate as it appears to neglect the convergence due to the extension in Bransfield Strait. This phenomenon has been accounted for in a communication by the same team at the IASPEI meeting in Istanbul in 1989, (unpublished). It is, however, clear that the cessation of spreading at the Aluk Ridge some 4 m.y. ago is a factor which constrained and finally hampered further convergence at the site of the South Shetland Trench. The possible extent to which the extensional basin of Bransfield Strait could widen is limited. It might have been more appropriate to write that the cessation of spreading at the Aluk Ridge heralds a cessation of subduction at the South Shetland Trench.

In this context, we believe that the strength of the argument "... the existence of active extension in Bransfield Strait at present ..." (the extent of which still has to be proved) "... means that convergence at the South Shetland Trench is required ..." is debatable. Stating that "all available evidence suggests that the South Shetland Trench is an active subduction zone" is also questionable, e.g. with regard to the reported lack of Benioff zone seismicity (Pelayo & Weins 1989). We have noted the hypotheses formulated by the latter authors for possibly explaining this phenomenon, but the virtual decay of subduction may be an explanation as well.

As to the interpretation of trench-fill sediments, we have written that "the *horizontal layering* of the youngest trench-fill sediments is continuous and undisturbed, arguing for deposition after the cessation of subduction *or* at least for a lack of compressional forces". We agree our unmigrated profile does not yield the same information as the one shown by Larter, which is of excellent quality. However, Larter's profile does not unambiguously support his interpretation. When stating " ... the frontal thrust overrides the youngest trench sediments. This demonstrates that convergence has taken place ..." he overlooks the hypothesis of slumped slope sediments, which simply may have covered the subhorizontal and undisturbed trench-fill sediments in recent times. The analogy between the frontal thrust shown by Westbrook *et al.* (1988) and the basal slope structure on Larter's profile is striking, but there is one fundamental difference; the reflectors below the toe of the accretionary complex on Larter's profile do not bend down as might be expected from an actively sinking slab, but they rise again, to an extent larger than any apparent rise due to a possible velocity effect on the time sections. In a way, Larter presents a profile which in this respect contradicts his own model of lithospheric flexure, associated with an actively converging margin setting.

The further remarks deal with second-order problems. The name 'Aluk' (ridge, plate) has not only been used by Herron & Tucholke (1976), but has also been used or referred to by other researchers, e.g. Barker (1982), Thomson *et al.* (1983), Pelayo & Wiens (1989). We do not consider it exotic.

Larter quotes us stating that the non-horizontal layering of sediments in a trough "... is evidence of recent deformation". In fact, we cautiously wrote "might suggest recent tectonic stresses", which has not the same strength. It is quite plausible that the moat-like structures may have been induced by currents, but we cannot rule out any tectonic deformation. In fact, would not the total absence of deformation of sediments in an evidently faulted trough, bounding a broken slab associated with an "actively subducting" environment as suggested by Larter, in itself be somewhat intriguing?

On the sloping oceanic slab near the South Shetland Trench we observed "normal faults, apparently related to slumping or extensional faulting on the basement". Larter correctly points out that such extensional faulting is frequently thought to occur in response to flexure. In fact we favour the slump hypothesis, but it is evident that basement faults, if any, would have occurred in response to flexure.

The statement that we made about the steepness of the continental slope near King George Island was incorrect and escaped our proof corrections. In the communication presented at IASPEI in Istanbul, we analyse in more detail the steepening observed from north-east to south-west, relating it to the margin progradation which can be observed farther south (a sequence stratigraphic interpretation of the sediments at the base of this slope has been proposed in the IASPEI paper, independently of Larter & Barker's interpretation published in 1989, which was not known to the present authors at the time they presented the IASPEI paper).

In Bransfield Strait, the determination of the nature of the crust was not the prime intention of this reflection survey, but we do not see a problem in recognizing the typical diffraction pattern as being related to an oceanic (basaltic) surface. Larter's statement that "oceanic crustal structure can only be conclusively demonstrated by determination of the detailed velocity structure using seismic refraction techniques" is partly correct but not conclusively substantiated by the not quite consistent interpretations of Ashcroft (1972) and Guterch *et al.* (1983). Moreover, we think that the similarity of diffraction patterns in Bransfield Strait and in typical oceanic basasltic sea floor is a striking feature.

A final remark is made by Larter about the small landward dip of the oceanic basement reported on the site of a ridge-trench collision which took place some 15 m.y. ago. We stated that the oceanic basement at the foot of the continental slope "still" shows a small landward dip. Larter doubts a relict downwarping and proposes a sole loading mechanism of sedimentary loading. Let us first specify what we mean by relict downwarping.

It is true that the trailing flank of the ridge during ridge-trench convergence would slope in seaward direction and that this configuration is expected to be preserved up to the moment of ridge-trench collision, as demonstrated by Cande & Lewis (1988) off southern Chile. It is also true that flexural stresses could not be transmitted across the ridge crest, but in an "en échelon" pattern of ridges and transform faults, the sinking slab may be expected to transmit a downward pull by shear stresses along the transform faults. As a result the trailing flank of a collided ridge may be dragged over some distance below the accretionary wedge, while decoupling occurs at the buried ridge axis. The trailing flank, loaded by the frontal thrust, then has to bend down. This is what we believe can be inferred e.g. from the Cande & Lewis profile over a 10 m.y. old post-collision zone off southern Chile, and it is such a "relict" structure that we believe can be seen in the profile over the 15 m.y. old post-collision zone off Graham Land. It involves postcollision thermal subsidence and sedimentary loading by the thrust wedge. Subsequent margin postgradation as has been observed on profile 3 (unpublished) and as described in the same area by Larter & Barker (1989) may have enhanced the subsidence, but is not believed to be essential as a primary factor, as demonstrated off Chile, where a substantial glacial margin progradation similar to that along the Antarctic Peninsula is not expected to have occurred.

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