DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

INTERNATIONAL WORKSHOP ON ANTARCTIC OFFSHORE ACOUSTIC STRATIGRAPHY (ANTOSTRAT): OVERVIEW AND EXTENDED ABSTRACTS

Asilomar Conference Facility
Pacific Grove, California

June 7 to 10, 1990

Conveners:

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PREFACE

In April 1989, the SCAR[1] Group of Specialists on the Evolution of Cenozoic Paleoenvironments of the Southern High Latitudes proposed a multi-year international project to study Cenozoic sedimentary deposits around Antarctica, focusing in particular on the extensive sedimentary bodies beneath the continental margin. The project seeks to integrate a variety of geophysical, geological, and glaciological data bases, and to incorporate them with ongoing studies to better understand the relationships between Cenozoic terrestrial and marine glacial-interglacial histories and between Cenozoic ice-volume and global sea-level variations.

A vast quantity of acoustic data of many types including high- and low-resolution seismic-reflection, bathymetry, side-scan sonar, and others, has been collected in offshore areas of Antarctica by numerous countries principally since the 1960's. However, the integration of all existing acoustic data to study a single thematic problem has not previously been attempted. The International Workshop on Antarctic Offshore Acoustic Stratigraphy (ANTOSTRAT) at Asilomar, Pacific Grove, California in June 1990 brings together scientists from countries that now have, or will imminently collect, offshore acoustic data from the Antarctic continental margin to discuss such a unified project. Objectives of the workshop are

* to describe the existing offshore Antarctic data bases and ongoing national programs,

* to identify important Cenozoic problems of global interest that can be addressed in Antarctica using existing acoustic, geologic sampling, and scientific drilling data bases,

* to discuss and implement resolutions for (a) integrating and analyzing existing Antarctic acoustic data bases and (b) planning international cooperative field and laboratory projects to augment, not replace, ongoing studies,

* to prepare a final report that summarizes the global Cenozoic problems that can be addressed in Antarctica and the plans to study these problems.

The first ANTOSTRAT workshop is guided by an international steering committee with nine members:

Dr. Alan Cooper	U.S. Geological Survey	USA
Dr. Peter Webb	Ohio State University	USA
Dr. John Anderson	Rice University	USA
Dr. Peter Barker	British Antarctic Survey	UK
Dr. Peter Barrett	Victoria Univ. of Wellington	NZ
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[1] Scientific Committee on Antarctic Research

This report was prepared before and released at the ANTOSTRAT workshop. The abstracts are reproduced, unedited, in the form that they were received by the conveners. A final report of the meeting giving further details of the ANTOSTRAT project, the thematic objectives, and project plans will be published elsewhere.

The ANTOSTRAT Workshop is made possible by financial support from the Scientific Committee on Antarctic Research, the U.S. National Science Foundation Division of Polar Programs (Grant NSF/DPP-9010852) and the U.S. Geological Survey. In particular, the conveners appreciate the assistance provided by Dr. Peter Clarkson, Dr. Herman Zimmerman, Dr. David Russ, Dr. Gary Hill, Dr. David Cacchione, Ms. Patricia Sliter, Dr. Henry Spall, Dr. Garrik Grikurov in supporting and expediting the workshop planning. We also wish to thank the local organizing committee including Ms. Jo Ann Gibbs, Mr. Guy Cochrane, Mr. Dennis Mann, Ms. Toby Williams, Dr. and Mrs. Franklin Cooper, and many colleagues at the U.S. Geological Survey. We also appreciate the drafting support provided by Ms. Brigit Fulop.

SCIENCE PROGRAM

The science program for the ANTOSTRAT workshop is partitioned into data sessions, thematic sessions and poster sessions to give all participants the opportunity to present, discuss, and examine offshore acoustic data illustrating Cenozoic sedimentary sections. Additionally, each of the five principal regions, where major Cenozoic sedimentary sequences exist beneath the continental shelf and slope, are discussed separately. The thematic sessions address the major factors (see below) that affect the acoustic geometry of offshore Antarctic Cenozoic sequences. Summary sessions, at the end of the workshop, are dedicated to discussion and implementation of workshop resolutions and plans.

The general format of the workshop is as follows.

<u>THURSDAY June 7 - Introduction, Weddell Sea, Queen Maud Land</u>

Morning: * Greetings and orientation talks
* Antarctic science overview talks
Afternoon: * Data talks - Weddell Sea and Queen Maud Land
Evening: * Poster session and discussions

<u>FRIDAY June 8 - Ross Sea, Wilkes Land, Prydz Bay</u>

Morning: * Data talks - Ross Sea
* Thematic session - Tectonics, crustal flexure, and marine stratigraphy (I)
Afternoon: * Data talks - Wilkes Land and Prydz Bay
* Thematic session - Glaciology, offshore ice, and marine stratigraphy (II)
* Thematic session - Geotechnical properties of glacial sediments and marine stratigraphy (III)
Evening: * Poster session and discussions

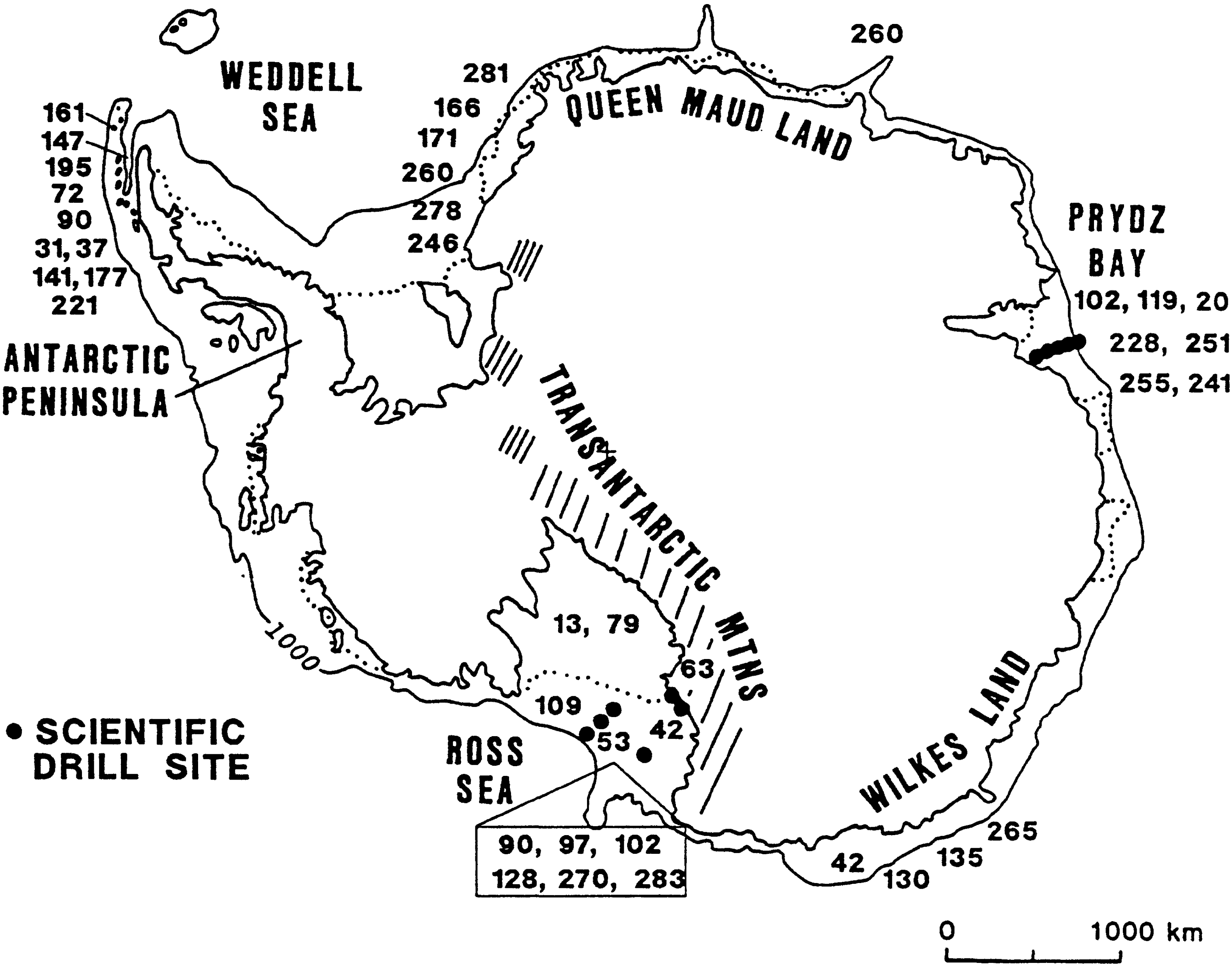
<u>SATURDAY June 9 - Antarctic Peninsula</u>

Morning: * Data talks - Antarctic Peninsula
* Thematic session - Offshore geologic sampling
Afternoon: * Thematic session - Paleogeography and Paleoceanography
* Thematic Session - Data compilations
Evening: * Poster session and discussions

<u>SUNDAY June 10 - Circum-Antarctic, Summary</u>

Morning: * Thematic Session - Planned studies
* Thematic session - Future directions

LOCATION OF STUDIES IN THE ABSTRACTS



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SEDIMENTARY HISTORY OF THE ROSS EMBAYMENT: A UNIFIED HYPOTHESIS FROM A GLACIOLOGICAL PERSPECTIVE

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The sedimentary history of the Ross Sea now is receiving considerable attention and has spawned much controversy; both depositional environments and ages of sediments sampled are subject to dispute. This is due largely to a shortage of samples, the highly reworked character of most materials sampled, and ongoing refinement of biostratigraphic zonations (Karl et al., 1987).

Our new evidence concerning the physics of glacier flow on ice stream B gives us considerable insight into how the system may have responded to sea-level fluctuations that are known to have occured in the past. We find (Alley et al., 1987; Blankenship et al., this volume) that the likely response of the ice sheet to sea-level fluctuations would lead to a sedimentary sequence similar to that described by some observers. Here we will give a brief summary of observations of sediments from the Ross Embayment, including areas of controversy, and then present our hypothesis for the sedimentary history and show how it relates to the observations; this discussion has been extracted from Alley et al. (1989).

OBSERVATIONS

To summarize from Houtz and Davey (1973), Hayes and Frakes (1975), Anderson et al. (1984), Dunbar et al. (1985), and Karl et al. (1987), the modern Ross Sea (Figure 1) is underlain by a sedimentary column typically hundreds of meters thick. The upper part of this sedimentary column contains a prominent unconformity, often called the Ross Sea unconformity, at a depth of <2 m to about 40 m below the sea floor. Erosion on this unconformity may have amounted to as much as several hundred meters. This erosion probably occurred beneath grounded ice, although marine bottom currents have been suggested as a possible cause (Mercer and Sutter, 1982). This unconformity is overlain by an unstratified or poorly stratified diamicton, which in turn is overlain by a thin veneer of Holocene sediments comprising ice-rafted clasts, terrigenous silt and clay, and biogenic silica; in this Holocene layer ice-rafted debris is sparse near the front of the Ross Ice Shelf, indicating that little englacial debris reaches the ice-shelf front, but is more abundant where outlet glaciers drain into the Ross Sea. The transition from the unstratified diamicton just above the unconformity to the modern sediments is marked by a water-sorted unit 0.1-0.5 m thick at some sites (Kellogg et al., 1979) but not in most locations (Anderson et al., 1984).

The ages of the Ross Sea unconformity and of the overlying diamicton are uncertain (Hayes and Frakes, 1975; Kellogg et al., 1979; Savage and Ciesielski, 1983), but the unconformity probably is Pliocene or Pleistocene in age. Based on appearance, grain-size distribution and other characteristics, Kellogg et al. (1979), Anderson et al. (1980; 1984), and others have argued that the diamicton above the Ross Sea unconformity is a basal till. Anderson et al. (1984) show that populations of transported clasts in this material are not mixed, but are traceable to discrete sources in the Transantarctic Mountains and in West Antarctica. Truswell and Drewry (1984) demonstrated that pollen grains in the diamicton also are traceable to discrete sources. This shows that deposition occurred from a grounded ice sheet, or from an ice shelf with marine currents to slow to mix pollen, rather than from floating icebergs. Estimated sedimentation rates of 6-8 m/Ma (Hayes and Frakes, 1975) seem too high for sedimentation beneath an ice shelf fed by West Antarctic ice streams, as discussed by Alley et al. (1989), so we consider that this diamicton probably is a basal till. Notice, however, that several authors including Hayes and Frakes (1975) and Fillon (1979) have interpreted the diamicton as glaciomarine rather than as basal till.

Beneath the Ross Ice Shelf, data are available only from the J9 site, downstream of ice stream B, where the bed is about 590 m below sea level (Figures 1 and 2; see Clough and Hansen, 1979). Sediments were collected thre to a maximum depth of about 1 m. These sediments originally were interpreted as a dropstone diamicton of Miocene age containing clasts transported from the Siple Coast; observed differences between the upper 0.1-0.2 m and deeper material were interpreted as the result of diagenesis in situ (Webb et al., 1979). Vigorous debate has focused on whether Pliocene or Pleistocene fossils are present in the material, which certainly is dominated by Miocene forms (e.g., Kellogg and Kellogg, 1981, 1983, 1986; Brady, 1983). Recent studies (Harwood, 1986; Harwood et al., 1989) question whether any undoubtedly post-Miocene diatoms occur at J9 and support a mid-late Miocene age for the youngest documented event of marine productivity in the interior Ross Embayment.

Anderson et al. (1980) have reconsidered the physical properties of the J9 sediments and concluded that the sediment probably is a basal till rather than a dropstone diamicton. However, Harwood et al. (1989) present evidence suggestive of a dropstone origin. A basal till might contain only recycled fossils from its source area, whereas a water-laid sediment probably would contain some fossils indicative of the time of deposition. In this regard it is worth noting that Raiswell and Tan (1985) have interpreted the chemistry of the J9 cores as indicating Pleistocene deposition of at least the upper 0.1-0.2 m, and possibly the entire length.

North of the Ross Sea, the continental rise and abyssal plain are blanketed by a Tertiary sedimentary wedge hundreds of meters to kilometers thick (Hayes and Frakes, 1975). Miocene to Recent sediments in this wedge contain clasts transported by ice (Hayes and Frakes, 1975).

GLACIOLOGICAL CONSIDERATIONS

Some glaciological models, including those of Thomas and Bentley (1978) and Stuiver et al. (1981) have reconstructed the Wisconsinan-maximum West Antarctica ice sheet as having advanced to the edge of the continental shelf and having developed an equilibrium, East Antarctic-type surface profile characterized by a steep surface slope near the coast and thick ice with a gradual surface slope inland. Other authors have suggested that the Wisconsinan-maximum West Antarctic ice sheet was grounded in what is now the Ross Sea but exhibited a low, ice-stream surface profile (Thomas, 1979; Denton et al., 1986; Alley et al, 1987). Drewry (1979) summarizes evidence from West Antarctica against an equilibrium high-profile ice sheet in the Ross Sea, noting that such an ice sheet would require greater increases in ice thickness in the vicinity of Byrd Station than are allowed by the data of Whillans (1976) and Robin (1977). Drewry (1979) then presents the hypothesis that the Ross Ice Shelf expanded during the Wisconsinan but that the grounding line advanced only about as far as J9.

The Ross Embayment is relatively deep near the modern grounding line, shallows outward to the edge of the continental shelf, and has relatively constant width from the modern grounding line to the shelf edge (Figure 1). In the absence of large increases in marginal ablation, a sufficiently large sea-level drop for a sufficiently long time necessarily would allow the Ross Ice Shelf to become fully grounded and allow grounded ice to expand to the edge of the continental shelf, regardless of basal conditions. The minimum sea-level drop required for this to occur has been termed a critical alue and estimated as about 120-130 m for $O(10^3-10^4$ a) (Weertman, 1974; Thomas and Bentley, 1978; Drewry, 1979; also see discussion by R.H. Thomas appended to Drewry, 1979).

The ability of a morainal bank or till delta to cause grounding in water that otherwise is too deep (Powell, 1984) suggests that conveyor-belt recycling of a till delta would allow grounding-line advance to the edge of the continental shelf for a sea-level drop less than the critical value. In this case, the rate of grounding-line advance would be limited by the rate of till-delta recycling. Data summarized by Drewry (1979) show that the actual Wisconsinan-maximum drop in sea level was within a few meters or tens of meters of this critical value, but whether the critical value was achieved for a sufficiently long time, if at all, is uncertain.

HYPOTHESIS

Wisconsinan-maximum sea-level fall caused the grounding line of the West Antarctic Ice Sheet to advance across the Ross Sea to the edge of the continental shelf. Sea-level fall caused increased interaction of the ice shelf with pinning points, increasing backstress on grounded ice and causing ice over the heads of till deltas to steepen and thicken to maintain force balance. This caused the water film at the ice-till interface to thin and increased the ice-till coupling and the till flux across the delta. The resulting conveyor-belt recycling of the delta accompanied the grounding-line advance, and may have been required to allow the grounding-line advance if the actual sea-level fall was less than the critical value for a grounded ice sheet in the Ross Sea without till deltas.

Grounding-line advance led to a low-profile ice sheet. Much of the newly grounded ice sheet was occupied by ice streams, but slow-moving ridges between ice streams may have existed, perhaps at Crary Ice Rise and elsewhere, and may have been frozen to their beds locally. The ice streams were lubricated by water-saturated till layers some meters thick, with erosion (including remobilization of older till) occurring beneath the till (Blankenship, et al., 1987; Rooney et al., 1987). Lubricating till for the ice streams was supplied by advection from upstream, by local remobilization and erosion, and by recycling of till deltas. This till was transported to the grounding line at the edge of the continental shelf, where it built till deltas and/or slumped downward to the abyssal plain.

During post-Wisconsinan sea-level rise the ice was floated off the bed to leave a meters-thick continuous layer of basal till across the Ross Sea. Sorted sand layers of the type reported by Kellogg et al. (1979) were left locally during grounding-line retreat where water flows were concentrated, and the till layer may have thickened locally as till deltas began to develop during any pauses in grounding-line retreat. The grounding line eventually stablilized near its present position about 5,000-10,000 years ago owing to cessation of sea-level rise and to back-stresses from interaction of the Ross Ice Shelf with its sides and with pinning points (Thomas and Bentley, 1978); deposition of modern till deltas then began. Floating of frozen-on regions of slow-moving grounded ice during grounding-line retreat may have allowed localized dropstone sedimentation during subsequent basal melting, as proposed for the Filchner-Ronne Ice Shelf by Orheim and Elverhoi (1981).

These events may have occurred several times during the latest Pliocene-Pleistocene, and possibly before. In each case, erosion beneath the grounded ice may have occurred wholly within the basal tills from earlier advances or may have cut through earlier tills to the older glaciomarine sediments beneath the Ross Sea unconformity. The Ross Sea unconformity thus may represent one or several latest Pliocene-Pleistocene erosional events, and the overlying till may have been deposited by the latest advances or may include material from several advances. The number of advances that contributed to erosion of the Ross Sea unconformity and to deposition of the overlying till may vary geographically. The unconformity observed at the base of the deforming till at UpB (Rooney et al., 1987) is the inland extension of the Ross Sea unconformity, and is still being eroded.

TEST OF HYPOTHESIS

The hypothesis presented above makes a number of testable predictions. The hypothesis requires that the material resting on the Ross Sea unconformity is a basal till, as argued by Anderson et al. (1980). It also seems to require that the material at J9 is a basal till or some part of a till delta that was deposited during the Pleistocene. However, the hypothesis does not require the J9 material to contain Pleistocene fossils. This is because the large fluxes of till envisioned here should allow "flushing out" of younger forms deposited near J9, so that only sediments eroded upglacier beneath the grounded ice of the West Antarctic ice sheet or from deeper, older sediments in the vicinty of J9 would be observed in the till there. We thus would expect the youngest abundant fossils at J9 to be no younger than the most recent period of marine productivity in the region now occupied by the grounded West Antarctic ice sheet.

Testing of our hypothesis clearly requires resolution of the existing conflicts about the age and depositional mode of sediments in the Ross Sea and beneath the Ross Ice Shelf. In addition, further geophysical and drilling studies are needed of deforming till and the till delta beneath ice stream B.

We also need to develop the modeling capability to quantify this hypothesis and to use it to make further testable predictions regarding sediments in the Ross Sea. These tests represent a large component of a new scientific initiative to study the Sea-Level Response to Ice Sheet Evolution (SeaRISE).

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FIGURE CAPTIONS

Figure 1

Bathymetry (depth below sea level in meters of base of water column or of grounded ice) of Ross Sea and most of the area of West Antarctica draining into it. The contour interval changes from 50 m in the Ross Sea and under the Ross Ice Shelf to 250 m beneath the West Antarctic inland ice. On a grid scale, 1° = 111 km. Byrd Station (Byrd), Upstream B camp (UpB), and J9 are shown. From Bentley and Jezek (1981).

Figure 2

Map showing Ross ice streams flowing into Ross Ice Shelf; ice streams are shown stippled. Modified from Shabtaie and Bentley (1987). Grounding line of Rose (1979) is shown on the ice streams by light dashed line and grounding line of Shabtaie and Bentley (1987) is shown by heavy solid line; ice plains occur between the two. Major camps and features are indicated.

Figure 1

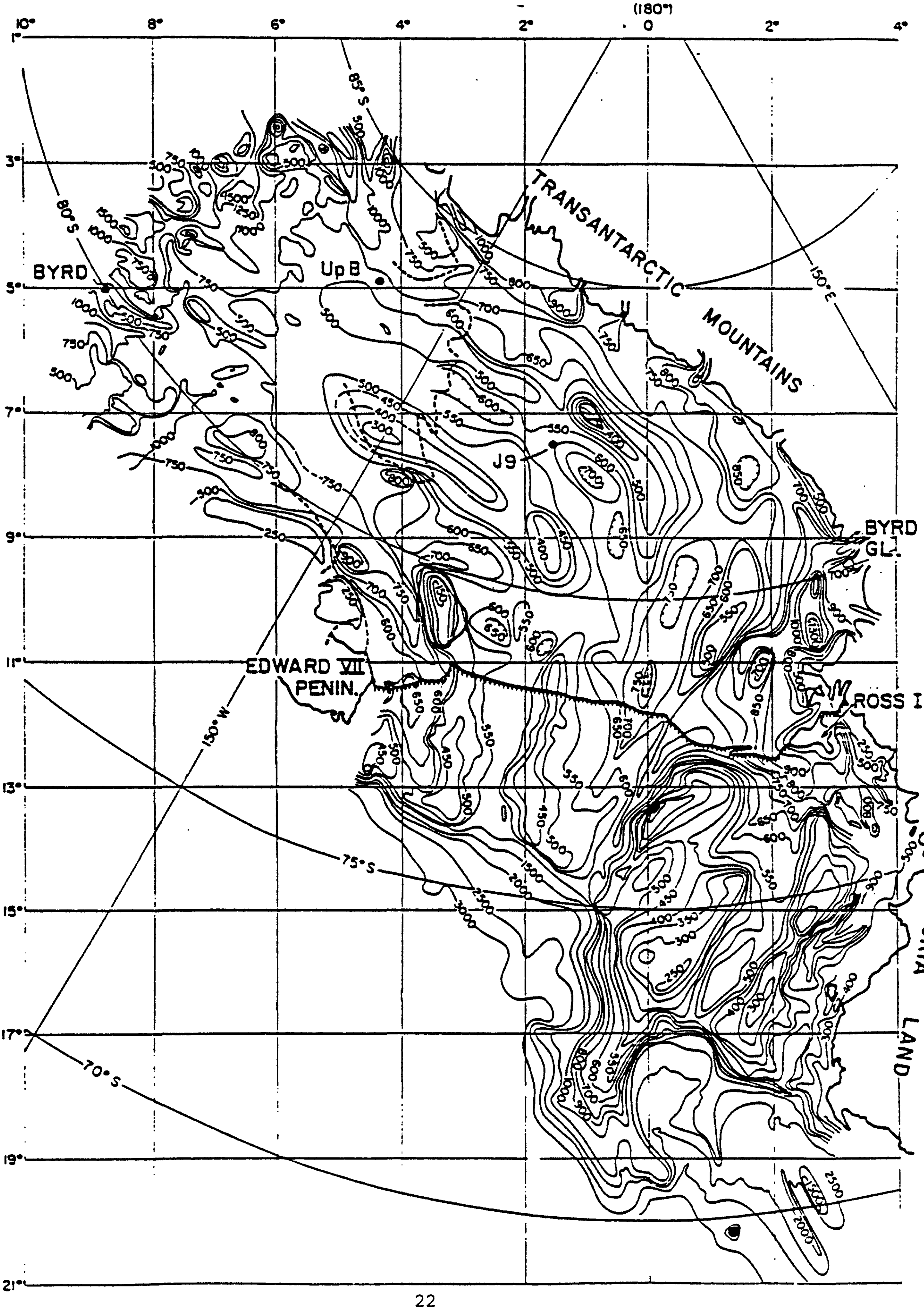
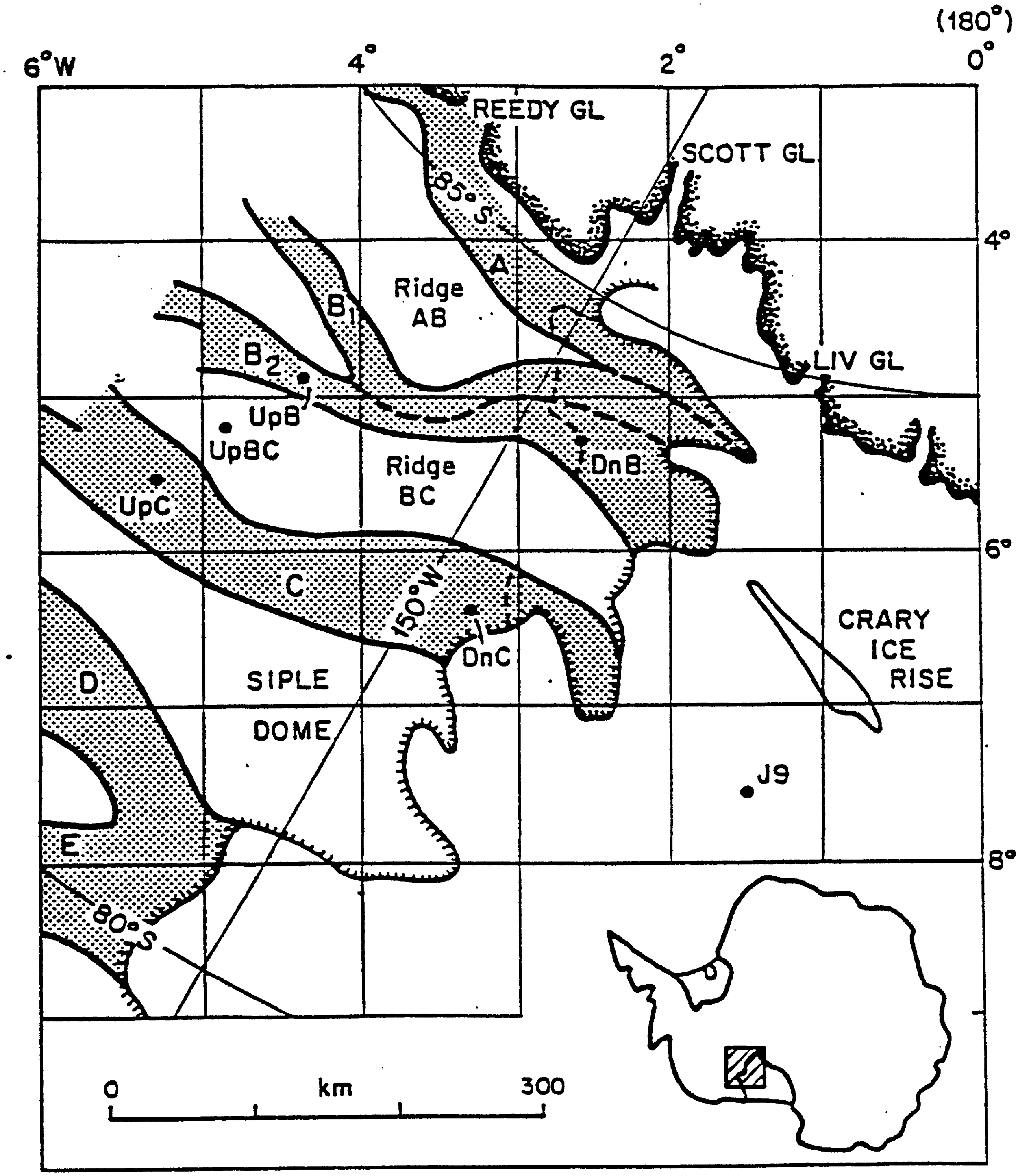

TRANSANTARCTIC MOUNTAINS
BYRD
Up B
J9
BYRD GL.
EDWARD VII PENIN.
ROSS I.
VICTORIA LAND
85° S
80° S
75° S
70° S
150° W
150° E
(180°)

Figure 2


(180°)
6°W
4°
2°
0°
REEDY GL
SCOTT GL
85°S
4°
A
Ridge
AB
B1
B2
LIV GL
UpB
UpBC
Ridge
BC
DnB
UpC
6°
C
150°W
DnC
CRARY
ICE
RISE
D
SIPLE
DOME
J9
E
8°S
80°S
0
km
300

SEAFLOOR SAMPLING ON THE ANTARCTIC CONTINENTAL MARGIN

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Drilling on the Antarctic continental margin has concentrated on portions of the Ross Sea (DSDP Leg 28 and MSSTS-CIROS sites), Weddell Sea (ODP Leg 113), and Prydz Bay (ODP Leg 119). During the late 1960's an ambitious piston coring program (Eltanin Program) sampled the Southern Ocean strata with an emphasis on the deep sea. Later, the Deep Freeze Program included a long-term piston coring effort. Several hundred piston cores and dredge samples were collected on the continental margin as a result of these programs. These cores now reside at the U.S. Antarctic Marine Geology Research Facility at Florida State University, Tallahassee.

Rugged glacial topography characterizes most of the Antarctic continental shelf; the result of erosion by marine ice sheets. In most areas, this erosion has cut deep into older sequences. Seismic records from several portions of the continental shelf show that much, if not all, of the Neogene shelf sequence subcrops on some area of the shelf. Hence, the ice sheets have exposed a rich record of the continent's geological and climatic history. Unfortunately, the same ice sheets that eroded the shelf also deposited a layer of till that is virtually inpenetrable with piston cores and gravity cores. Very few of the cores from the continental margin penetrated outcrops older than late Pleistocene.

Studies of piston cores have provided an understanding of sedimentological processes active on the continental shelf, and of the more recent climatic record of the continent. But the true "mother load" of geological knowledge lies just below the seafloor. Unfortunately, drill ships rarely visit the Antarctic region, so a need exists to develop a coring device capable of subbottom penetration of a few tens of meters. Coupled with detailed high resolution seismic surveys, this type of coring program would advance our understanding of Antarctica's climatic and tectonic history.

INTERPRETATION OF GLACIAL MARINE DEPOSITS AND THE STRATIGRAPHIC RECORD OF ANTARCTICA'S GLACIAL, CLIMATIC, AND OCEANOGRAPHIC HISTORY: PROBLEMS, PROGRESS, AND FUTURE NEEDS

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The most complete stratigraphic record of Antarctica's glacial/climatic history exists in the sedimentary basins of the continental margin. In this workshop, we will discuss how and where to sample these strata. But we also must consider the need for research that provides the information needed to interpret this record. Geologists still are debating the paleoclimatic and paleoceanographic implications of the few sites that already have been drilled; this debate will continue until our understanding of glacial marine sedimentation improves. This requires studies of cores and high resolution seismic records from the varied glacial marine settings that presently exist around Antarctica.

Thousands of piston cores, box cores, and grab samples have been acquired from the seafloor surrounding Antarctica since the 1960's.

During the late 1960's and throughout the 1970's, sedimentological studies concentrated on the deep seafloor; resulting in the publication of several maps showing the regional distribtution of surface sediments (Lisitzin, 1962; Goodell, 1973; McKoy et al., 1985; Anderson, 1990). Over the years, a number of papers dealing with paleoceanographic and paleoclimatic interpretations of Southern Ocean sediments have appeared in the geologic literature, too many to summarize in this paper.

Modern abyssal sediments of the Antarctic region consist of biogenic carbonate, biogenic silica, fine-grained terrigenous material (derived mainly from Antarctica), and ice-rafted material. Manganese nodules and micronodules abound within scour zones. The relative concentrations of these components varies widely across the seafloor, and a variety of processes influence the distribution of major sediment types is. Such processes includ oceanographic circulation and water mass properties, sea ice cover, the drift paths of icebergs, and variations in the amount and character of sediment transported from the Antarctic continent. Previous attempts to reconstruct the paleoclimatic and paleoceanographic record from abyssal sediments, more often than not, concentrat on variations in only one of the above components. The underlying assumtions in such studies are that 1) variations in the concentration or size of a single component reflect variations in its rate of flux to the seafloor and 2) the flux rate of other components remain constant. Another common mistake is to assume that the rate of flux of a single component corresponds to variations in a single supply mechanism, for example the assumption that down-core variations in the concentration of ice-rafted debris reflect variations in the volume of ice on Antarctica. Such variations could indicate changes in the glacial maritime setting of the continent, iceberg drift tracks, sea surface temperatures, or varitations in the flux of other sedimentary components to the seafloor. Extracting a valid history of Antarctic glaciation from the literature on deep sea deposits may be one of the greatest challenges facing Antarctic sedimentologists.

A paucity of samples hampered early studies of sedimentation on the Antarctic continental margin. The first detailed studies of sedimentation processes on the Antarctic continental margin concentrated on the Ross Sea (Chriss and Frakes, 1972) and the Weddell Sea (Anderson, 1972). Later investigations were conducted on the Wilkes Land (off the George V Coast) continental shelf (Anderson et al., 1980; Domack, 1982; Dunbar et al., 1985); Ross Sea (Kellogg et al., 1979; Anderson et al., 1984); Weddell Sea (Anderson et al., 1980; Elverhoi, 1981); Marguerite Bay (Kennedy and Anderson, 1988); and northern Antarctic Peninsula region (Griffith and Anderson; 1989). Anderson and Molnia (1989) provide an up-to-date review of these and other works.

Late Pleistocene tills are widespread on the Wilkes Land, Ross Sea, and Weddell Sea shelves (Kellogg et al., 1979; Anderson et al., 1980; Domack, 1982; and Elverhoi, 1981) and posess all the characteristics of continental tills (Anderson et al., 1980). Holocene glacial marine sediments overlying the tills vary widely in texture and composition across the shelf. These differences reflect differences in the glacial marine setting, oceanographic circulation, sea ice cover, and the influence of sediment gravity flow processes. We are making steady progress toward understanding how these different mechanisms affect sedimentation. Thus, the shelf contains a dramatic record of climatic and glacial changes since the late Pleistocene. Future work should concentrate in two areas: 1) study of how these changes manifested themselves in the deep sea record; and 2) the improvement of biostratigraphic resolution within continental margin deposits.

Drilling on the Antarctic seafloor has been limited to the Ross Sea (DSDP Leg 28; MSSTS and CIROS sites), Bellingshausen Sea (DSDP Leg 35), Weddell Sea (ODP Leg 113), Prydz Bay (ODP Leg 119), and a few scattered sites from the Southern Ocean abyssal floor (DSDP Leg 29 and DSDP Legs 114 and 119). The sequences drilled on the continental shelf indicate that climatic cooling and ice sheet development were diachronous around the continent. The oldest glacial deposits yet drilled on the shelf were recovered in Prydz Bay. These show that the ice sheet grounded on the shelf as early as middle Eocene time (Barron et al., 1988). In the Ross Sea, glacial marine sediments of Early Oligocene age were drilled at CIROS-1 (Barrett, 1989), and cores from the central shelf (DSDP Leg 28, sites 270-273) contain glacial marine deposits that date back to at least early Miocene (Hayes and Frakes, 1975). Drilling in the Weddell Sea and Bellingshausen Sea concentrated exclusively on the deep sea floor, and the results from these sites remain ambiguous.

One of the problems with past drilling projects in Antarctica has been the virtual absence of high resolution seismic data during site selection and drilling. We must capitalize on our limited drilling opportunities by conducting high resolution seismic surveys on the shelf, and use these data to study the sequence stratigraphy and seismic facies of each area. These data can aid in the development of testable glacial evolution models.

Considerable progress has been made over the past decade toward understanding seismic facies on high latitude continental shelves; most of this work has been carried out on the Canadian shelf and in the North Sea (King and Fader, 1986). We can build on these studies by collecting high resolution seismic data in those areas of the Antarctic already drilled and by comparing these data with those from different glacial marine settings. The results of one such study in the Ross Sea will be presented at this workshop (Bartek and Anderson). It would be interesting to undertake a similar study in Prydz Bay.

Besides the obvious questions concerning Antarctica's long-term glacial climatic history, there is a need to develop a better understanding of short-term (century to millinium scale) climatic changes. This too will rely upon acquiring a better understanding of glacial marine sedimentation. Tectonic basins and glacial troughs on the Antarctic continental shelf contain thick Pleistocene-Holocene sequences. In the past we were unable to date these deposits; they seldom contained sufficient material for radiometric dating. However, recent advances in radiocarbon dating, specifically the development of the tandem accelerator mass-spectrometer (TAMS), provide a means of dating these sediments using very small concentrations of carbon (Domack et al., 1989).

The sole study conducted to date within one of these thick Holocene sections is that of Domack and Jull (in press). They examined a 23 m thick, late Pleistocene-Holocene section drilled at ODP Leg 119, site 740A. The record shows slow and progressive warming since about 10,700 years B.P., with a short term cooling event about 7300 to 3800 years B.P. But Prydz Bay is lies well within the polar regions of Antarctica, and therefore, is subjected less frequently to minor and/or short term climatic changes.

The basins and troughs of the Antarctic Peninsula should contain the most interesting record of short-term climatic events. Studies of recent bay and fiord deposits situated within different climatic zones of the peninsula region indicate very different types of sediments (Griffith and Anderson, 1989). These results are encouraging, and idemonstrate that we can reliably date and interpret the sedimentary record of Holocene climate in Antarctica.

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RESULTS OF HIGH RESOLUTION SEISMIC REFLECTION SURVEYS OF THE NORTHERN ANTARCTIC PENINSULA REGION

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High resolution (single channel/water gun and sparker) surveys of the continental shelf between, and including, Marguerite Bay and Bransfield Strait, conducted during the 1985, 1986, 1987, and 1989 field seasons, resulted in a data set exceeding 6,000 kilometers (Fig. 1). These data are being used to examine the tectonic and climatic history of the region.

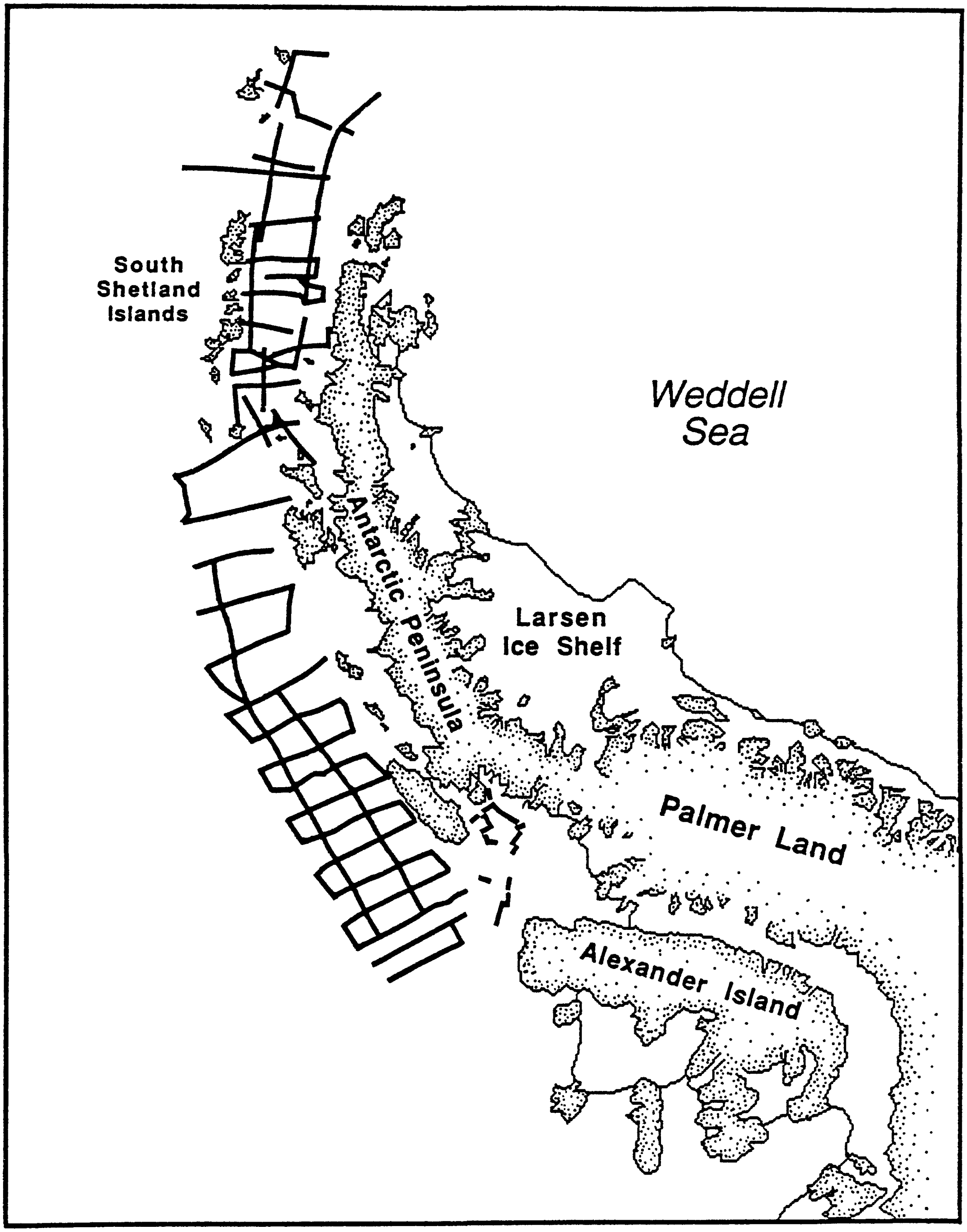
The continental margin in this part of Antarctica has evolved from an active margin to a passive one as the Aluk Ridge gradually was subducted at the Antarctic Plate Boundary. This transition occurred diachronously; as the timing of ridge subduction proceeded from south to north (oldest to youngest). Thus, the shelf exhibits both tectonic and sedimentologic segmentation, and seismic data show that the extent of tectonic deformation and post-tectonic sedimentation varies correspondingly.

Seismic records from the shelf south of Bransfield Basin show four sequences (Fig. 2). The oldest of these, S4, consists of folded and faulted pre- and syntectonic deposits, presumably consisting of volcaniclastic deposits. Sequence S3 represents an accretionary sequence resting sharply on S4, and reflects efficient sediment transport across the shelf following ridge subduction. The age of this sequence boundary is inferred from paleomagnetic data. A major unconformity (glacial erosion surface) separates S3 from the overlying sequence (S2). Abundant glacial erosion surfaces and massive till tongues characterize S2. This sequence marks an episode of ice sheet waxing and wanning across the shelf. The youngest sequence, S1, is a draping sequence consisting of glacial marine sediments.

Sequence S2 rests directly on S4 in the segment of continental shelf situated between the Biscoe and Anvers fracture zones. Here, ridge subduction occurred approximately 18 Ma. This implies that an ice sheet grounded on the shelf by, or shortly after, this time. This corresponds approximately with the Melville Glaciation in the King George Island area.

Three subbasins, shown by the overall morphology of the basin, divide Bransfield Strait (Fig. 3). Geophysical data demonstrate that the three subbasins represent discrete tectonic segments with different tectonic and depositional histories (Fig. 4). Tectonic segmentation of the back-arc basin reflects the continuing influence of the South Shetland subduction zone. Relative ages of back-arc and forearc sequences suggest that forearc subsidence resulting from cessation of subduction pre-dates back-arc rifting.

Two distinct systems tracts stack to form depositional sequences of the basin. Organic-rich hemipelagic sediments drape the basin during highstand/interglacial periods. In contrast, large volumes of glacially-derived terrigenous sediments prograde into the basin during lowstand/glacial maxima. Subsidence rates and sediment thicknesses suggest that these glacial/interglacial cycles are of ~0.8 Ma duration.


South
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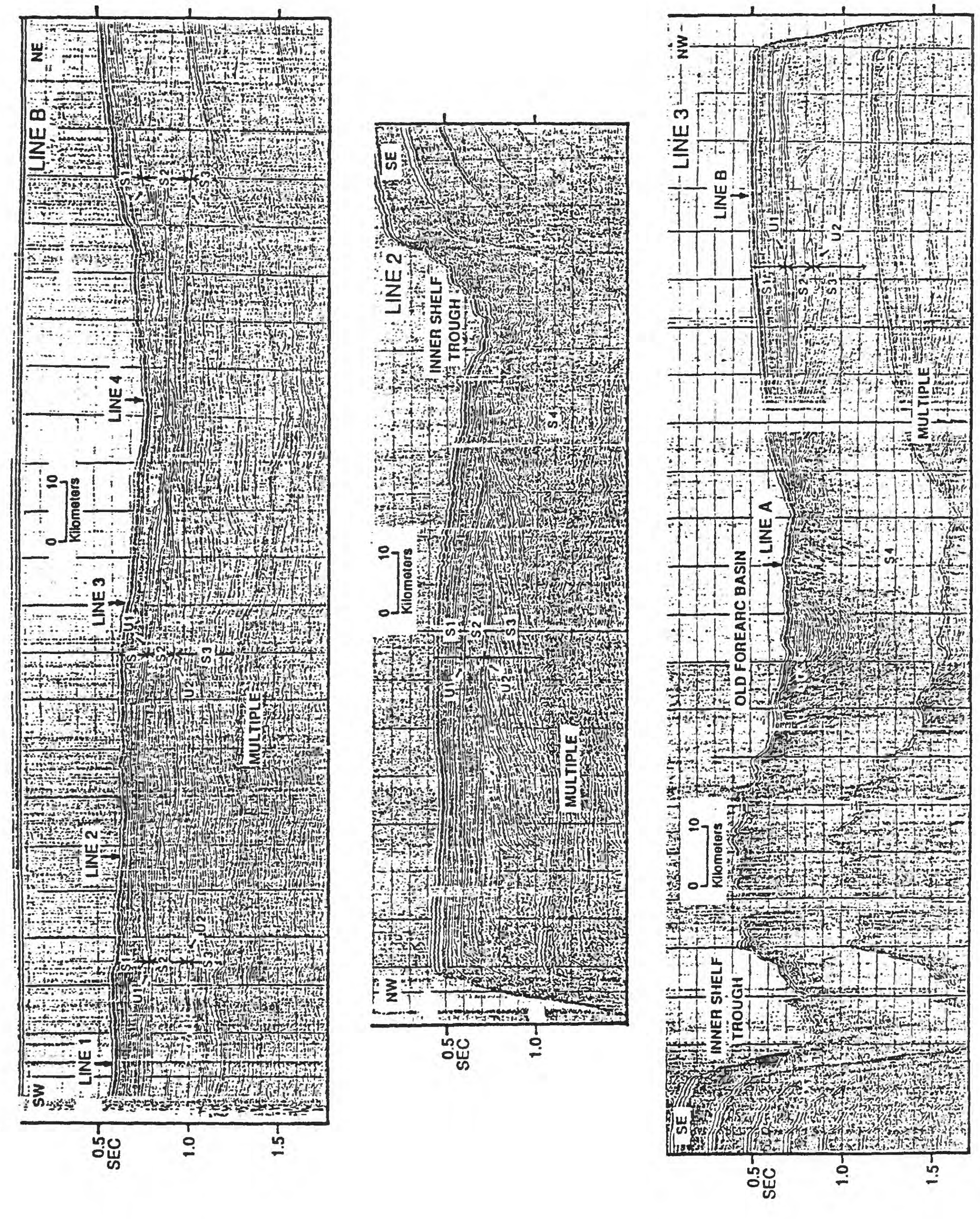
Weddell
Sea
Antarctic Peninsula
Larsen
Ice Shelf
Palmer Land
Alexander Island

Figure 1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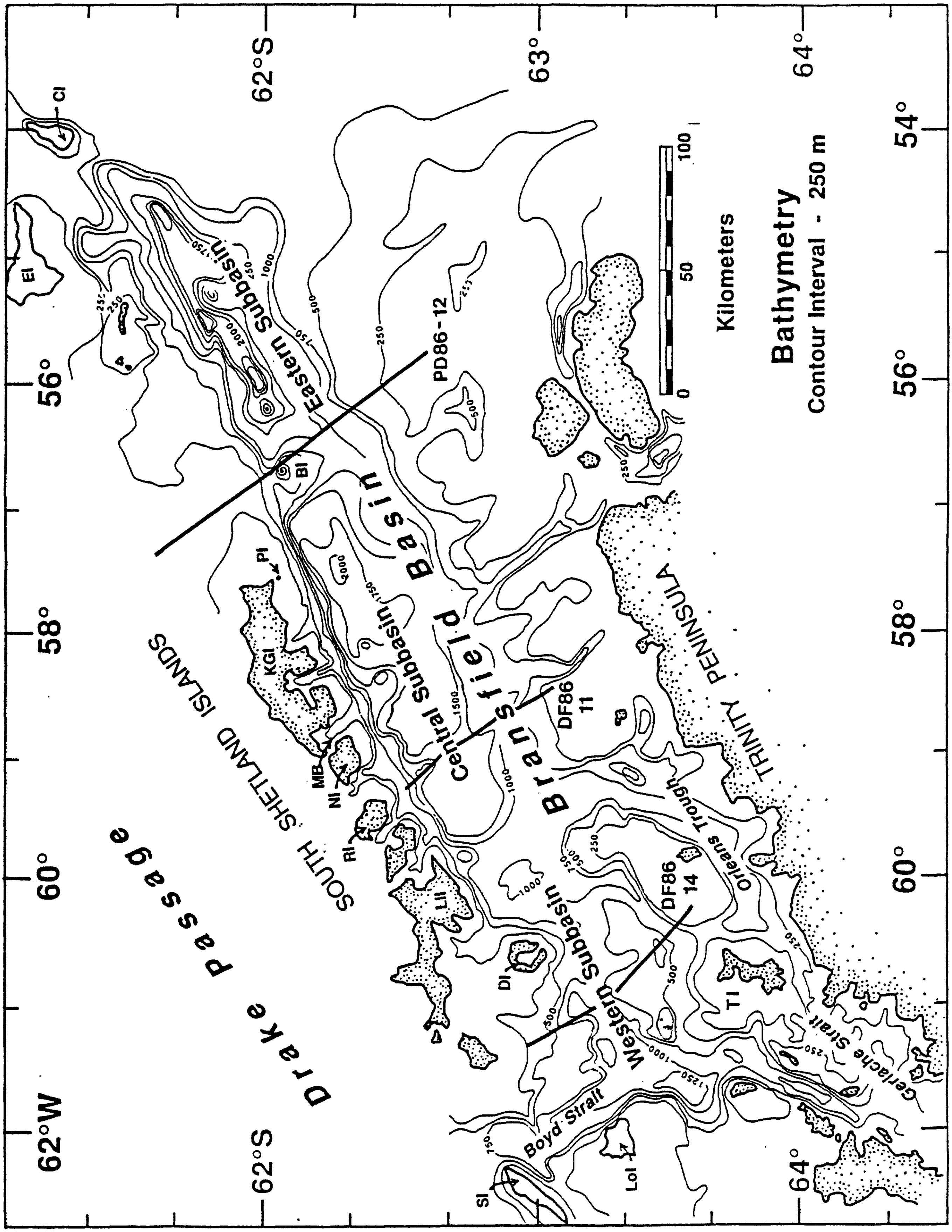
OLD FOREARC BASIN

Figure 2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Drake Passage
SOUTH SHETLAND ISLANDS
Bransfield Basin
Eastern Subbasin
Central Subbasin
Western Subbasin
Orleans Trough
TRINITY PENINSULA
Boyd Strait
Gerlache Strait
PD86-12
DF86 11
DF86 14
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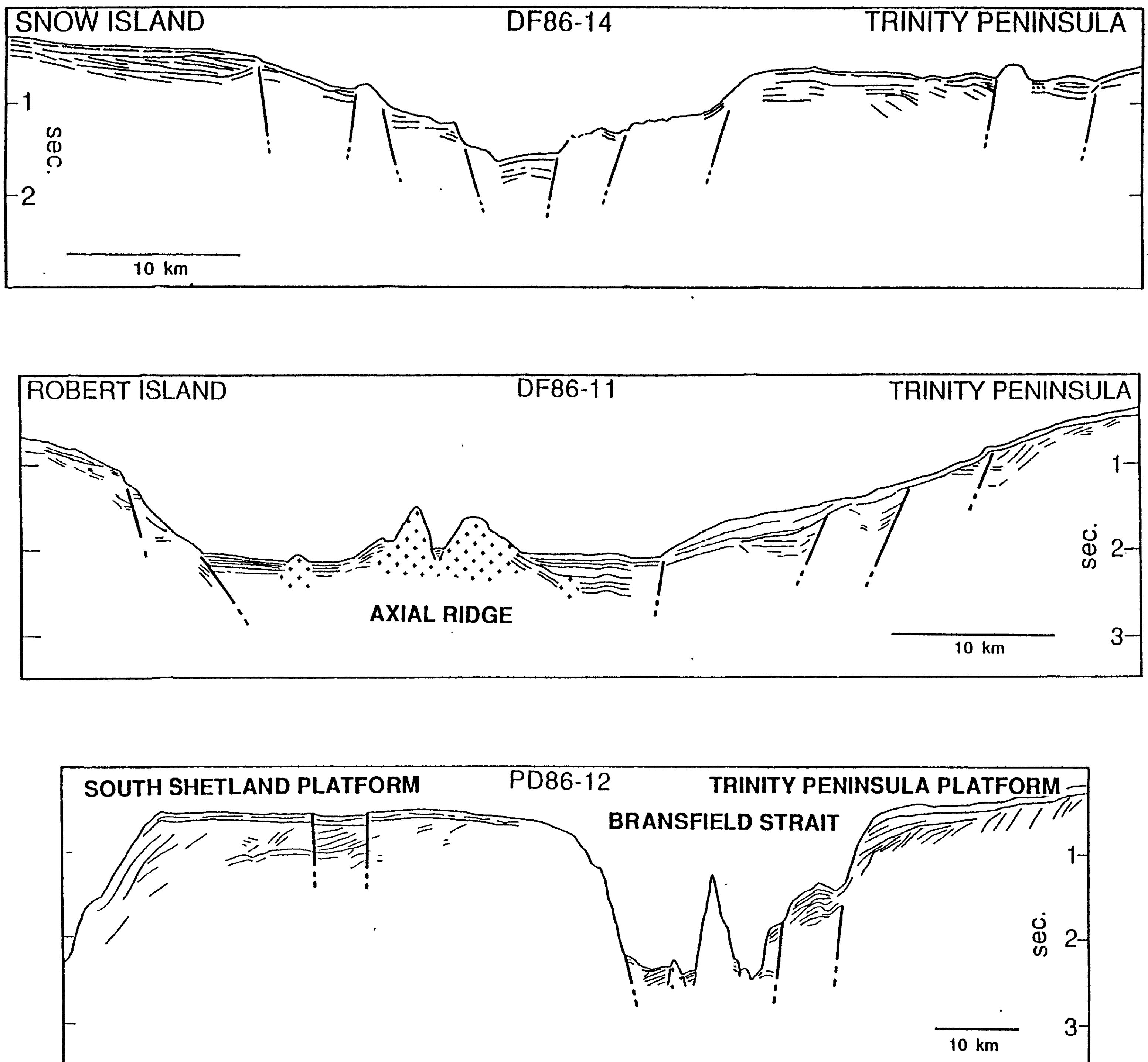
Figure 3


SNOW ISLAND
DF86-14
TRINITY PENINSULA
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ROBERT ISLAND
DF86-11
TRINITY PENINSULA
AXIAL RIDGE
1
2
3
sec.
10 km
SOUTH SHETLAND PLATFORM
PD86-12
TRINITY PENINSULA PLATFORM
BRANSFIELD STRAIT
1
2
3
sec.
10 km

Figure 4

Antarctic Continental Margin: British Antarctic Survey Data

P F Barker, R D Larter, C J Pudsey

The British Antarctic Survey, and before 1987 the University of Birmingham, UK, have acquired marine geophysical and geological data in the SW Atlantic, SE Pacific, Scotia and Weddell Sea, over many years. This report confines its attention to

(a) the continental margins of the Antarctic Peninsula and South Orkney microcontinent

(b) multichannel seismic, GLORIA and shallow sidescan data, 3.5 KHz profiles and sediment cores

(c) (therefore) the three cruises RRS Discovery 154 and 172, and RRS Charles Darwin cruise 37, in the period 1985-9.

Multichannel Seismic profiles were acquired on Discovery Cruises 154 (D154) and 172 (D172), in early 1985 and 1988. The source on D154 was small, generally a 4-gun array totalling 8.5 litres, fired at 50 metre intervals. The streamer had an active length of 2.35 km, comprising 48 50-m groups. Sampling interval was 4 ms, and most data were recorded to 10 s TWT. The 24-fold CDP data were commercially processed through to stacked time sections, and short lengths have been migrated, f-k filtered etc as appropriate. Out of 3770 km of MCS data acquired during D154, 2310 km are relevant here. Lines AMG845-1 to -11, totalling 1110 km, were an examination of ridge crest subduction, and sediment transport under a glacial regime, across the Antarctic Peninsula continental shelf and slope (Larter and Barker, 1989; in press). Lines AMG845-12 and -13 (370 km) crossed the South Shetlands margin, and -14 was a 460 km-long transect of the northeast Peninsula shelf, from the South Shetland block, across Bransfield Strait and ultimately into the Weddell Sea (Barker and Lonsdale, in press). Lines AMG845-16, -17 and -18 (370 km total) on the South Orkney microcontinent were shot in preparation for drilling during ODP Leg 113, aimed at an examination of the history of West Antarctic glaciation and palaeo-circulation. Sites 695 and 696 were drilled on Line -18 (Barker, Kennett et al, 1988a,b).

A hull-mounted shallow sidescan system (1-side only) was operational most of the time on the continental shelf during the acquisition of lines -1 to -11 and -14, and along small parts of lines -16 and -17. A 3.5 KHz profiler was operational throughout D154, and magnetic and gravity data were obtained along most lines. Heat flow measurements were made on the Antarctic Peninsula margin during D154 (Dougherty et al, 1986). Among direct sampling efforts during D154 were dredges D98 to 104 on the Antarctic Peninsula margin and gravity cores GC018 to 028 on the eastern margin of the South Orkney microcontinent (Pudsey et al, 1987; 1988).

Multichannel seismic data were acquired during Discovery cruise 172 using the same system with a slightly larger source (usually 4 guns, 15.8 l). Sampling interval was 4 ms, and record lengths were typically 6 s TWT on the shelf, 9 s TWT across the margin and rise. A total line length of 3640 km was acquired, of which 2140 km, acquired during Leg 3 along the Pacific margin of the Antarctic Peninsula, are relevant here. Unfortunately, the 48-channel streamer was lost at the end of Leg 2, after probable collision of the tail buoy with a bergy bit in southern Powell Basin. Leg 3 data were acquired with a 16-channel streamer, built from spare sections, and giving only 8-fold cover. Of these data, lines BAS878-11 to -18 supplemented the main body of D154 data on the continental shelf close to Anvers Island, whereas Lines -19 to -21 formed a separate survey, farther to the southwest and extending out to DSDP Site 325 on the continental rise. BAS has now implemented a small in-house seismic processing capability, which has started to process the 1988 data. Line 19 has been processed externally, and is interpreted by Larter and Barker (in press).

Magnetic, gravity and 3.5 KHz profiles were acquired along all of these lines; the same hull-mounted sidescan system was on board as on D154, but failed early in the Leg, and produced few useful data. Direct sampling included 6 dredge and 8 core stations on the Antarctic Peninsula shelf.

Charles Darwin Cruise 37 was essentially a GLORIA cruise. Four main surveys were compiled, including one of the Pacific margin of the Antarctic Peninsula. These are the only long-range sidescan data from the Antarctic margin. They were acquired along 3100 line km of ship track, and cover 85000 km^2. The GLORIA swath width is up to 45 km. GLORIA data were acquired at between 11 and 16 km/hr, and other data were acquired at the same time. A dual channel seismic system, digitally recorded, employed a single water gun (1.3 l) fired at 30 s intervals, 2 s before a single air gun (4.9 or 11.5 l) fired at 15 s intervals, synchronised with GLORIA to prevent water gun signals contaminating GLORIA data. Magnetic, gravity and 3.5 KHz data were also recorded. The aim of this survey was to help existing studies of shelf/slope/rise sediment transport, and of ridge crest subduction. It will be used as the basis for more detailed investigation and sampling on future cruises. GLORIA and associated seismic data are being processed in-house.

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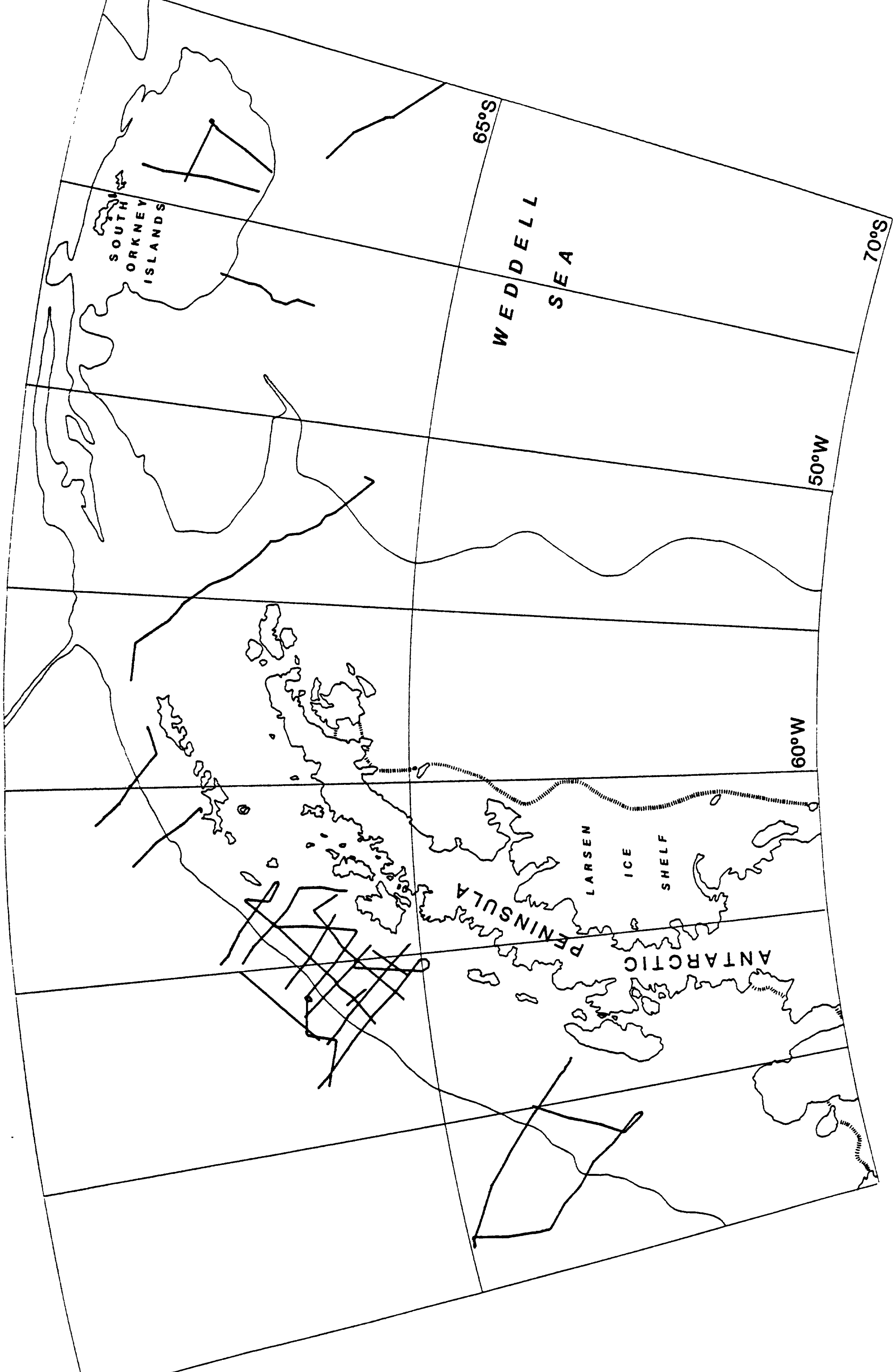
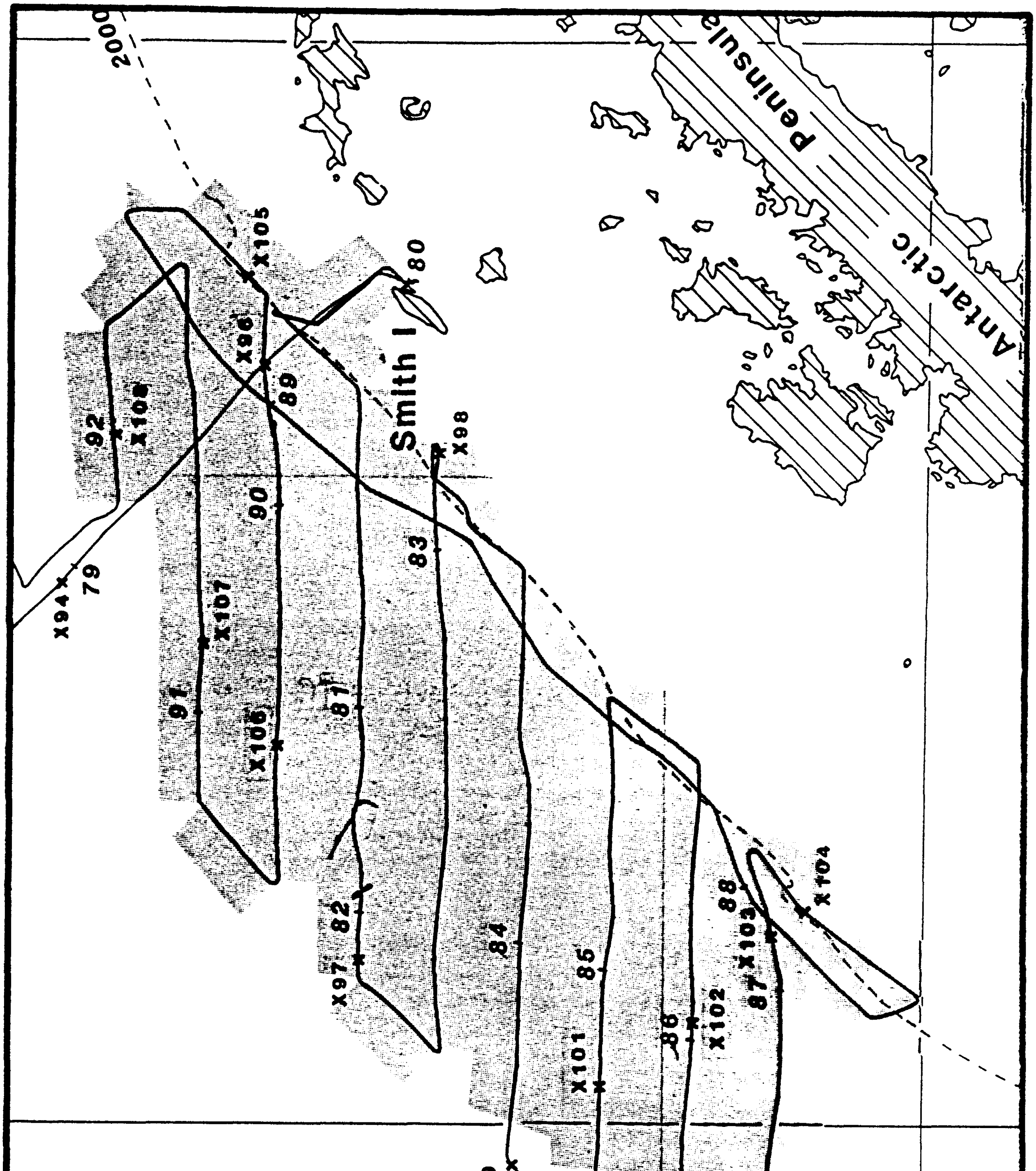
Figure 1. Locations of MCS profiles on margins of Antarctic Peninsula and South Orkney microcontinent, RRS Discovery cruises 154 and 172, 1985 and 1988.

Figure 2. Location of GLORIA survey of Pacific margin of Antarctic Peninsula, RRS Charles Darwin cruise 37, 1989.



SOUTH
ORKNEY
ISLANDS
65°S
70°S
WEDDELL
SEA
50°W
60°W
LARSEN
ICE
SHELF
ANTARCTIC
PENINSULA


Antarctic Peninsula
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Morphologic, stratigraphic, and sedimentologic studies of surficial sediments off Wilkes Land and in the western Ross Sea

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Bathymetry, side-scan sonar, high resolution seismic-reflection data and cores were obtained from portions of the continental shelf off Wilkes Land and in the western Ross Sea from back to back cruises in January and February, 1984. The data consist of paper records, cores and digital side-scan sonar tapes which are archived at the US Geological Survey in Palo Alto, California. At the present time there are no ongoing studies based on the data and no future plans to re-study the existing data or to obtain new data. The following further describes the data and its interpretation.

A small section of formerly glaciated mid- to outer-shelf off Wilkes Land was studied with side-scan sonar and seismic reflection techniques (12-, 7-, and 3.5-kHz transducers, and 1-kHz boomer). The data delineate the seismic signature of surficial sediments and allow detailed examination of small-scale morphologic features associated with banktop, bank slope, and self trough environments to water depths of about 600 m (Figure 1). Moraine-like ridges, 30 to 50 m high rim the southern flank of the bank top. Discontinuous and chaotic reflectors from the bank top and bank slope suggest a sub-glacial or iceberg keel disruption origin for these diamicts. The association of these reflectors with crisp disruption bedforms on the seabed, ascribed to iceberg groundings, supports the latter interpretation for chaotic bedding. Ice gouges from the bank top to depths over 500 m were sparse and were typically multiple-grooved incisions a few meters deep and 10's of meters wide. Semi-circular, flat floored depressions 30 to 150 m in diameter were prevalent in the same environment and are also ascribed to modern ice keel groundings. In the shelf trough environment, acoustically transparent siliceous Holocene ooze drapes and blankets what are interpreted to be sub-glacial ridges and furrows having 5 to 10 m of relief. There ridges and troughs trend offshore and are ascribed to pre-Holocene glacial advance onto the shelf.

Western Ross Sea high-resolution seismic-reflection records (12- and 3.5-kHz transducers, and 1-kHz boomer) led to the identification of eight echo-character facies and six microtopographic facies in the sediment deposits that overlie the Ross Sea unconformity. These facies identify 3 depositional regions (Figure 2). 1) McMurdo Sound facies suggest turbidity current deposition in the western part of the basin. 2) The region between 77°S and 75°S at water depths greater than 600 m water depth contain thin, pelagic deposits typical of deep water environments. 3) To the north (75°S to north of 74°S) the signature of acoustic facies indicates higher energy conditions or, ice related processes. Also seen in this region are thick lodgement tills deposited from the most recent advance of the West Antarctic Ice Sheet. This advance is also recorded in relief features indicative of the base of the grounded ice sheet prior to decoupling form the seafloor.

A region of hummocky topography northeast of Drygalski Ice Tongue at depths of 270 to 750 m occurs entirely in a 1 to 30 m thick acoustically transparent unit. These hummocks unconformably overlie a stratified, gently deformed and truncated sequence interpreted as Late Oligocene to Late Miocene in age whose upper surface is probably the regional Ross Sea Unconformity of Late Miocene-Pliocene age. The hummocky topography has relief of 1 to 20 m and apparently consists of linear furrows and ridges. Cores from the furrow crests and troughs indicate the hummocks to be a basal till of unstratified gravelly sandy mud. The topography is interpreted as relict from the the irregular base of the moving Ross Sea Ice shelf prior to decoupling from the sea floor during the Holocene or from groundings of large icebergs calved from the ice shelf shortly after decoupling. The absence of acoustically resolvable sediment overlying the till indicates sparse sedimentation during the Holocene.

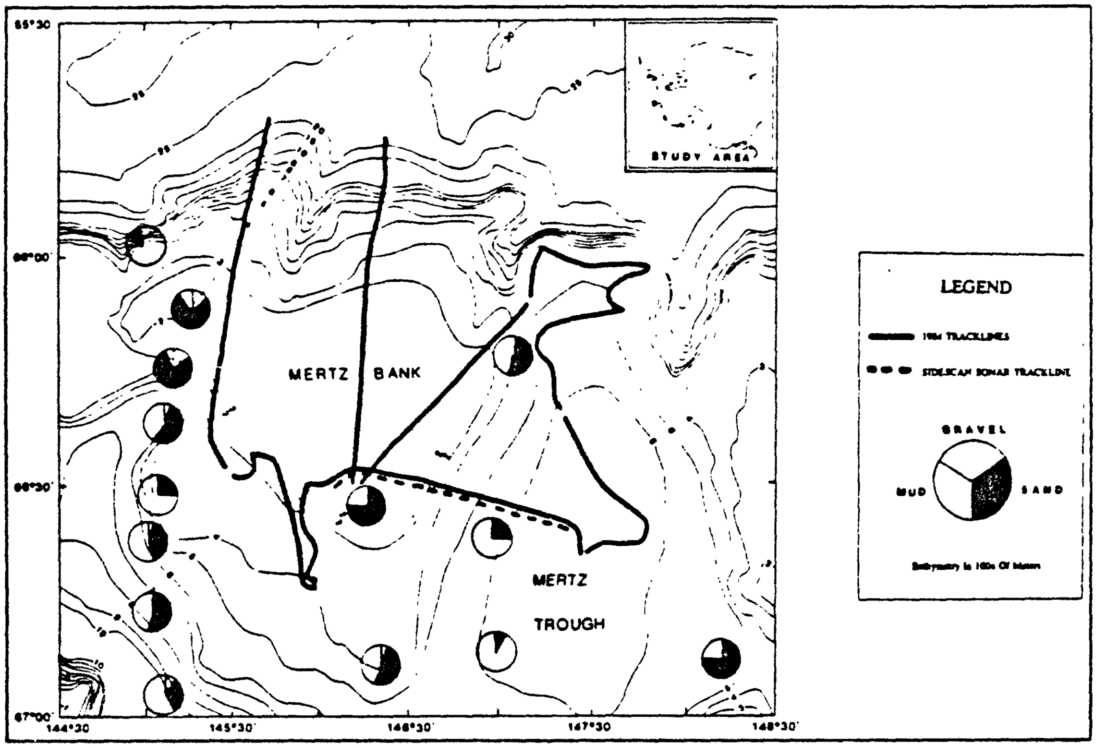

Figure 1. Mertz Bank and Trough on Wilkes Land Margin. Bathymetry, ships tracklines and surficial sediment textures (From Domack, written communication).

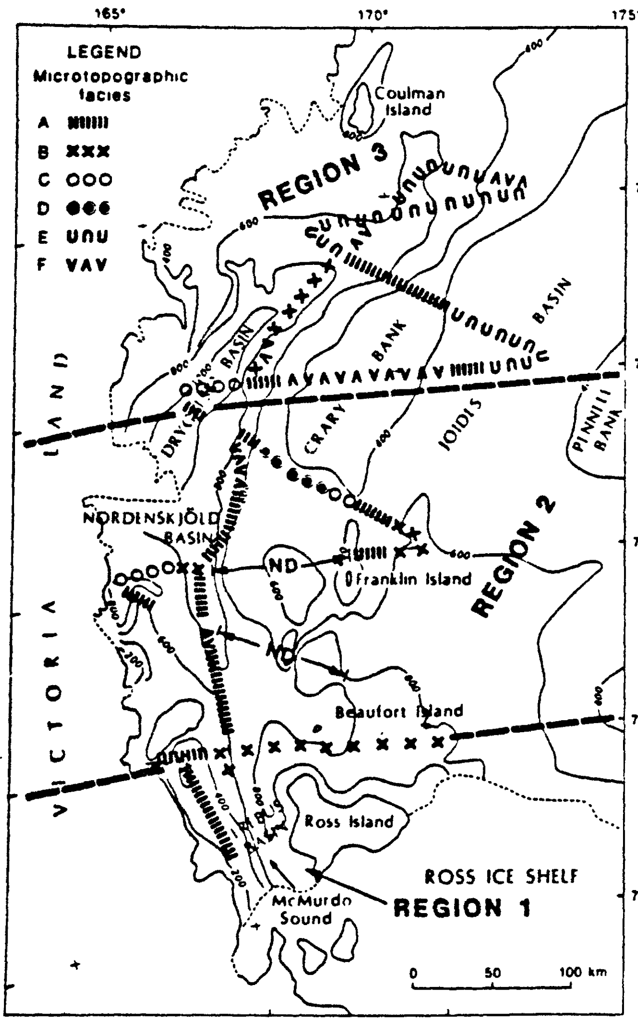

Figure 2. Western Ross Sea showing bathymetry, and distribution of microtopographic facies along tracklines and the three depositional facies regions. ND - no data. Facies A: A smooth surface with small-scale irregularities and "roughness". Facies B: A smooth surface and gently rolling or low relief (less than Facies A). Facies C: A smooth flat surface of negligible relief. Facies D: Similar to C but punctuated by small gullies and mounds. Facies E: "Hummocky" surface of high relief (5-10m). Facies F: "Hummocky" surface of low relief (< 5m).

ANTARCTIC CENOZOIC GLACIAL HISTORY FROM ANTARCTIC GEOLOGIC EVIDENCE

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Geologic evidence from drillcores and outcrops from several parts of the Antarctic indicates an old and varied glacial history for the continent in Cenozoic times (Webb, 1990). Glaciation as old as middle Eocene has been reported from King George Island at the tip of the Antarctic Peninsula and ice-contact volcanics of similar age have been dated from Marie Byrd Land, West Antarctica. However, clear evidence of continental glaciation is found only in Oligocene and younger strata.

Strata on the Antarctic continental shelf have now been drilled in two areas, the Ross Sea and Prydz Bay (Fig. 1) 3000 km apart, revealing a post-Eocene blanket of glacigenic strata deposited in slowly subsiding rift basins. In the eastern Ross Sea at DSDP-270, where the glacial sequence is underlain by glauconitic sandstone, glacial sedimentation began around 26 Ma ago (Hayes, Frakes et al. 1975). In the western Ross Sea, however, the CIROS-1 drillhole, which cored the delta of a major outlet for East Antarctic ice, records ice-rafting going back to 36 Ma and grounded ice, advancing and retreating in phase with sea level falls, from 30 to 22 Ma (Barrett 1989). Broad covariance of glacial advances and sea level falls suggests the growth and decay of large ice sheets (capable of raising sea level at least tens of meters). The occurrence of a beech leaf in mudstone at 28 Ma between two diamictite beds (and beech pollen clusters at other levels in the core) indicates the survival of beech forest on the coast through several such glaciations, and attests to their temperate character.

On the other side of the Antarctic ice sheet, ODP drilling in Prydz Bay cored a seaward dipping wedge of diamictite considered to be deposited largely from grounded ice and as old as Early Oligocene or Late Eocene (Barron et al., 1990). Chronology for Prydz Bay core is not well established and core recovery was poor but it is nevertheless clear that the Lambert Glacier extended out to the edge of the continental shelf for at least some of Oligocene time, and possibly also late Eocene time, requiring the existence of large ice sheets during much of this period (Hambrey et al., 1989).

The post-Oligocene record is poorly represented in Antarctic shelf cores drilled to date, but the discovery of Pliocene (and older) marine diatoms in outcrops of glacial debris termed the Sirius Group at high elevations in the Transantarctic Mountains and near sea level in Prydz Bay indicates major ice volume changes into the late Pliocene (Webb et al., 1984; Pickard et al., 1988). Specifically the diatoms indicate that there were periods until the latest Pliocene when seas were present in the interior of East Antarctica and hence periods when the continental ice sheet was greatly reduced or even absent. The subsequent discovery of beech wood in the Sirius Group (Carlquist, 1987) requires that, as in the Oligocene, these Antarctic ice sheets could not have been so cold as to wipe out coastal forest enclaves. On present data this implies a minimum average monthly summer coastal temperatures of 8 degrees C, about 10 degrees warmer than today's (interglacial) climate.

The style of glaciation outlined above, and summarized in figure 2, is of growth and decay of continental ice sheets on Antarctica on a ~ 1 m.y. timescale, beginning at least 30 Ma, and possibly 40 Ma, ago. This is not consistent with the widely held view, based on deep-sea sediments and the oxygen isotope record, that Antarctic glaciation became progressively intense with two main thresholds at 40 Ma (beginning extensive non-ice cap glaciation), and at 14 Ma (ice cap formation) (Kennett, 1977). However, it is consistent with the eustatic sea level changes implied by the third and fourth order components of coastal onlap/offlap curves derived from seismic stratigraphy of continental shelves (Haq et al., 1987). It is also feasible from glaciological considerations (Robin, 1988).

A dynamic ice sheet history for Antarctica is also supported by recent analysis of seismic data from parts of the Antarctic continental shelf, where near-surface strata comprise many packages of steeply dipping foresets and thin topsets, each of which is considered to be related to the advance of an ice sheet, at times as far as the continental margin (Larter and Barker 1989; Cooper et al., 1990). Further, the growing body of seismic data from the Antarctic shelf provides the potential for reconstructing this history in much more detail, when erosional, depositional and tectonic processes can be taken into account, and when sampling and stratigraphic study can improve the chronologic framework.

Figure 1. Map of Antarctica.

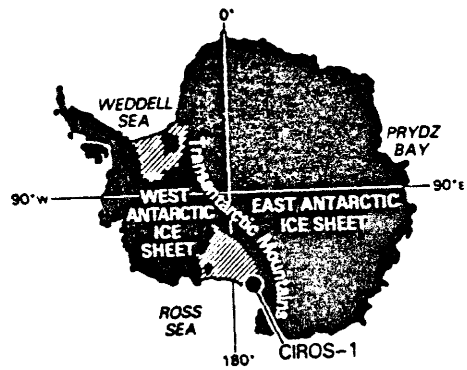
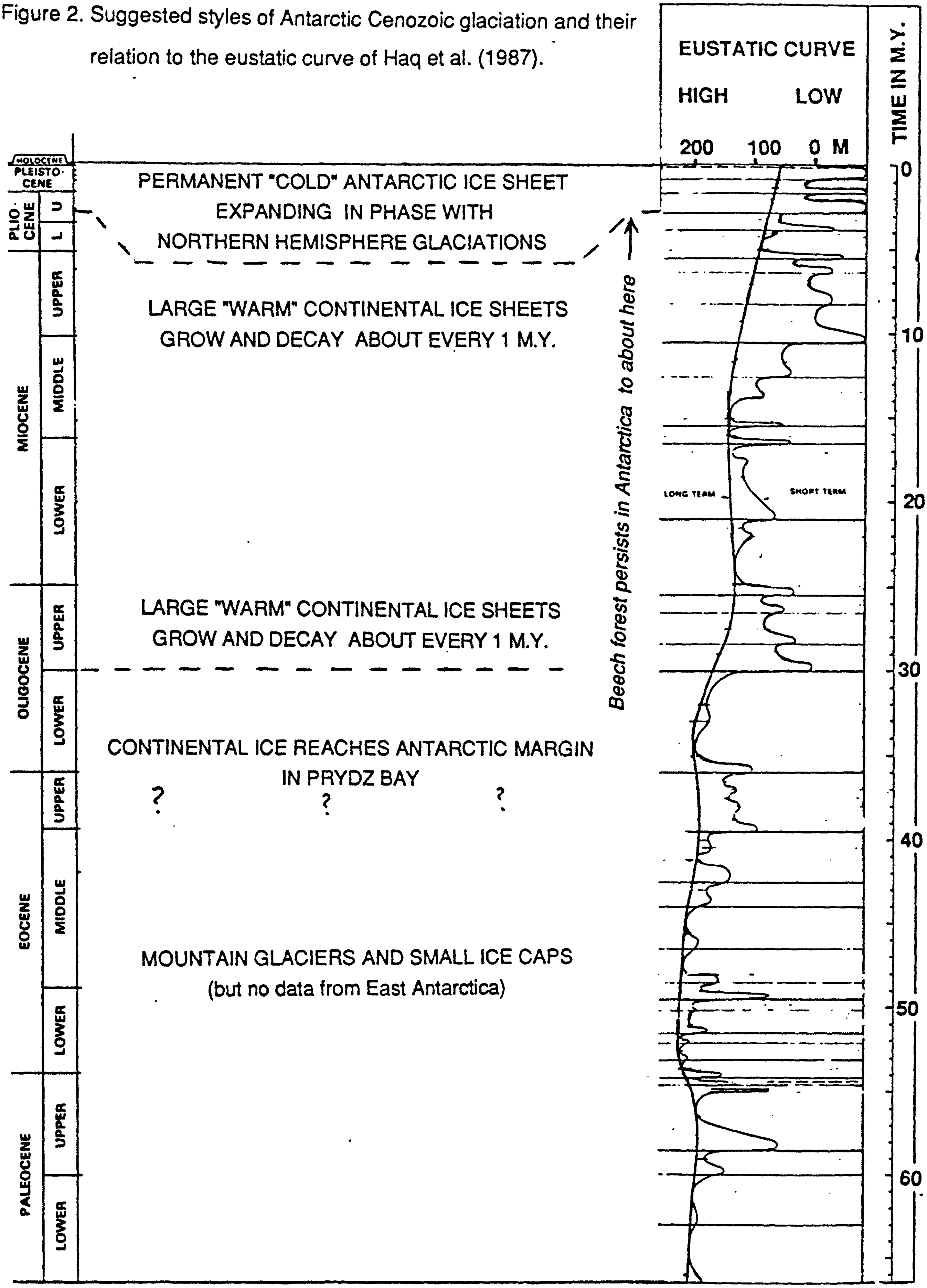


Figure 2. Suggested styles of Antarctic Cenozoic glaciation and their relation to the eustatic curve of Haq et al. (1987).



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CENOZOIC PALEOCEANOGRAPHY OF THE SOUTHERN OCEAN: A SUMMARY

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An evolving picture of the Cenozoic paleoceanography of the Southern Ocean is emerging from study of cores collected on Deep Sea Drilling Project Legs 28, 29, 35, 36, and 71 and Ocean Drilling Program Legs 113, 114, 119, and 120 (Fig. 1). In contrast to cores recovered from the Antarctic continent, Southern Ocean pelagic sediment records are relatively complete and document a more continuous history of Cenozoic paleoclimatic conditions in the waters around Antarctica. However, data from pelagic cores constitute a proxy for environmental conditions present on Antarctica, and models for the Cenozoic evolution of Antarctic ice sheets must consider the possibility of conditions vastly different than those of today (e.g., the possibility of a large temperate ice sheet on East Antarctica surrounded by relatively warm seas).

Paleoceanographic core data used in determining the Cenozoic climatic record of Antarctica provide mainly proxies for the size and character of the Antarctic ice sheets and more direct evidence for estimating the temperature, circulation pattern, and intensity of flow of surface, intermediate, and deep water masses.

ICE SHEET HISTORY

Isotopes

Much of the debate over the Cenozoic history of Antarctic glaciation has centered on differing interpretations of the deep-sea oxygen isotope record. Shackleton and Kennett (1975) proposed that the beginning of the Oligocene was the first time that the mean annual temperature in high southern latitudes was near freezing, thus allowing glaciers in Antarctica to descend to sea level and produce sea ice. They argued that if an ice sheet were present in the earliest Oligocene, it could not have been more than a small fraction of its modern size. These authors and their supporters call for a progressive, stepwise growth of the Antarctic ice sheet.

Miller et al. (1987) used a composite benthic foraminiferal oxygen isotope record of Cenozoic deep-sea sediments to suggest that significant continental ice sheets have existed on Antarctica since the beginning of the Oligocene (36-35 Ma); however, they pointed out that the ice sheets may have disappeared during parts of the Oligocene and early Miocene. They employed covariance of the benthic and low- to middle-latitude planktonic $\delta^{18}O$ records to infer several growth and decay events with growth at about 35, 31, 25, 14, and 10 Ma.

Prentice and Matthews (1988) argue that tropical sea-surface temperatures have remained essentially stable throughout the Cenozoic, whereas bottom water temperatures have fluctuated significantly. Their reconstructions suggest that the last 42 m.y. (since the latest middle Eocene) have been typified by at least as much ice volume as exists today and that the Paleocene and early Eocene (65-50 Ma) of Antarctica were essentially ice free.

None of the isotopic models allow for significant deglaciation of Antarctic ice sheets after the early middle Miocene.

Ice-Rafted Detritus

Ice-rafted detritus (IRD) provides evidence of glaciers calving at sea level, but the absence of IRD in any given interval is not direct evidence of the absence of icebergs in Antarctic seas. The tracts of icebergs may differ with differing patterns of sea-surface circulation, and the survivability of icebergs will depend of sea-surface temperatures. Consequently, there is both a latitudinal control on the age of the first occurrence of IRD in the Southern Ocean and a diachroneity of IRD records around Antarctica.

Unequivocal earliest Oligocene IRD was reported by ODP Legs 119 and 120 on the Kerguelen Plateau, but reports of Eocene IRD have been questioned. The appearance of IRD in late Miocene (about 8 to 9 Ma) sediments in the Drake Passage is cited as evidence for the initial development of the West Antarctic ice sheet. A latest Miocene (about 6 Ma) increase in IRD is documented throughout the Southern Ocean, and Pliocene and Pleistocene sediments are typified by significant, but highly variable, amounts of IRD.

Clay Mineralogy

The ratio of smectite to illite in the clay minerals of pelagic Southern Ocean sediments has been used to infer conditions on the Antarctic continent. Smectite is more typical of warm and humid climatic conditions, whereas illite is more readily formed in cooler climates by physical weathering. Southern Ocean records adjacent to East Antarctica show a switch from clay minerals dominated by smectite to those dominated by illite in the earliest Oligocene attesting to a major increase in glacial conditions in East Antarctica at this time. The increase of illite and chlorite in the upper Miocene of Site 696 (Fig. 1) may reflect the formation of the West Antarctic ice sheet. In assessing the clay mineral record of the Southern Ocean, the possibility that some of the smectite component might be recycled by the erosion of older Antarctic sediments containing smectite clays must be considered.

Pollen

The presence of in situ pollen in Eocene and Oligocene Antarctic sediments provides evidence of vegetation on the Antarctic continent, but not, necessarily, the absence of ice sheets during parts of the Eocene and Oligocene. Any Oligocene and Eocene ice sheets on East Antarctica were most likely temperate in character and subject to large scale fluctuations. Vegetation may have been present in local areas during interglacial periods.

SURFACE WATER MASSES

The character and distribution of the surface water masses of the Southern Ocean have been inferred by the succession of Cenozoic microfossil assemblages, pelagic sediment character (carbonate vs. biosiliceous), and oxygen isotope studies of near-surface dwelling planktonic foraminifers. These investigations document a progressive cooling of surface waters during the Cenozoic with major cooling steps in the middle Eocene, earliest Oligocene, middle part of the Oligocene, middle Miocene, early late Miocene, latest Miocene, and late Pliocene. This Cenozoic cooling trend is generally attributed to the progressive establishment of open ocean circulation around

Antarctica caused by the separation of Australia from Antarctica, which began in the middle Eocene, and by the opening of the Drake Passage (near the Oligocene/Miocene boundary).

Today, the Antarctic convergence marks the approximate boundary between biosiliceous sediments deposited in subantarctic waters to the south and dominantly carbonate sediments deposited in subtropical waters to the north. The Subtropical convergence to the north separates subantarctic waters, which are characterized by low diversity calcareous nannoplankton and planktonic foraminiferal assemblages, from subtropical waters, which are typified by higher diversity calcareous assemblages (Fig. 1).

The Cenozoic evolution of the Southern Ocean is characterized by a progressive northward displacement of subtropical waters by an increasingly stronger Antarctic Circumpolar Current. Southern Ocean calcareous microfossil assemblages decline in diversity during the middle Eocene and again at the Eocene/Oligocene boundary signalling cooling of surface waters. Provincial radiolarian and diatom assemblages become established in the Southern Ocean during this time, and biosiliceous sedimentation first became prominent in the Southern Ocean during the latest Eocene to earliest Oligocene. Cooling trends continued into the late Oligocene, but the early Miocene saw a reversal to warmer conditions and less provincial microfossil assemblages. Major cooling in the middle Miocene and early late Miocene was marked by a further drop in the diversity of calcareous microplankton and an expansion of biosiliceous sedimentation (diatoms and radiolarians). Carbonate sedimentation south of 50°S declined abruptly in the latest Miocene, but it reappeared in part during warmer periods of the Pliocene and Quaternary. The Antarctic convergence became established near its present-day location during the latest Miocene (about 6.5 Ma) to earliest Pliocene (4.8 Ma), and Pliocene-Pleistocene fluctuations in the location of this oceanic front have responded in concert with glacial-interglacial cycles.

INTERMEDIATE AND DEEP WATER MASSES

Isotopes

Oxygen and carbon isotopes reveal that intermediate and deep waters of the Southern Ocean underwent significant evolution during the Cenozoic. Most researchers think that the Southern Ocean was the primary source of deep water during the Cenozoic, with the exception of the latest Paleocene and early Eocene (the periods of maximum Cenozoic warmth). During this warm period, deep waters may have been dominated by warm saline deep water which was formed at low latitudes. Such warm saline deep water was apparently important during the earlier parts of the Cenozoic (Paleocene and Eocene) in the formation and circulation of both the deep and intermediate waters of the world's oceans. Some researchers believe that warm saline intermediate waters produced in the Indian Ocean also had a significant affect on global thermohaline circulation as late as the early middle Miocene (15 Ma). Northern-component deep water (analogous to North Atlantic Deep Water) was important briefly in the earliest Oligocene before increasing in the Southern Ocean during the late early Miocene and again at the end of the middle Miocene (10 Ma). By the late Miocene, deep and intermediate waters of the Southern Ocean were essentially modern in most aspects.

Deep-sea Hiatuses

Deep-sea hiatuses are commonly linked to increases in bottom-water velocity and, indirectly, to periods of increasing Antarctic ice volume. Intensification of the flow and/or corrosiveness of Antarctic Bottom Water (AABW), which is usually active at depths below 4000 m, and/or Circumpolar Deep Water (CPW), which occurs above 4000 m, are usually cited as the cause of deep-sea hiatuses in the Southern Ocean. Even if deep-sea hiatuses result from increased production of either AABW or CPW, it is presently unclear how the Antarctic ice sheet affects the formation of either water mass; some researchers suggest increased AABW should occur during Antarctic glacial periods, others favor increases during interglacial periods. Nevertheless, apart from deep-sea hiatuses which can be linked with tectonic events, hiatuses are more common in Oligocene and Neogene sediments (coincident with the development of an Antarctic ice sheet) than they are in older sediments.

Numerous authors have argued that extensive Oligocene deep-sea hiatuses in the Tasman Sea, Coral Sea, and other regions of the world were caused by intensified oceanic circulation resulting from Antarctic glacial development. Southern Ocean hiatuses across the Oligocene-Miocene boundary are typically correlated with the opening of the Drake Passage and an intensification of flow of the Antarctic Circumpolar Current. The middle and late Miocene is either missing or dissected by numerous unconformities in most Southern Ocean deep-sea sequences, attesting to an increased production of AABW and/or CPW during this general period of cooling and expansion of the Antarctic ice sheets. Studies of well-dated Pliocene and Pleistocene sediments from different water depths reveal that hiatuses caused by AABW (below 4000 m water depth) are not synchronous with hiatuses caused by CPW (about 4000 to 1000 m water depth).

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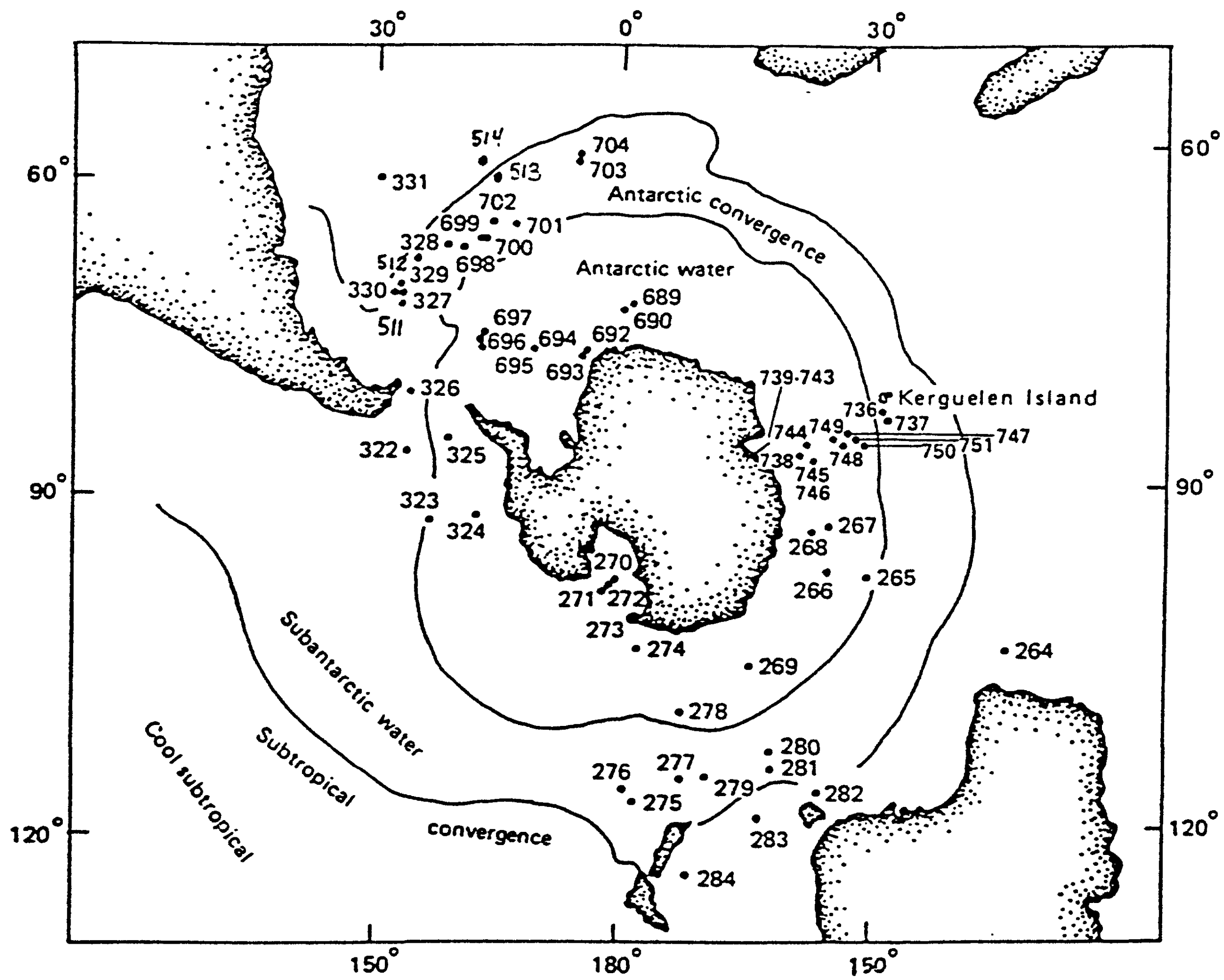

Figure 1. Present-day locations of surface-water masses of the Southern Ocean showing Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) sites.

	Leg	Sites
DSDP:	28	264-274
	29	275-284
	35	322-325
	36	326-331
	71	511-514
ODP:	113	689-697
	114	698-704
	119	736-746
	120	747-751

Neogene Stratigraphy of the Ross Sea Continental Shelf: Revelations from Leg 2 of the 1990 Ross Sea Expedition of the R/V Polar Duke

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Introduction and Methods

Leg 2 of the 1990 R/V Polar Duke expedition in the Ross Sea began on the morning of February 11 in McMurdo Sound, and ended on March 17 at King George Island. The scientific objective of the cruise was to acquire a high resolution seismic reflection data base on the continental shelf that, in conjunction with existing drill core from the shelf (DSDP Leg 28 sites 270, 271, 272, and 273) and McMurdo Sound (MSSTS and CIROS), will provide the basis for developing a high resolution seismic stratigraphy for the late Paleogene and Neogene strata of the continental shelf.

Approximately 6,000 kilometers of seismic data were collected within the Ross Sea and McMurdo Sound (Figs. 1 and 2). During the survey of the shelf, gravity and magnetic data were acquired continuously, and a new seismic source, the G.I. (Generator/Injector) gun, was utilized as a seismic source. This "bubble-free" air gun, developed by Seismic Systems Inc., produces a "clean" outgoing signal with a 0-128 Hz frequency spectrum. During a brief servicing of the G.I. Gun, a 100 in^3 Hamco water gun provided the seismic source. The two data sets are very similar in terms of resolution, however, the G.I. gun provided greater subbottom penetration (between 1.5 and 2.0 seconds two way travel time for the G.I. gun compared to 1.0 second for the Hamco water gun). High quality digital and analogue data (Fig. 3) were acquired on a single channel Litton-Teledyne streamer.

Discussion of Problems and Data

The Ross sea continental shelf has long been recognized as a key region for investigating the long-term glacial history of Antarctica. During DSDP Leg 28 four sites were drilled on the continental margin in order to examine the history of glaciation in the region (Hayes and Frakes, 1975). Unfortunately, recovery was poor at these sites and the interpretation of the recovered strata has remained problematic. For example, massive diamictites, as old as early Miocene age, were recovered at all of the sites, but the subglacial versus glacial marine origin of these diamictites remains controversial, even after detailed sedimentologic analysis (Barrett, 1975; Balshaw, 1981). This is a crucial controversy because a subglacial origin for these diamictites implies expansion of a marine ice sheet onto the shelf; a glacial marine origin for these deposits may imply the presence of tidewater glaciers in the region. The former implies a polar climate whereas tidewater glaciers can exist in a temperate climatic setting.

While the recovery at sites 270 through 273 is too sparse to allow confident paleoclimatic interpretations from lithologic units, these sites provide a rare stratigraphic column with which to conduct sequence stratigraphic studies in Antarctica. The only other sites on the continental shelf of Antarctica are in Prydz Bay, East Antarctica (ODP Leg 119, Barron et al., 1990). Recent seismic studies on the Canadian shelf (King and Fader, 1986), in the North Sea (King et al., 1987) and at Ice Stream B in Antarctica (Alley et al., 1989) provide important information about the nature of seismic facies associated with both subglacial and glacial marine sequences. These results provide a framework for seismic studies in Antarctica aimed at deciphering the history of glaciation on the continental shelf in areas, such as the Ross Sea, where drill sites provide needed chronostratigraphic information.

The seismic facies work conducted by King and Fader (1986) and King et al. (1987) relies on high resolution (Boomer, sparker, water gun) records. Although the Ross Sea seismic reflection data base is large, these data constitute either multichannel air gun data, which lack the needed resolution for seismic facies analysis, or high resolution data (mostly sparker records) which consist of short and discontinuous lines. Hence, the existing data set (prior to this cruise) was unsuitable for seismic facies and high resolution sequence stratigraphic analyses. The objective of our cruise was to acquire high resolution data suitable for these types of analyses. Our planned cruise track (Figs. 1 and 2) relied upon existing data sets to avoid structural features that disrupt the stratigraphic sequences on the shelf, especially in the western Ross Sea. Stratigraphic correlations are facilitated where our tracklines cross existing drill sites on the shelf and in McMurdo Sound (Figs. 1 and 2).

Only preliminary analysis of the seismic data has been performed to date. The results indicate that grounded ice sheets existed on the Ross Sea continental shelf at least as early as late Oligocene time. This is based on the first occurrence of glacial erosional surfaces and till tongues that are similar to those described by King and Fader (1986) and King et al. (1987). These surfaces have been tied to DSDP site 270 (Fig. 3). The width of the scours associated with the till tongues is also comparable with the width of modern ice streams. The massive tongue-like units in figure 3 are at least 70 to 80 kilometers wide and modern ice streams have widths on the order of 100 to 150 kilometers (Alley et al., 1989). The widths of the trough-like scours on the Ross Sea continental shelf also exceeds the widths of incisions carved by fluvial entrenched valley systems. Incisions carved by entrenched valley systems are typically 10 to 20 kilometers wide (Berryhill, 1986; and Thomas and Anderson, 1989). Extensive shelf aggradation and progradation followed the late Oligocene grounding event (Fig. 4). Waxing and waning of ice sheets on the continental shelf appears to be intimately related with the aggradation and progradation of the shelf (Fig. 3). The ice grounding stratigraphy appears to have been produced by two mechanisms. The till tongue-like stratigraphy, which appears to be the most prevalent, may have been produced by the buoyancy line migration mechanism discussed by King and Fader (1986). In this model tongues of till are deposited on the shelf as wet-based ice sheets wax and wane.

Data from the eastern side of the Eastern Basin of the Ross Sea show evidence of the subglacial delta stratigraphy discussed by Alley et al. (1989). The seismic character (oblique, sigmoid, and complex oblique-sigmoid seismic reflections) of the sections indicates that the shelf margin was migrating seaward during the interval of time that these glacial sediments were deposited (Hinz and Block, 1983). The Alley et al. (1989) model for sedimentation beneath the ice streams of marine-based ice sheets that may also explain the origin of some of the prograding seismic sequences and glacially derived sediments in DSDP Sites 270-272.

Theoretical arguments and seismic data indicate to Alley and others (1989) that ice stream B is rapidly gliding along on a layer of water-saturated, unconsolidated, deforming till. It is thought that erosion of unlithified subjacent sediments by hard clasts contained in the deforming till (topsets in seismic data) has produced the angular unconformity that is observed in seismic data acquired along ice stream B

(Alley et al., 1989). Calculations performed by Alley and others (1989) indicate that erosion rates are high along ice streams and require relatively rapid deposition at the grounding line of an ice stream. Alley and others (1989) indicate that at the grounding line, the highly unconsolidated water-saturated sediment, that is transported through the topset (till), loses contact with the ice. This is thought to cause slumping, and development of foresets and bottomsets that are composed of turbidites and debris flows. The stratigraphic succession of foresets and bottomsets composed of glacially derived sediment gravity flow deposits, unconformably overlain by topsets of highly unconsolidated, water-saturated till is termed a subglacial delta by Alley et al. (1989).

Alley and others (1989) hypothesize that the Ross Sea Unconformity (Unconformity U1 of Hinz and Block (1983) was produced by the migration of ice stream grounding lines and subglacial deltas during the Wisconsinan glacial maximum. They believe that these events may have also occurred during the latest Pliocene-Pleistocene, and possibly before, and suggest that erosion beneath the grounded ice may have occurred entirely within the basal tills or may have cut through earlier tills to older glacial marine sediments (Fig. 5). They also suggest that "conveyor belt recycling" of till deltas would allow grounding line advance in water that would otherwise be too deep. It is suggested by the authors of this paper that the process of sediment recycling within subglacial deltas would produce subglacial deposits that bear no resemblance to the characteristics that are ascribed to classic tills. Homogenization of clasts from various source areas and incorporation of marine flora and fauna from interbedded glacial marine deposits would make it very difficult to distinguish subglacial deposits and glacial marine deposits in core. Thus, the stratal geometry of cored sequences, as revealed in seismic data, may provide the only insight into their origin. We suggest that the pattern of prograding sedimentary sequences composed entirely of "glacial marine" sediments (DSDP Sites 270-272) may have been produced by the waxing and waning of marine-based ice sheets on the Ross Sea continental shelf since late Oligocene time.

It is important to note that the stratal patterns in the eastern Ross Sea are very similar to those from many other continental margins (Bartek et al., in press). The obvious implication of this observation is that the waxing and waning of the Neogene ice sheets that produced the stratigraphy of the Ross Sea involved ice volume fluctuations that may have been large enough to effect eustasy and hence coastal onlap on a global scale. More drilling of the stratigraphic succession, which is literally exposed at the sea floor, is needed to better constrain these relationships.

We have also found that the Plio-Pleistocene strata on the Ross Sea continental shelf vary considerably in thickness and include at least four major glacial erosional surfaces separating packages of predominantly subglacial deposits. The implications of an increase in the scale of glacial features during late Pleistocene (?) time remain problematic. Perhaps this relates to the evolution of the present ice stream systems of the region. Drilling in appropriate localities and acquisition of more high resolution seismic data may lead us to the solution of these interesting problems. Another problem related to the Cenozoic stratigraphy of this region is what role did tectonics play in the generation of the Neogene stratal patterns of the Ross Sea? Did declining thermal subsidence on this margin increase the probability of ice sheet grounding on the continental shelf? Is the pattern of aggradation and progradation a manifestation of this event?

Acknowledgements

We thank Alan Cooper for informative discussions and assistance in planning our cruise track. Adrien Pascouet and Jim Hedger of Seismic Systems Inc. loaned the G.I. gun to us and trained us to use and maintain it. Rick Shiftman of Teledyne Inc. provided assistance in streamer repair. Lastly, the highly professional crew of the Polar Duke deserves a special word of thanks for making this a productive and pleasant cruise. This project was funded by the National Science Foundation-Division of Polar Programs grant number DPP 8818523.

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Figure Captions

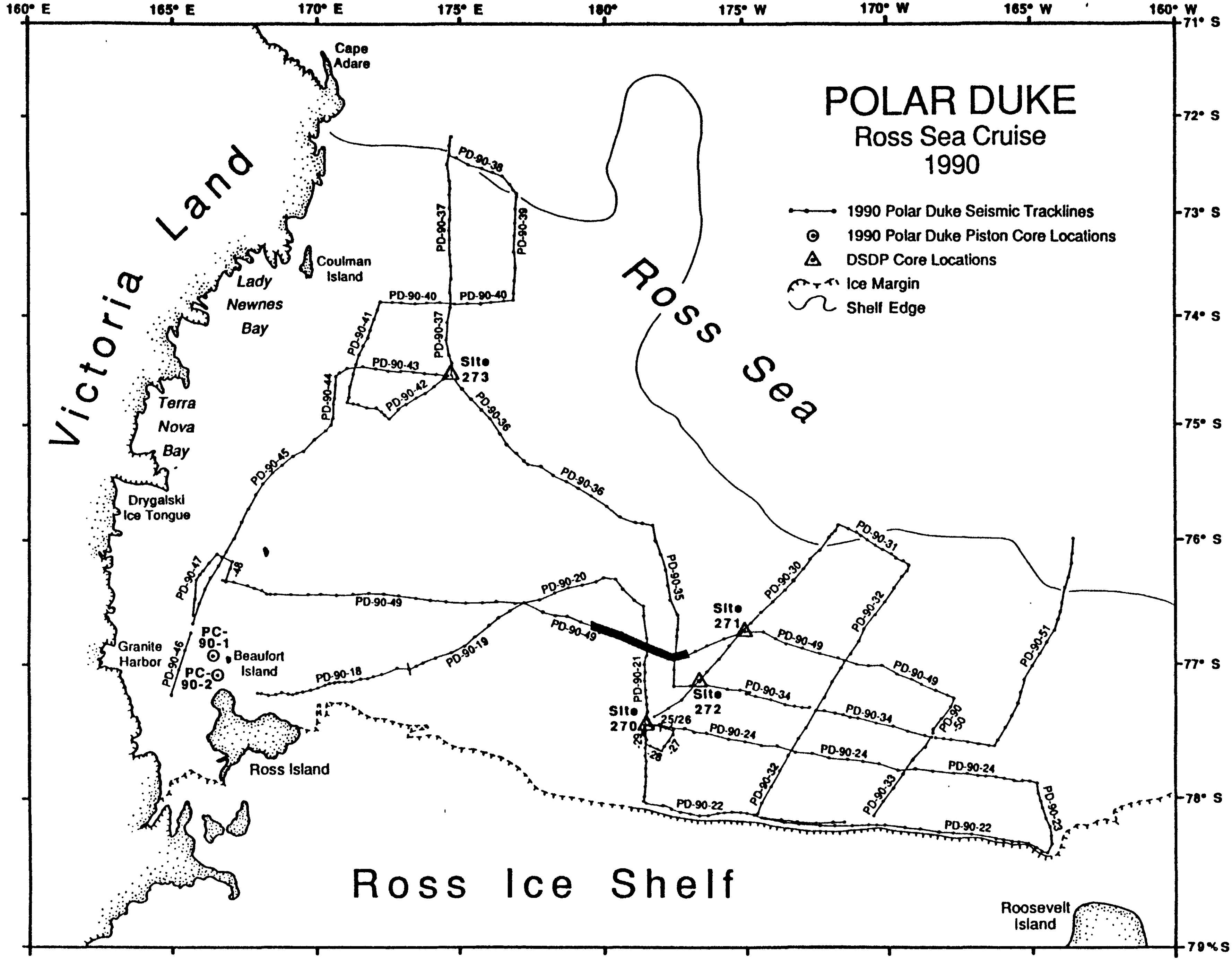
Figure 1: Location of Polar Duke 90 (PD-90) seismic tracklines and DSDP core locations in the Ross Sea, Antarctica. The heavier line along PD-90-49 indicates the location of the profile that is displayed in Figure 3.

Figure 2: Location of Polar Duke 90 (PD-90) seismic tracklines and MSSTS-1 and CIROS-1 core locations in McMurdo Sound, Antarctica.

Figure 3: Portion of seismic line PD-90-49 and line drawing illustrating the presence of subglacial seismic facies as old as late Oligocene. The location of the profile is indicated by the heavier line along PD-90-49 in Figure 1. Note the massive intervals and the cross cutting relationships of the Neogene strata in this strike section. These are features that are similar to the till tongue stratigraphy described by King and Fader (1986).

Figure 4: This cross section, from Bartek (1989) is a composite of the data that have been published by Hayes and Frakes et al. (1975), Hinz and Block (1983), Sato et al. (1984). It illustrates that the basement has been subsiding in the northeast faster that it has on the southwest and that following an early Miocene transgression, the shelf margin aggraded and then prograded seaward. Notes under the cross section suggest possible causes for the stratal geometry.

Figure 5: These block diagrams are schematic representations of the stratigraphy of the Eastern Basin of the Ross Sea continental shelf. The lower strata of the block diagram (a.) illustrate a hypothetical stratigraphy that would be seen in a strike section if the prograding shelf margins that are seen in the dip sections were produced by fluvially dominated processes. The upper portion of block diagram (a.) and all of block diagram (b.) illustrate the stratigraphy that would have been produced if the shelf margin progradation was generated by the waxing and waning of marine-based ice sheets. Note that wide cross-cutting, trough-like incisions are associated with the subglacial sequences (see Fig. 3 for an example of this) and that relatively narrow v-shaped incisions are associated with the fluvial successions (Berryhill 1986; and Thomas and Anderson, 1989).



POLAR DUKE
Ross Sea Cruise
1990
1990 Polar Duke Seismic Tracklines
1990 Polar Duke Piston Core Locations
DSDP Core Locations
Ice Margin
Shelf Edge
160° E
165° E
170° E
175° E
180°
175° W
170° W
165° W
160° W
71° S
72° S
73° S
74° S
75° S
76° S
77° S
78° S
79° S
Victoria Land
Ross Sea
Ross Ice Shelf
Cape Adare
Coulman Island
Lady Newnes Bay
Terra Nova Bay
Drygalski Ice Tongue
Granite Harbor
Beaufort Island
Ross Island
Roosevelt Island
PC-90-1
PC-90-2
Site 270
Site 271
Site 272
Site 273
PD-90-18
PD-90-19
PD-90-20
PD-90-21
PD-90-22
PD-90-23
PD-90-24
25/26
-27
-28
-29
PD-90-30
PD-90-31
PD-90-32
PD-90-33
PD-90-34
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PD-90-41
PD-90-42
PD-90-43
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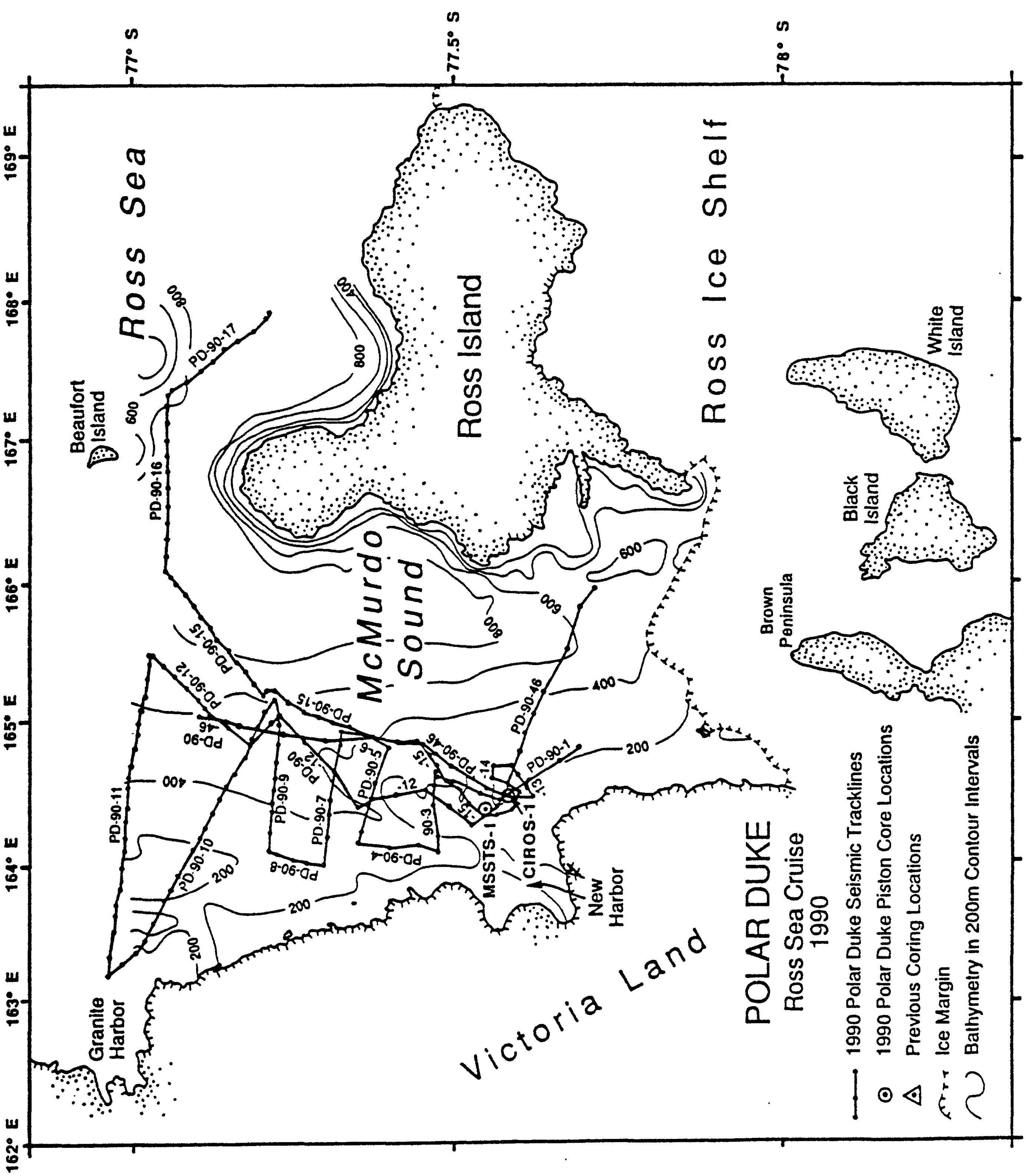
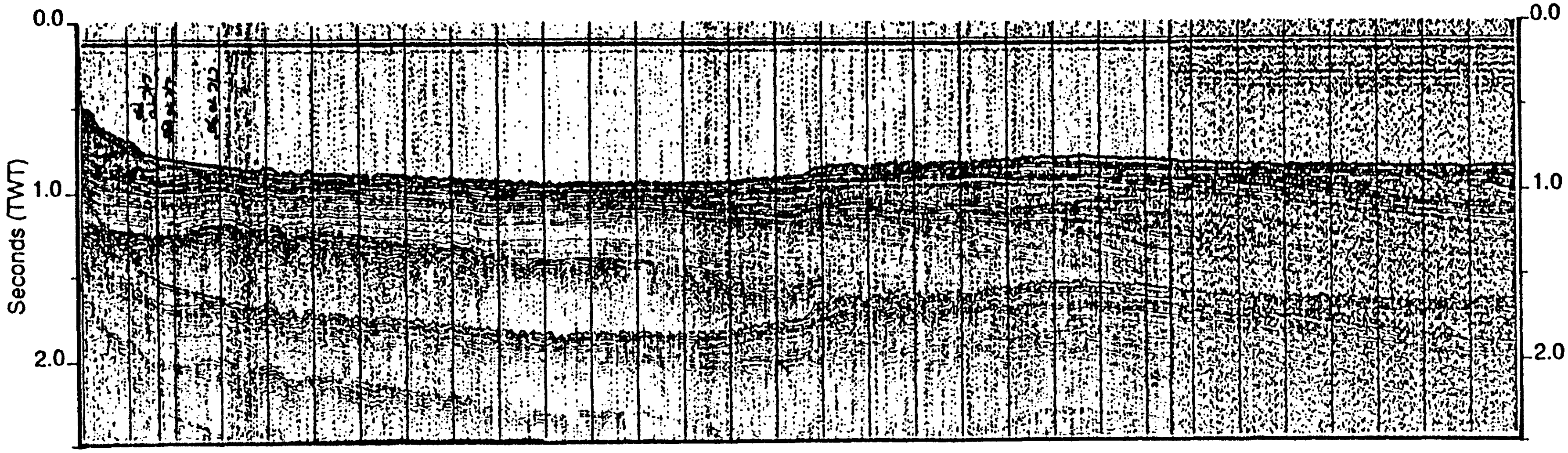
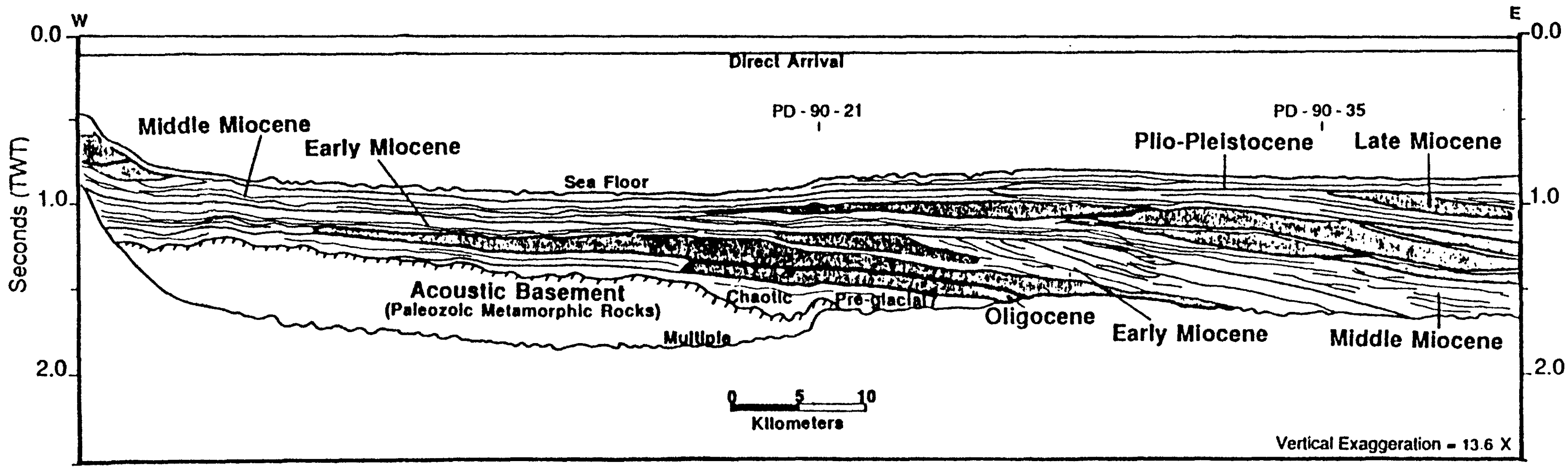
PD-90-45
PD-90-46
PD-90-47
-48
PD-90-49
PD-90-50
PD-90-51


POLAR DUKE
Ross Sea Cruise
1990
1990 Polar Duke Seismic Tracklines
1990 Polar Duke Piston Core Locations
Previous Coring Locations
Ice Margin
Bathymetry in 200m Contour Intervals
Ross Sea
Ross Island
Ross Ice Shelf
McMurdo Sound
Victoria Land
Beaufort Island
White Island
Black Island
Brown Peninsula
Granite Harbor
New Harbor
MSSTS-1
CIROS-1
PD-90-1
PD-90-3
PD-90-4
PD-90-5
PD-90-7
PD-90-8
PD-90-9
PD-90-10
PD-90-11
PD-90-12
PD-90-15
PD-90-16
PD-90-17
PD-90-46
162° E
163° E
164° E
165° E
166° E
167° E
168° E
169° E
77° S
77.5° S
78° S
200
400
600
800

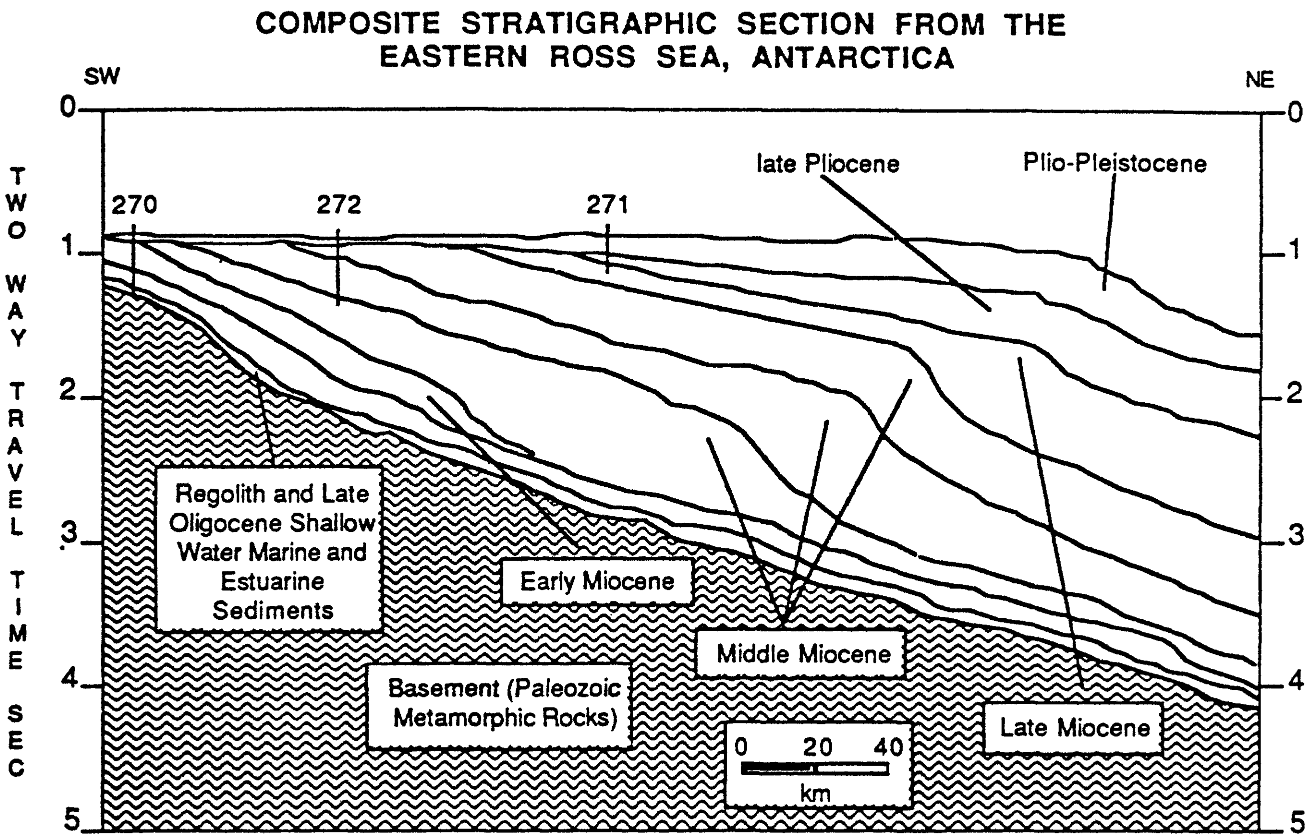


0.0
1.0
2.0
Seconds (TWT)

PD - 90 - 49B



W
E
0.0
1.0
2.0
Seconds (TWT)
Direct Arrival
PD - 90 - 21
PD - 90 - 35
Middle Miocene
Early Miocene
Sea Floor
Plio-Pleistocene
Late Miocene
Acoustic Basement
(Paleozoic Metamorphic Rocks)
Chaotic
Pre-glacial
Multiple
Oligocene
Early Miocene
Middle Miocene
0 5 10
Kilometers
Vertical Exaggeration = 13.6 X



POSSIBLE CAUSES OF STRATAL GEOMETRY

Late Oligocene- Accomodation decreases and an ice sheet advances onto shelf (Possibly as a result of the exponential decrease in thermal subsidence reaching a critical value ?)

Early Miocene- Accomodation high, ice sheets unable to advance extensively onto shelf (Warm Climate ?)

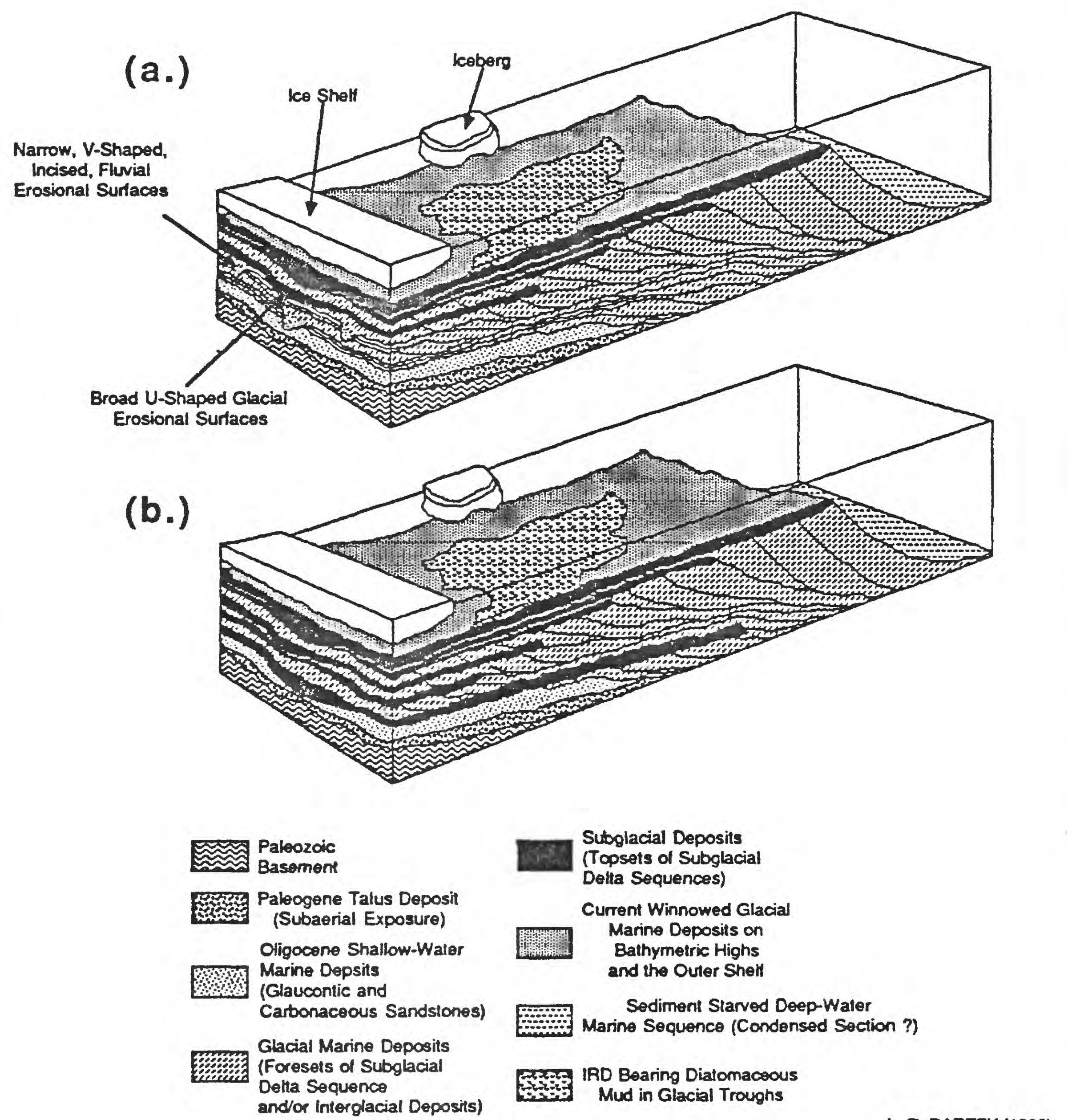
Middle Miocene- Accomodation decreasing (exponential decrease in rate of thermal subsidence ?) and increasing rates of change in accomodation (increase in ice volume due to thermal isolation -Drake Passage opened 22 Ma)

late Pliocene and Pleistocene- rate of change of accomodation very high (i.e. Rates of fluctuation are faster than rate of basin subsidence so sequences are canabalized)

L.R. BARTEK (1989)

Block Diagrams Illustrating the Differences Between Sequence Boundaries in Glacial and Temperate Continental Shelf Successions

The lower portion of the stratigraphic succession in the upper block diagram is dominated by temperate conditions and undergoes fluvial incision during falls of relative sea level. Sequence Boundaries in the upper strata of this diagram are are produced by glacial erosion as ice sheets wax and wane on the continental shelf. In the lower block diagram the entire succession is completely dominated by glacial erosion.



L. R. BARTEK (1989)

Speculation on the Uplift of the Shoulder Escarpment of the Cenozoic West Antarctic rift system, and its Relation to Late Cenozoic Climate Change

by

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INTRODUCTION

The Cenozoic West Antarctic rift system (LeMasurier et al., 1978) extends over a 3000 x 750 km, largely ice-covered area from the Ross Sea to the Bellingshausen Sea, comparable in area to the Basin and Range and the East African rift systems (Figure 1). A spectacular rift-shoulder scarp extends from North Victoria Land to the Queen Maud Mountains to the Horlick-Whitmore-Ellsworth Mountains along which peaks reach 4-5 km maximum elevation. The rift shoulder has maximum present relief of 5 km in the Ross Embayment and 7 km in the Ellsworth Mountains-Byrd Subglacial basin area. The Cenozoic West Antarctic rift system is characterized by exposures of bimodal alkaline volcanic rocks (LeMasurier,1990) in Marie Byrd Land and the Transantarctic Mountains bordering the Ross Embayment ranging from about 38 Ma to the present. In contrast, the Jurassic tholeiites (Ferrar dolerites, Kirkpatric basalts) marking the Jurassic Transantarctic rift (Schmidt and Rowley, 1986) crop out coincidently with the late Cenozoic volcanic rocks only along the section of the Transantarctic Mountains from North Victoria Land to the Horlick Mountains (Craddock et al., 1969). The Cenozoic rift shoulder diverges here from the Jurassic tholeiite trend and the tholeiites are exposed continuously (including the Dufek intrusion) along the lower-elevation (1-2 km) section of Transantarctic Mountains to the Weddell Sea, whereas the late Cenozoic alkaline volcanic rocks are exposed throughout Marie Byrd Land to the southern Antarctic Peninsula, but not in the Ellsworth Mountains area.

GEOPHYSICAL EVIDENCE

Aeromagnetic profiles in West Antarctica indicate the absence of Cenozoic volcanic rocks in the ice-covered part of the Whitmore-Ellsworth-Mountain area and suggest their widespread occurrence beneath the western part of the ice sheet overlying the Byrd subglacial basin (Behrendt 1964; Jankowski et al., 1983; Behrendt et al., in prep). An approximately 200-mGal (+50 to -150) Bouguer anomaly, having 4-7 mGal/km gradients where measured in places, extends across the rift shoulder from North Victoria Land possibly to the Ellsworth Mountains (where data are too sparse to determine maximum amplitude and gradient). In contrast, the maximum Bouguer gravity range is only about 130 mGal with a maximum 2 mGal/km gradient in the Pensacola Mountains area of the Transantarctic Mountains, which is easily explained by 24 km Moho deepening about 8 km at a dip of 15^{o}-20^{o} to about 30 km beneath the mountains (Behrendt et al., 1974). The steepest gravity gradients across the Cenozoic rift shoulder in the Ross Embayment require high density (mafic or ultramafic?) rock within the crust as well as about 20 km thinner crust beneath the Cenozoic West Antarctic rift system in contrast to East Antarctica (Behrendt et al., in prep). Sparse land refraction seismic data (Bentley and Clough, 1972) reported along the rift shoulder, where a few velocities are greater than 7 km/s, and marine data indicating lower crustal velocities greater than 7 km/s beneath the Ross Sea continental shelf support this interpretation.

Large offset seismic profiles over the Ross Sea shelf collected by the German Antarctic North Victoria Land Expedition V (GANOVEX V) (Trehu et al., 1989 and O'Connell et al., 1989) combined with earlier USGS (Cooper et al., 1987b) and other results (McGinnis et al., 1985) indicate 17-21 km thickness for the crust in the Ross Sea which we interpret as evidence for crustal extension. A regional (relative) positive gravity anomaly extends from the Ross Sea continental shelf throughout the subglacial area (Byrd subglacial basin) of the Cenozoic West Antarctic rift system and suggests that the crust there is approximately 20 km thick rather than the 30 km reported in earlier interpretations.

The absence of seismicity in the Cenozoic West Antarctic rift system probably results from a combination of sparse seismograph coverage, suppression of earthquakes by the grounded ice sheet (e.g. Johnston, 1987) and high seismicity immediately after deglaciation in the Ross Embayment followed by abnormally low seismicity at present (following the interpretation for Fennoscandia by Muir Wood, 1989).

We suggest that the origin of the Cenozoic West Antarctic rift system is due to a continuation of the rifting that started in the Jurassic when Africa rifted from East Antarctica, proceeded clockwise (Lawver, 1990) around East Antarctica to the separation of New Zealand and the Campbell Plateau from Marie Byrd Land about 85-95 Ma, and has continued (with perhaps a spreading center jump) to its present location in the Ross Embayment and West Antarctica. The major extension in the Byrd subglacial basin-Ross Embayment probably occurred during late Mesozoic time, but as much as 300 km possibly took place during the Cenozoic. The Cenozoic West Antarctic rift system appears to be continuous in time with rifting in the same area that began in the late Mesozoic.

UPLIFT OF RIFT SHOULDER

We examined the amount of uplift of the rift shoulder in the Cenozoic West Antarctic rift system in light of extreme elevations (Figure 2). The steep scarp suggests a very youthful topography; it is interpreted to be the expression of a major normal or extensional fault that defines the boundary of the Cenozoic West Antarctic rift system and the rift shoulder. If a maximum uplift of 5-6 km in the southern Victoria Land or 10 km in northern Victoria Land (Fitzgerald, 1989) area is correct, 1-2 km and up to 6 km, respectively, of erosion has occurred from the highest topography in this area to result in the maximum elevation of about 4 km observed now. The range in extreme topography seen in Figure 2 along the rift shoulder is probably due to erosion. We interpret that the main cause of uplift, along the Cenozoic West Antarctic rift shoulder, is late Cenozoic tectonism associated with rifting, probably as modeled by Stern and Ten Brink (1989), for a continental lithospheric plate heated at the free edge.

Examination of Figure 2, reveals several interesting features. The maximum elevations vary from about 4 km in Victoria Land and the Queen Maud Mountains (Figure 1), dropping to about 3 km in the Horlick and Whitmore Mountains (perhaps resulting from a greater rate of erosion) and rising again to 5 km in the Ellsworth Mountains. In contrast, elevations along the Transantarctic Mountains are much lower toward the Weddell Sea (see the solid-line profile of Figure 2). The maximum elevations along the solid-line profile range from about 2 km in the Thiel and Pensacola Mountains (including the Dufek intrusion) dropping to about 1 1/2 km in the Shackleton Mountains and 1 km in the Theron Mountains. We emphasize that the lower topography at the Weddell Sea end of the Transantarctic Mountains is not a part of the late Cenozoic rift. The age of this uplift is not known, but appears to be significantly older than that of the Cenozoic West Antarctic rift shoulder. However, because the Jurassic Dufek intrusion is faulted by the early uplift, it must post date its emplacement.

Fitzgerald (1989), using fission track dates, identified 5-6 km of uplift in the Transantarctic Mountains of South Victoria Land beginning about 60 Ma and calculated an average uplift rate of about 100 m/m.y. since that time (the extreme uplift he inferred in North Victoria Land is 10 km). Seismic reflection data from the Ross Sea adjacent to the Transantarctic Mountains show several angular unconformities that have been interpreted by Cooper et al. (1987a) as evidence for episodic uplift. Therefore we infer that the uplift of the Transantarctic Mountains and entire rift shoulder was episodic, probably being as much as an order of magnitude faster at times probably including the present than the mean rate of 100 m/m.y. calculated by Fitzgerald (1989) for the last 60 Ma.

Various lines of evidence, the total of which, lead us to conclude that the Transantarctic Mountains part of the rift shoulder (and possibly the entire shoulder) has been rising at a rate of the order of 1 km/m.y. probably since early or mid-Pliocene time rather than the 100 m/m.y. average since 60 Ma. Table I tabulates evidence for this order of magnitude of uplift, no single item of which is definitive or which cannot be explained by other mechanisms, as several of the authors cited have done. Nonetheless, we feel that, using an Occam's Razor or "Principal of Least Astonishment" approach, a compelling case is made.

LATE CENOZOIC CLIMATIC IMPLICATIONS

It is interesting to note that our estimated start (Behrendt et al., in prep.) of the latest episode of uplift (2-4 Ma) is approximately coincident with the most recent "warm conditions" cited by Webb (1990) for Antarctica. While he notes that "overall the present Antarctic ice sheet appears to have had only a small effect on uplift of the Transantarctic Mountains" (about 100 m) we suggest that the converse is not necessarily true. The rapid uplift of about 1 km/m.y. since early- or mid-Pliocene which we discuss here, may in fact have triggered the most recent advance of the East Antarctic ice sheet by a mechanism similar to that proposed for the northern hemisphere (winter cooling by mountain uplift there culminating in the Plio-Pleistocene ice ages) by Ruddiman and Kutzbach (1989). We suggest this to focus attention on the likely synergistic relation between episodic tectonism in the Cenozoic West Antarctic rift system and the waxing and waning of the Antarctic ice sheet (Webb, 1990) approximately coincident in time with rifting, mountain uplift and volcanism since about 38 Ma.

TABLE I

Evidence for Tectonic Uplift of Transantarctic Mountains of the Order of 1 km/m.y. Since (early?) Pliocene Time.

1) The Cenozoic West Antarctic rift shoulder has the highest elevation (4-5 km, Figure 2) of any suspected rift mountains on earth and therefore appears youthful (this also applies to 2).

2) The relief on the rift shoulder of 5-7 km peak elevations to seafloor or glacier bed (Drewry, 1983), is the greatest of any rift mountains, even if the ice (basin fill, LeMasurier and Rex, 1983) were compressed to the density of sedimentary rock.

3) Other neotectonic rift topography has demonstrated uplift rates of the same order of magnitude or higher, [e.g., East Africa, 2 and 8 km/my, Ebinger (1989); western U.S., e.g., Pacific Coast Ranges (about 1 km/m.y.) Christiensen (1986); Wasatch Mountains (2-2.5 km/my) Naeser et al. (1983); other areas, Ruddiman et al. (1989); Perry and Bruhn (1987); and Lajoie (1986)]. Other extreme uplift rates in different tectonic settings are up to an order of magnitude greater, [e.g., New Zealand 10 km/m.y., Wellman (1979); Tibetan Plateau, more than 3 km during the Quaternary, England and Houseman (1989); Ventura area California, about 9 km/m.y., and Lajoie (1986)].

4) Presence of Holocene fault scarps (Behrendt, 1991; Christoffel, personal commun., 1986) interpreted from high resolution marine reflection profiles of about 10 m displacement, and Late Pliocene or younger faults (McKelvey et al., 1990) with up to 300 m vertical displacement along the front of the Transantarctic Mountains bordering the Ross Embayment.

5) Up to 300 m of Post Wisconsin tectonic uplift in the Transantarctic Mountains has occurred in Wright Valley near McMurdo inferred from glacial geologic studies (Denton, 1984). This is on the thick, "strong" lithosphere side of the inferred stress-free boundary in the model of Stern and Ten Brink (1989), separating thin hot "weak" lithosphere beneath the Ross Embayment.

6) Seismic reflection evidence of unconformities in the Victoria Land Basin (Cooper et al., 1987a) in conjunction with fission track interpretation of 100 m/m.y. average uplift rate for Transantarctic Mountains since 60 Ma (Fitzgerald, 1989) requires episodic uplift. We know of no active rift in the world that has had a constant rate of uplift for 60 m.y.

7) Glacial straie indicate 600-1000 m higher ice levels on peaks in Transantarctic Mountains (Hoefle, 1989; McKelvey, 1990). Although possibly an indication of a higher ice sheet elevation in the past, we think this evidence more likely supports tectonic uplift of the peaks.

8) The presence of Nothofagus (Pliocene) in situ occurrences in moraines at high elevations in the Transantarctic Mountains is compatible (Mercer, 1987) with, but does not require this uplift rate (Harwood et al., 1990).

9) Late Pliocene marine microfossils from Wilkes subglacial basin at elevation between 1750 and 2500 m in Transantarctic Mountains can be explained by this uplift rate (Webb et al., 1984).

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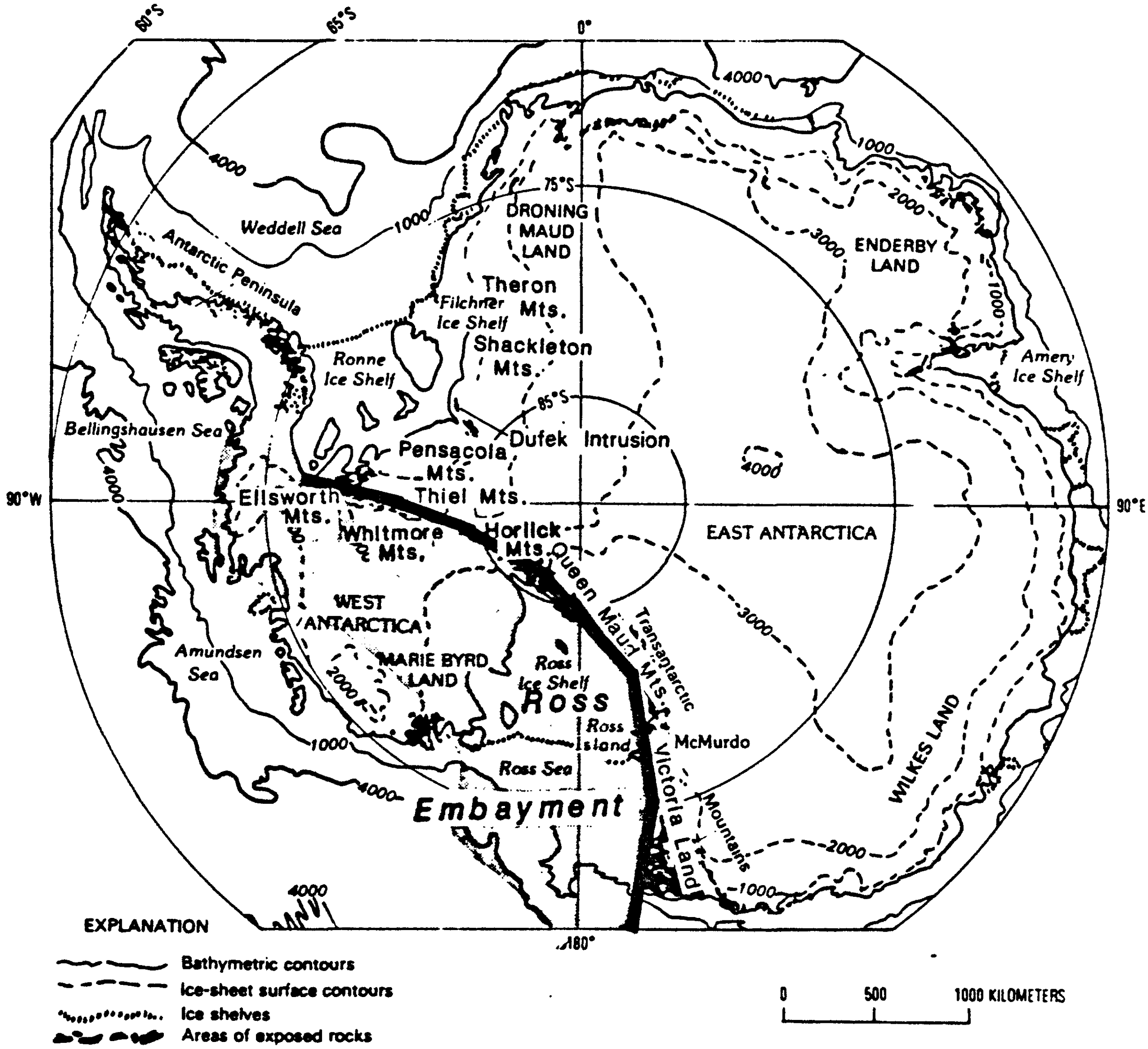

Figure 1. Index map of Antarctica showing some of the features discussed in the text. Shaded area is approximate location of Cenozoic West Antarctic rift system. Heavy line is approximate rift shoulder.

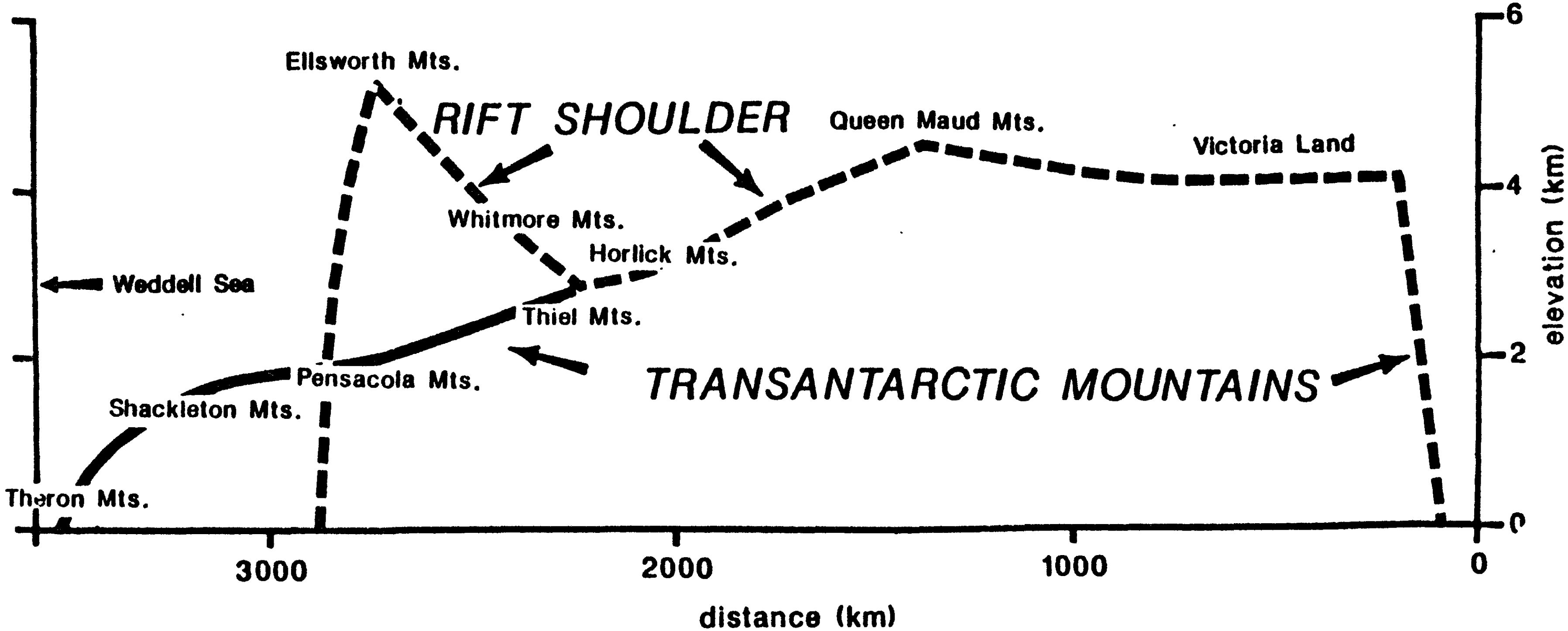

Figure 2. Generalized topographic profile along crest of highest peaks along interpreted rift shoulder (Figure 1) (dashed line) from the north coast of Victoria land at right to the Ellsworth Mountains at left compared with lower topography (solid line) of highest peaks in Transantarctic Mountains from Horlick Mountains to Weddell Sea coast at left. The interpreted Cenozoic West Antarctic rift shoulder has highest topography of any rift in the world. Low areas within the mountains probably are the results of glacial erosion and are not shown in this profile.

Seismic Investigations along the Antarctic Peninsula

Bialas, J. and the GRAPE-Team

During the "Polarstern" - cruise ANT-VI/2 (Oct.-Dec. 1987) about 1400 km of marine reflection lines were collected in the north-western part of the Antarctic Peninsula. Structures like the South Shetland Trench and the Bransfield Strait as well as several fracture zones (e.g. Hero Fracture Zone) were investigated (Fig. 1).

The Bransfield Strait, an area of recent extension, was traversed by three profiles. In the north-east the oceanic basement as indicated by a dense diffraction pattern is covered with young sediments. In the south-west an extensional horst-graben structure is found while the crust is of pure continental type (Fig. 2).

Active subduction along the South Shetland Trench is at present restricted to the northern part between Hero and Shackelton Fracture Zones. Sediments (200-500 m in thickness) covering the oceanic basement with its landward dipping slope are cut by normal faults. These faults show an increasing offset with depth. Further to the south up to 2 km of sediments are found on the oceanic plate, which has only a small landward dip. Here the Aluk ridge collision with the trench stopped the subduction between 4.5 and 15 Ma (Fig.3).

The strong segmentation of the oceanic lithosphere along the various fracture zones (Fig. 4) can be demonstrated by the magnetic anomaly pattern. Most of these fracture zones were transform faults before the ridge - trench collision, the whole system of ridges and transform faults being transported towards the trench. Only the Tula (in the south-west) and the Shackelton Fracture Zone (in the north-east) can be regarded as plate boundaries with completely different spreading velocities on both sides.

Seismic data processing provided stacked and migrated sections. Karhunen - Loeve transform and deconvolution could only partly reject the strong water bottom multiple.

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Figure Captions

Fig. 1. Location map of the survey area showing seismic reflection lines (thick lines 1–9) and marine magnetic anomalies after Barker and Dalziel, 1983.

HB : Hope Bay	KGI: King George Island
DI : Deception Island	SFZ: Shackelton Fracture Zone
HFZ: Hero Fracture Zone	AFZ: Anvers Fracture Zone

Fig. 2. Line drawings of the three reflection lines 1, 2 and 9 crossing the Bransfield Strait.

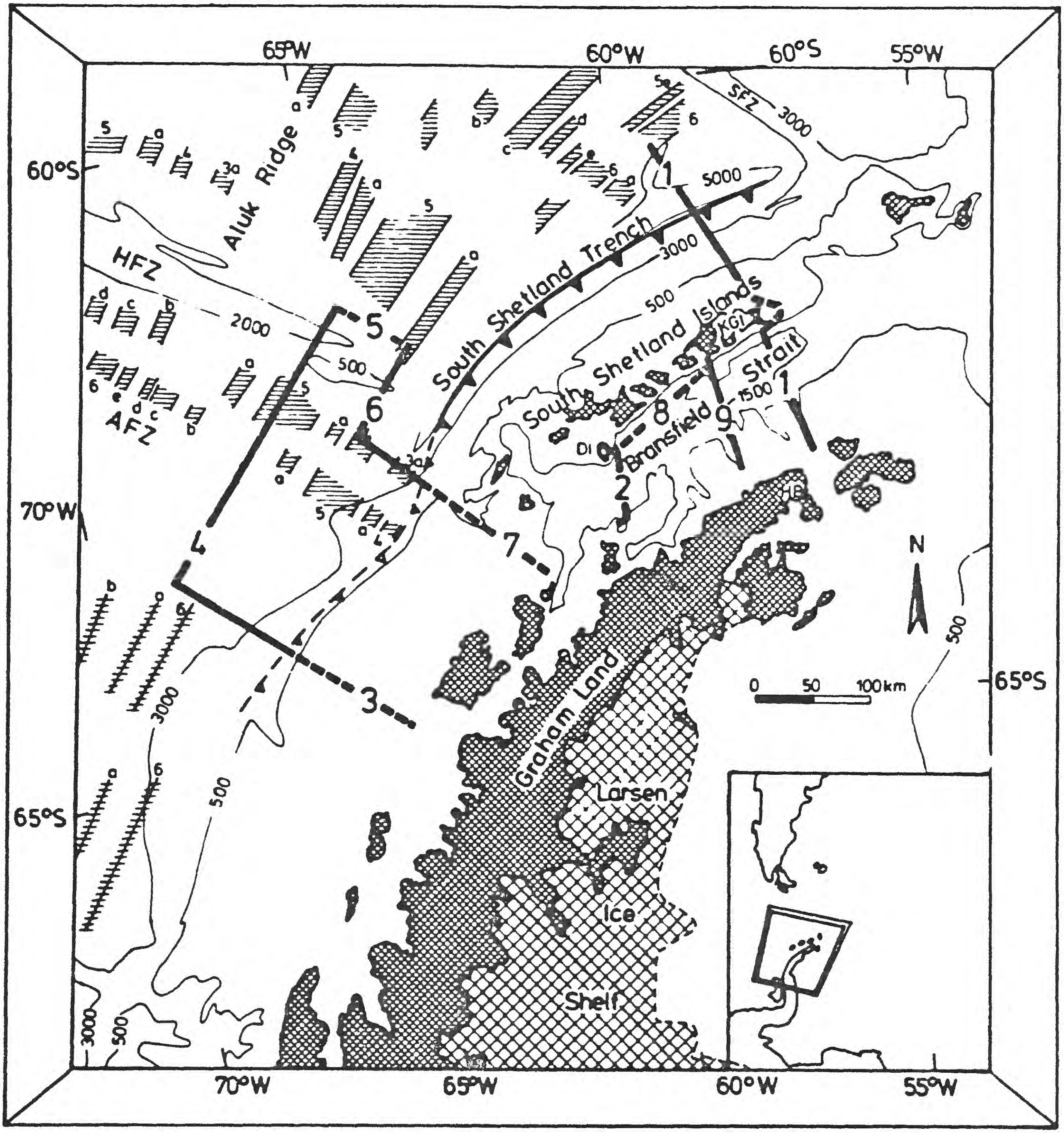
top:	I undisturbed sediments	II diffraction events
	II rift–like structure	
middle:	I undisturbed sediments	II diffraction events
bottom:	I rift basin	

Fig. 3. Line drawings of the three reflection lines 1, 3 and 7 crossing the South Shetland Trench.

top:	I sediment infill of trench	II oceanic sediments
	III accretionary wedge	IV trench–like structure
middle:	I sediment infill of trench	TOB top of basement
bottom:	I basement step	II turbitides
	III normal faults	

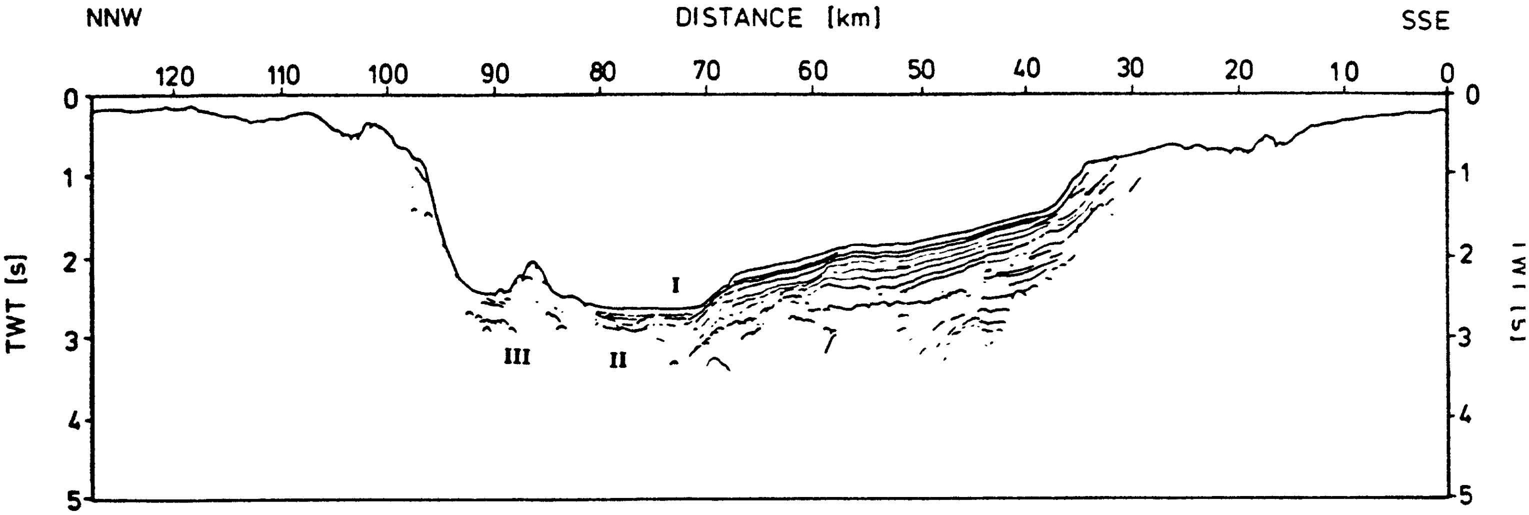
Fig. 4. Line drawings of reflection lines 4 and 6 across fracture zones.

I volcanic dome	TOB top of basement

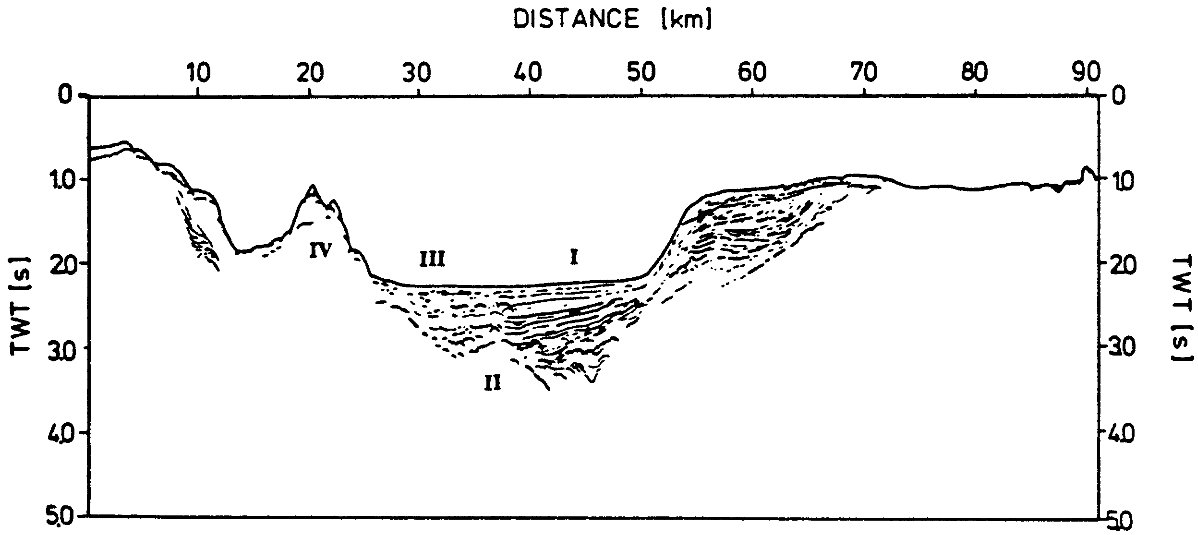


65°W
60°W
60°S
55°W
60°S
70°W
65°S
65°S
70°W
65°W
60°W
55°W
Aluk Ridge
HFZ
AFZ
SFZ
South Shetland Trench
South Shetland Islands
Bransfield Strait
KGI
DI
Graham Land
Larsen
Ice
Shelf
N
0 50 100km
5000
3000
2000
500
1500
1
2
3
4
5
6
7
8
9

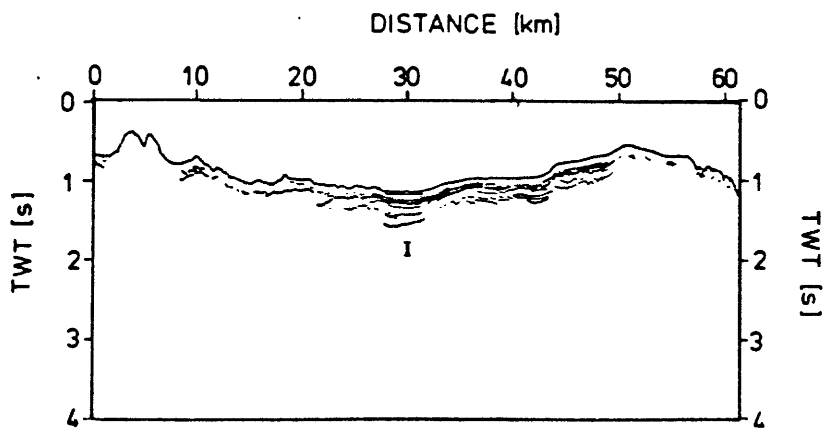
Profile 1

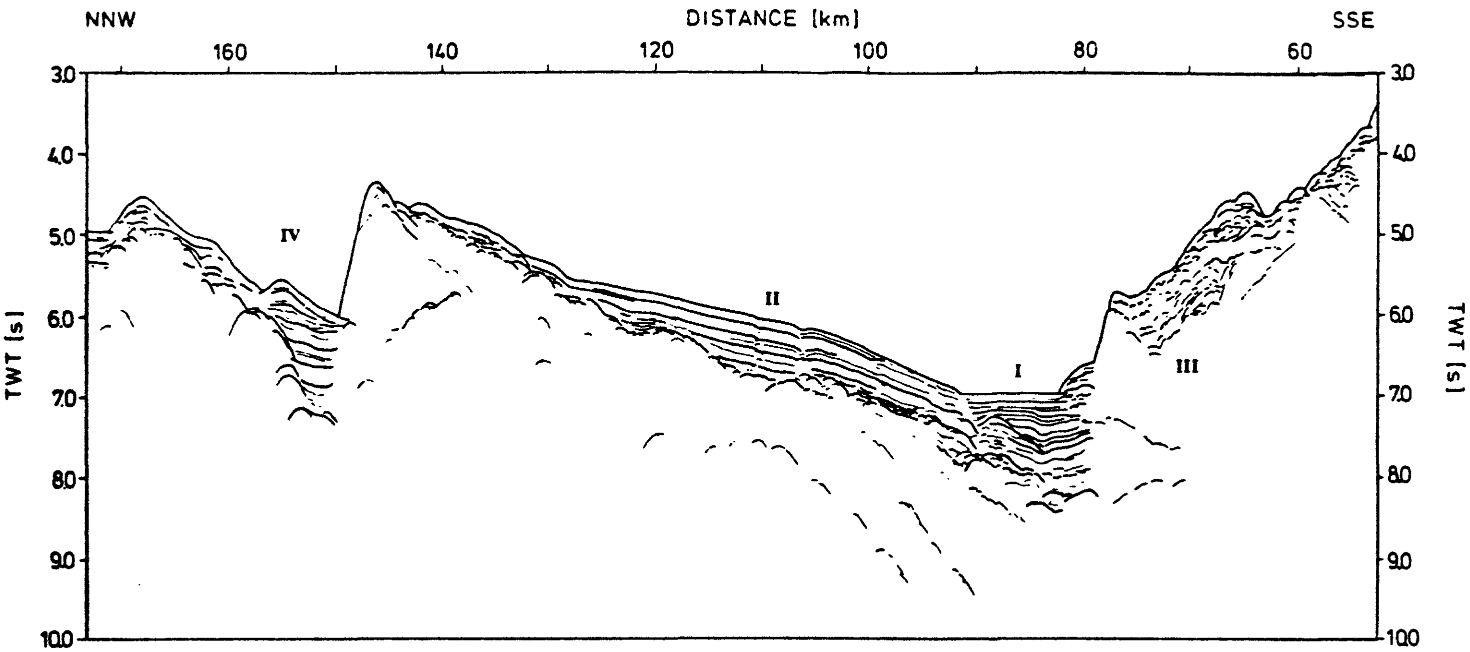


Profile 9

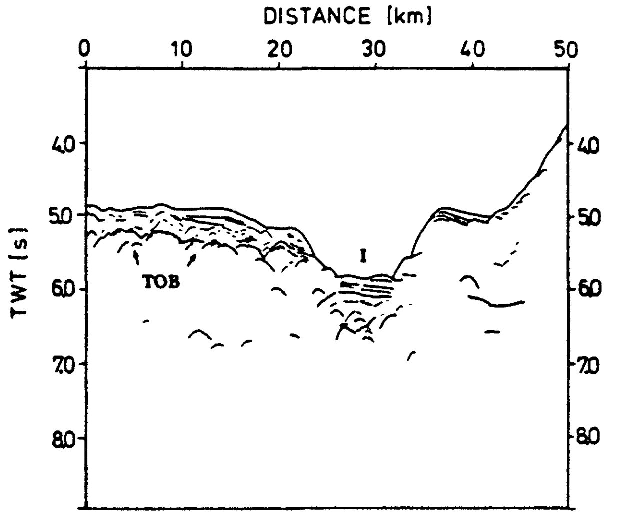


Profile 2

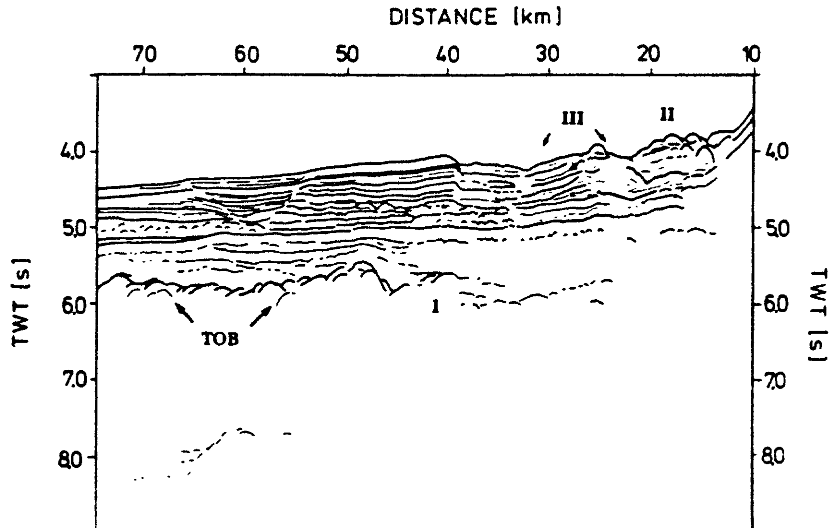


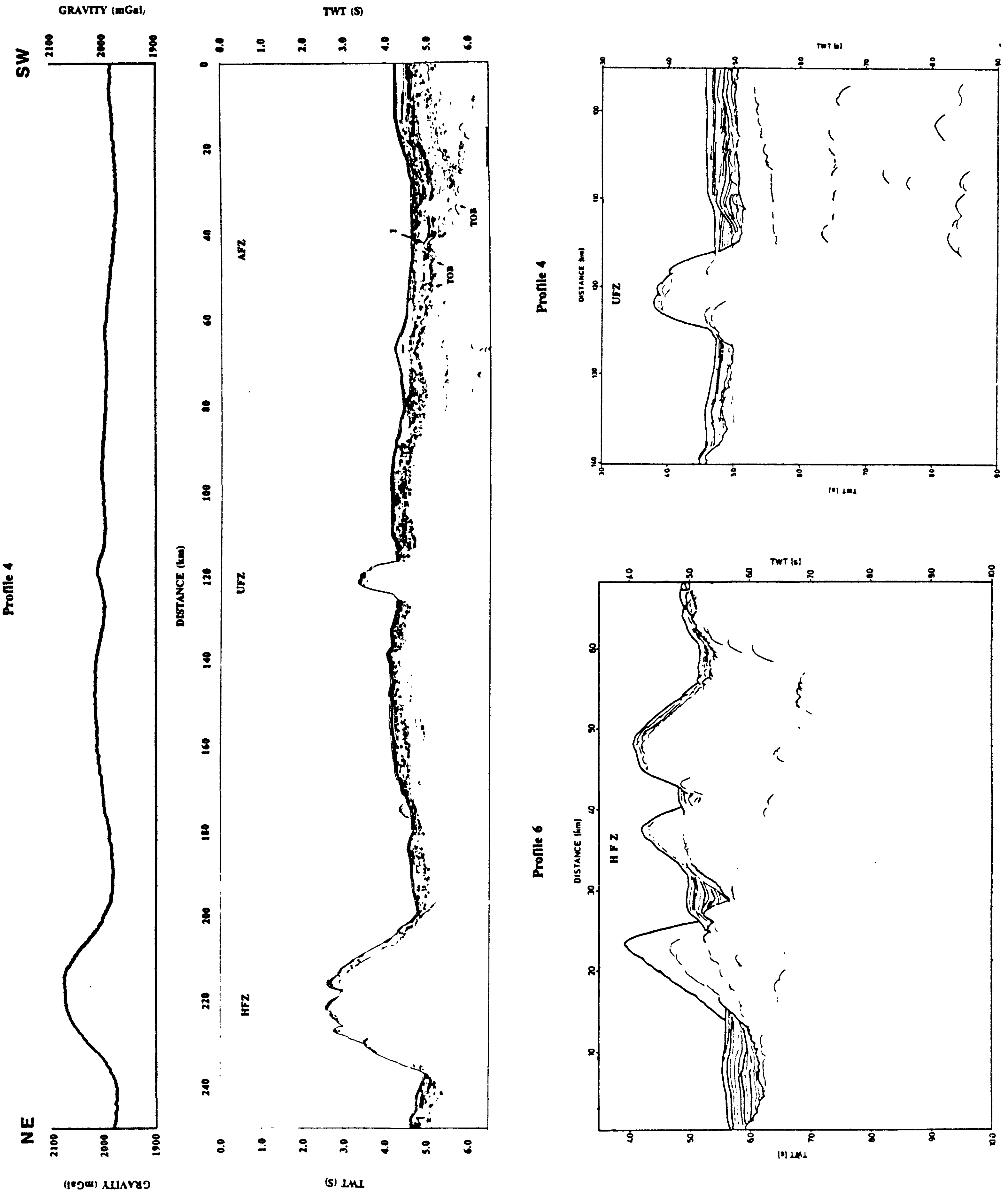


Profile 7



Profile 3





Profile 4
SW
NE
GRAVITY (mGal)
2100
2000
1900
TWT (S)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
DISTANCE (km)
AFZ
UFZ
HFZ
TOB
Profile 4
UFZ
DISTANCE (km)
TWT (s)
Profile 6
H F Z
DISTANCE (km)
TWT (s)

GLACIOLOGICAL INFLUENCES ON SEDIMENTOLOGICAL PROCESSES IN THE ROSS EMBAYMENT

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The Cenozoic sedimentary basins in the Ross Sea and Weddell Sea regions of coastal Antarctica are both adjacent to large ice shelves. These ice shelves are fed primarily by ice streams which are fast-moving rivers of ice flowing through a comparatively stagnant ice sheet. The dynamics of these ice streams and the response of the ice stream/ice shelf system to changes in climate and sea level must be understood to decipher the Cenozoic marine geological record of Antarctica. Below, I will present the evidence gathered from ice stream B in West Antarctica that has been used to formulate a hypothesis for the sedimentary evolution of the Ross Embayment (Alley et al., this volume). The following discussion as well as this hypothesis have been extracted from a paper by Alley et al. (1989).

For the last several years the Siple Coast Project has been conducting a cooperative glaciological and geophysical survey of the Siple Coast, which is that region where ice from West Antarctica drains into the Ross Ice Shelf (Figure 1; Siple Coast Steering Committee, 1988). Seismic surveys at the UpB camp on ice stream B have shown that the ice stream there is underlain by a meters-thick layer of water-saturated, unconsolidated sediment with about 40% porosity in which the water pressure is within about 50 kPa (0.5 bar) of the overburden pressure (Blankenship et al., 1986; 1987). The layer is continuous, or nearly so, along a 9-km line transverse to flow (Rooney et al., 1987) and along a 12.5-km line in the direction of flow (Rooney et al., in press). The layer has a smooth upper interface with the ice, but the lower surface is an angular unconformity that is eroded into flutes about 10 m deep and 300-1000 m across, oriented parallel to ice flow. The rocks beneath the angular unconformity probably are poorly consolidated Neogene marine or glaciomarine sediments (Rooney et al., in press). Preliminary seismic results from the DnB camp (Figure 1) suggest that the layer is present there and has a similar thickness (Blankenship et al., 1989).

The high porosity of this meters-thick subglacial layer indicates that it is dilated and thus is deforming; force-balance and water-balance calculations also suggest that it is deforming. We thus have hypothesized (Alley et al., 1986, 1987) that this layer is a deforming, water-saturated till similar to that described by Boulton (1979) beneath Breidamerkurjokull in Iceland, that it extends beneath the entire ice stream, that the ice velocity arises largely from deformation within this till, and that erosion/remobilization of soft subjacent sediments by clasts in this till has eroded the observed angular unconformity. (Drewry [1986, p. 61-62] has discussed the analgous case of erosion by clasts in ice frozen to its bed). In the discussion that follows we will assume that our interpretation of the seismic data from UpB as indicating a deforming till is correct; however, direct measurement of a velocity profile within the meters-thick layer beneath a kilometer of ice has not been conducted, although the presence of saturated and unconsolidated sediment possessing a porosity and water pressure consistent with our hypothesis has been verified by drilling (Engelhart et al., 1990).

We have estimated the velocity profile and thus the till flux in the layer, and find that it corresponds to a steady-state erosion rate of tenths of a millimeter of rock per year averaged over the catchment area and the upstream part of the ice stream (Alley et al., 1987). This sediment flux also requires relatively rapid deposition at the grounding line. We have estimated (Alley et al., 1987) a rock flux of hundreds of cubic meters per year per meter width of grounding line, which would have formed a deposit tens of kilometers long into water tens of meters deep if the grounding line has been near its present position for the last 5-10 ka (Thomas and Bentley, 1978; Greischar and Bentley, 1980). Geophysical data suggest that such a deposit does exist at the grounding line of ice stream B (see below).

Terminology for such an extensive grounding-line deposit poses a bit of a problem. Powell (1981; 1984) argues that grounding-line deposits of ice shelves should be called "morainal banks," but describes such banks as "elongate ridges or isolated mounds" comprising "grounding-line melt-out till, dropped, compound, and residual para-tills...fluvial sediment and sediment gravity flow deposits" (Powell, 1984, p. 19). The features we propose are not elongate ridges or isolated mounds and, as described below, we believe that they comprise basal-till topsets with minor sorted sediments, and gravity-flow foresets and bottomsets; the topsets will parallel the base of the ice and may dip upstream. We have termed these deposits "till deltas" to emphasize their delta-like nature and the likely dominance of till in the topset beds (Alley et al., 1987).

A thick, extensive accumulation of sediment near the grounding line, where the water pressure is almost as large as the overburden pressure, would be quite soft and would support only a small basal shear stress. This in turn requires a small ice-air surface slope, which implies a small pressure gradient driving water flow, a thickened water film, and enhanced sliding between ice and till in addition to ongoing till deformation. The base of an ice shelf typically rises downstream, and if sediment filling the sub-ice-shelf cavity retained this slope, water drainage would be slowed further. The downglacier end of a till delta is the grounding line, where flotation begins, and we have called the up-glacier end the "coupling line" (Figure 2; Alley et al., 1987), where the ice-stream surface slope decreases onto the delta.

It seems unlikely that water drainage or possible basal freeze-on over the till delta could remove most of the till supplied from upglacier by deformation, as discussed above, although limited sediment sorting might occur. Deformation then must continue across the delta, creating a meters-thick topset bed that may have a shallow ($\leq 1^{\circ}$) upglacier dip. The highly unconsolidated, water-saturated sediment transported through this topset must lose contact with the ice at the grounding line, leading to slumping and development of foreset and bottomset beds of turbidites and debris-flow deposits (Prior et al., 1981; Powell, 1984). The depositional dip of foreset beds might be similar to dips in other low-energy, turbidite-dominated, progradational clastic settings, or about 1° or less in the downstream direction (Mitchum et al., 1977; Sangree and Widmier, 1977).

When we first predicted the existence of a large, lobate region of grounded ice at the mouth of ice stream B, the grounding line was mapped as shown by the lightly-dashed line in Figure 1, with a surface slope immediately upstream of the grounding line about equal to values farther upstream (Rose, 1979). Detailed mapping using satellite altimetry and airborne-radar data now has shown that the grounding line is as indicated by the solid line in figure 1, tens of kilometers downstream of the old grounding line (Shabtaie and Bentley, 1987). The surface slope on the newly discovered regions of grounded ice, or "ice plains" (Bentley, 1987), is significantly less than on the main part of the ice stream and is almost as small as ice-shelf values (Shabtaie and Bentley, 1987).

Reinterpretation of seismic data collected during RIGGS on the ice plains suggests that, at least in most places, they are underlain by water-saturated, unconsolidated sediments probably tens of meters thick (Shabtaie and Bentley, 1987). Preliminary analysis of new seismic data from near the DnB camp (Figure 1) shows a meters-thick layer overlying a unit tens of meters thick containing beds dipping downstream at about $1/2^{\circ}$; these may be the predicted topset and foresets (Blankenship et al., 1989; Figures 3 and 4). The grounding line mapped by Rose (1979) probably represents the coupling line.

Of course, the simple existence of unconsolidated sediments beneath an ice shelf does not demonstrate that the sediments were transported by subglacial deformation. Rapid melting of debris-rich basal ice at the grounding line and discharge of subglacial melt streams can form morainal banks at grounding lines (Powell, 1984). Melt-stream discharge would build a deltaic deposit, but this would have sorted sediments and thus would tend to have steeper foreset beds, perhaps dipping 1° to 10° (Mitchum et al., 1977; Sangree and Widmier, 1977). Basal melt-out probably would produce a dropstone-diamicton layer lacking deltaic form.

Based on radar data, Drewry et al. (1980, p. 48) suggested that part of the grounding line of the Filchner Ice Shelf is "just touching a sea floor, composed of soft, water saturated sediment." Drewry and Cooper (1981) noted that this zone was tens of kilometers wide and suggested that it was formed by sedimentation owing to debris melt-out filling the sub-ice-shelf cavity. A similar zone of soft basal sediments in contact with ice near the grounding line in a region previously assumed to be afloat was discovered by drilling on the Lazarus Ice Shelf (Korotkevich et al., 1978). In the case of ice stream B, the sediment volume beneath the ice plains seems too large to have been deposited by melt-out or by subglacial streams without a deforming till in the time during which the grounding line has been near its present position (assuming that this sediment is post-Wisconsinan), and the seismically observed sedimentary structures resemble those expected from a deforming till. A deforming till cannot be ruled out for the Filchner Ice Shelf and elsewhere, but data to assess this are not available.

The existence of till deltas introduces certain other interesting possibilities. Because of the small surface slope over a till delta, a relatively small rise in sea level could cause a relatively large grounding-line retreat. For example, on ice stream B a sea-level rise of about 25 m would cause a grounding-line retreat of about 75 km (Shabtaie and Bentley, 1987). However, this would introduce a water layer varying from 25 m thick at the old grounding line to zero thickness at the new grounding line, and the estimated sediment flux from the ice stream of hundreds of m^3/a per meter width would fill this water layer with sediment in only $O(10^3 a)$. Sea-level rise slower than $O(10^{-2} m/a)$ would be compensated entirely by sedimentation on the till delta of ice stream B and would cause no grounding-line retreat (Shabtaie and Bentley, 1987).

The stabilizing effect of sedimentation on grounding-line position would be lost if the sediment supply were terminated. It now is clear that ice steam C was an active ice stream that stopped about two centuries ago (Shabtaie and Bentley, 1987). This stoppage reduced the ice flux across the grounding line, and ongoing ice-shelf spreading is causing thinning of the ice there; the effect of such thinning on grounding-line position is analogous to the effect of sea-level rise. The stoppage also ended sediment supply to the grounding line (presuming that ice stream C moved by a similar mechanism to ice stream B). The grounding line of ice stream C now is retreating in response to the thinning ice (Thomas et al, 1989), and the shape of the grounding line (Figure 1) suggests that it has retreated tens of kilometers along most of the ice-shelf front since ice stream C became inactive. (The region of ice stream C closest to ice stream B may have remained grounded on its till delta thus far because flow lines from ice stream B have bent towards ice stream C [Shabtaie and Bentley, 1987], partially replacing the ice loss from stoppage of ice stream C and preventing rapid thinning of ice there).

Another interesting possibility comes from our calculation (Alley et al., 1989) that partial ice-till decoupling across a thickened water film on the till delta reduces the flux of deforming till below its maximum possible value. If any perturbation to the system were to thin the water film, till flux across the delta would increase by erosion of the head of the delta. For example, a falling sea level would increase the interaction of the ice shelf with pinning points downstream, increasing the backstress and probably causing the ice over the till delta to thicken and steepen to maintain force balance. This would increase the pressure gradient driving water flow, thin the water film, increase ice-till coupling, and cause till flux across the delta to exceed till input from upstream of the delta (Alley et al., 1987). This would give the classic "conveyer belt" grounding-line advance (Powell, 1984), in which the upstream end of the delta (the coupling line) and the grounding line advance through sediment recycling. Behind the advancing till delta would be an extended ice stream lubricated by a thin till layer. This idea figures in our hypothesis for the Quaternary history of the Ross Embayment which is presented as a separate abstract (Alley et al., this volume).

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FIGURE CAPTIONS

Figure 1

Map showing Ross ice streams flowing into Ross Ice Shelf; ice streams are shown stippled. Modified from Shabtaie and Bentley (1987). Grounding line of rose (1979) is shown on the ice streams by light dashed line and grounding line of Shabtaie and Bentley (1987) is shown by heavy solid line; ice plains occur between the two. Major camps and features are indicated.

Figure 2

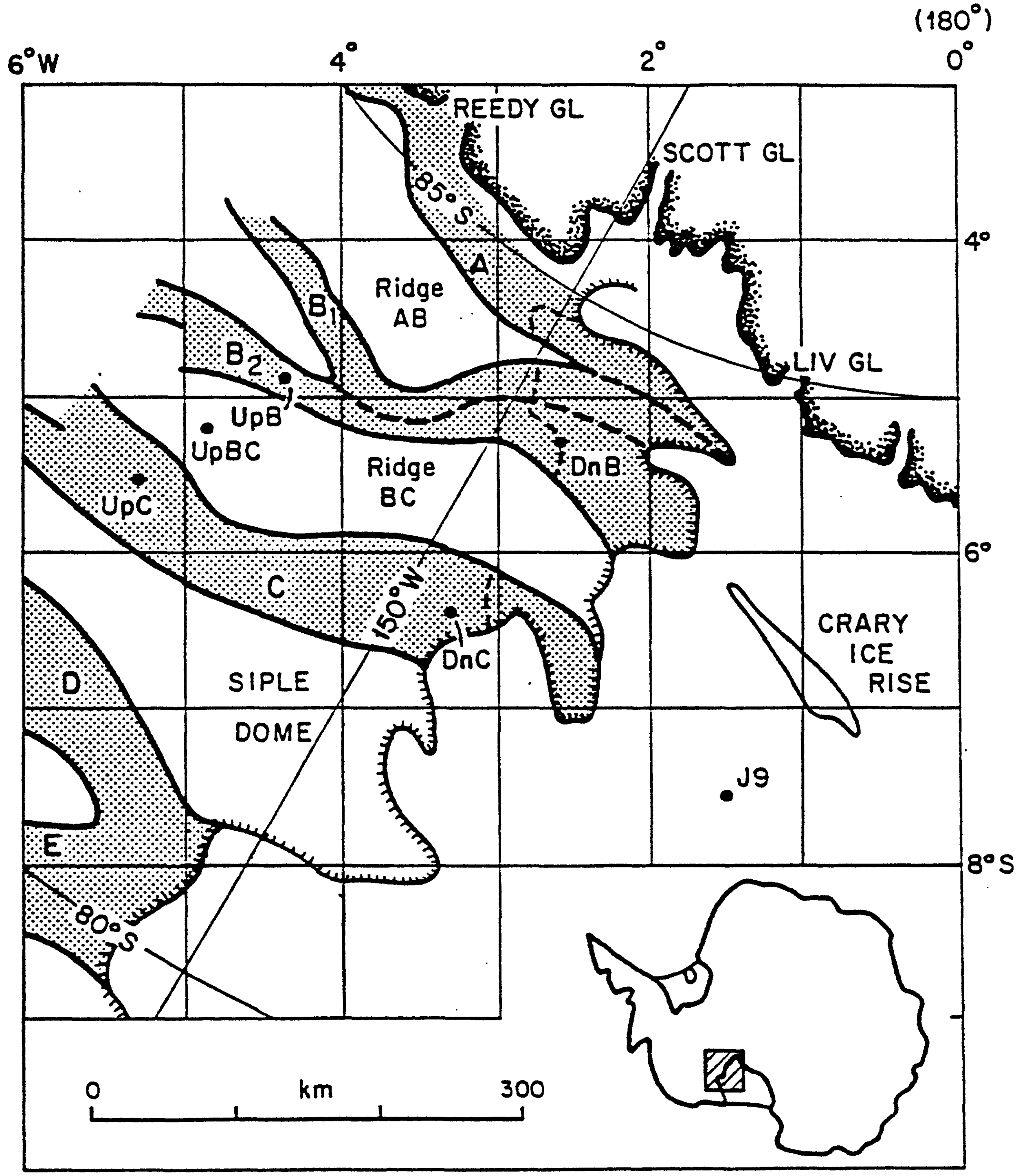
Cartoon of likely configuration of ice stream, till delta, and ice shelf.

Figure 3

Seismic reflection section along a parallel-to-flow line near DnB. An interpretation of the ice bottom, the bottom of the active (?) till layer (the topset), and the forset bedding planes have been inked in.

Figure 4

Seismic reflection section along a transverse-to-flow line near DnB. An interpretation of the ice bottom, the bottom of the active (?) till layer, and one internal reflector within the active (?) till have been inked in.



(180°)
6°W
4°
2°
0°
REEDY GL
SCOTT GL
85°S
4°
A
Ridge
AB
B1
B2
LIV GL
UpB
UpBC
Ridge
BC
DnB
UpC
6°
C
150°W
DnC
CRARY
ICE
RISE
D
SIPLE
DOME
J9
E
8°S
80°S
0
km
300

Figure 1

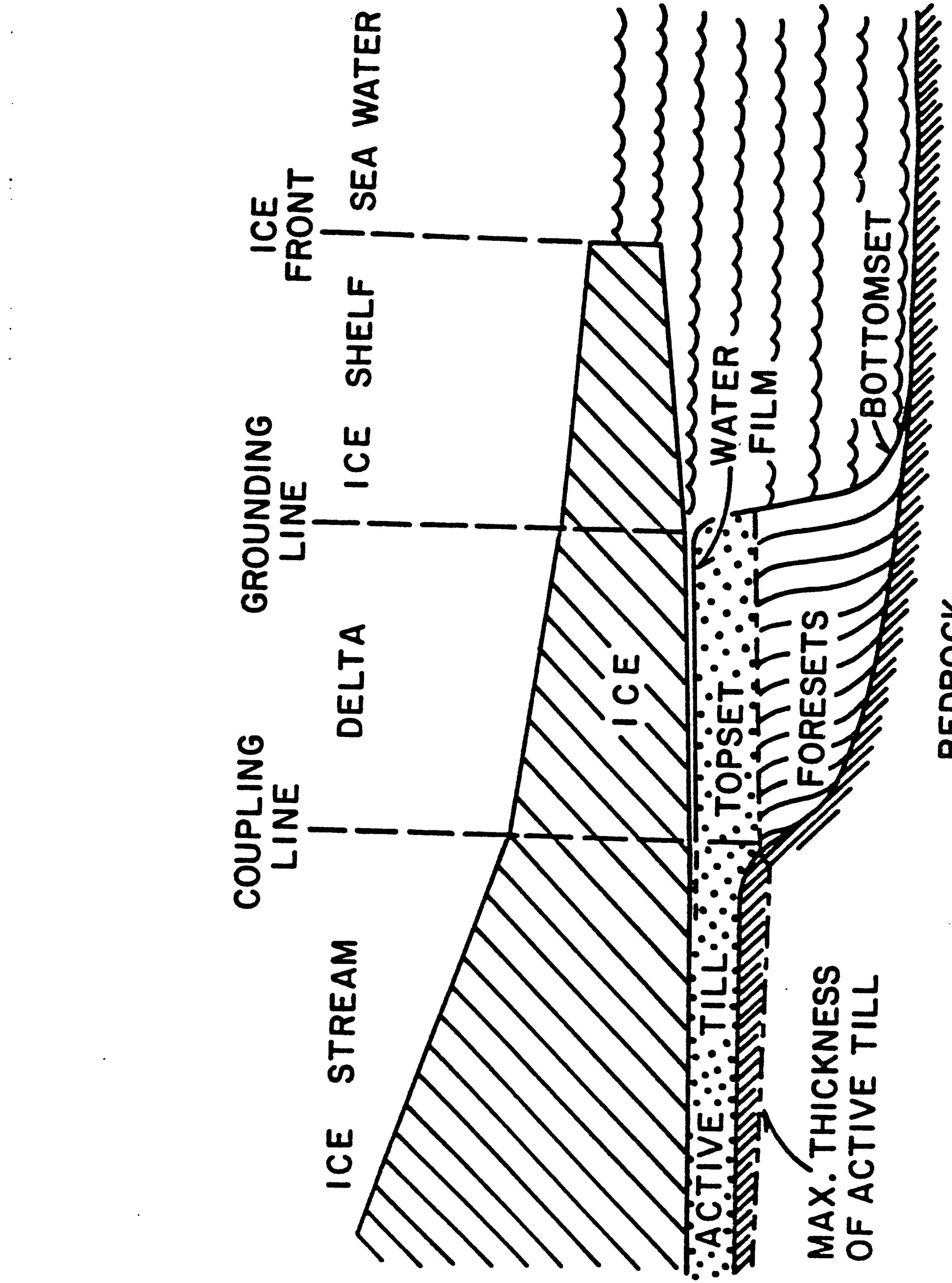

ICE STREAM
COUPLING LINE
DELTA
GROUNDING LINE
ICE SHELF
ICE FRONT
SEA WATER
ICE
WATER FILM
BOTTOMSET
TOPSET
FORESETS
ACTIVE TILL
MAX. THICKNESS OF ACTIVE TILL
BEDROCK

Figure 2

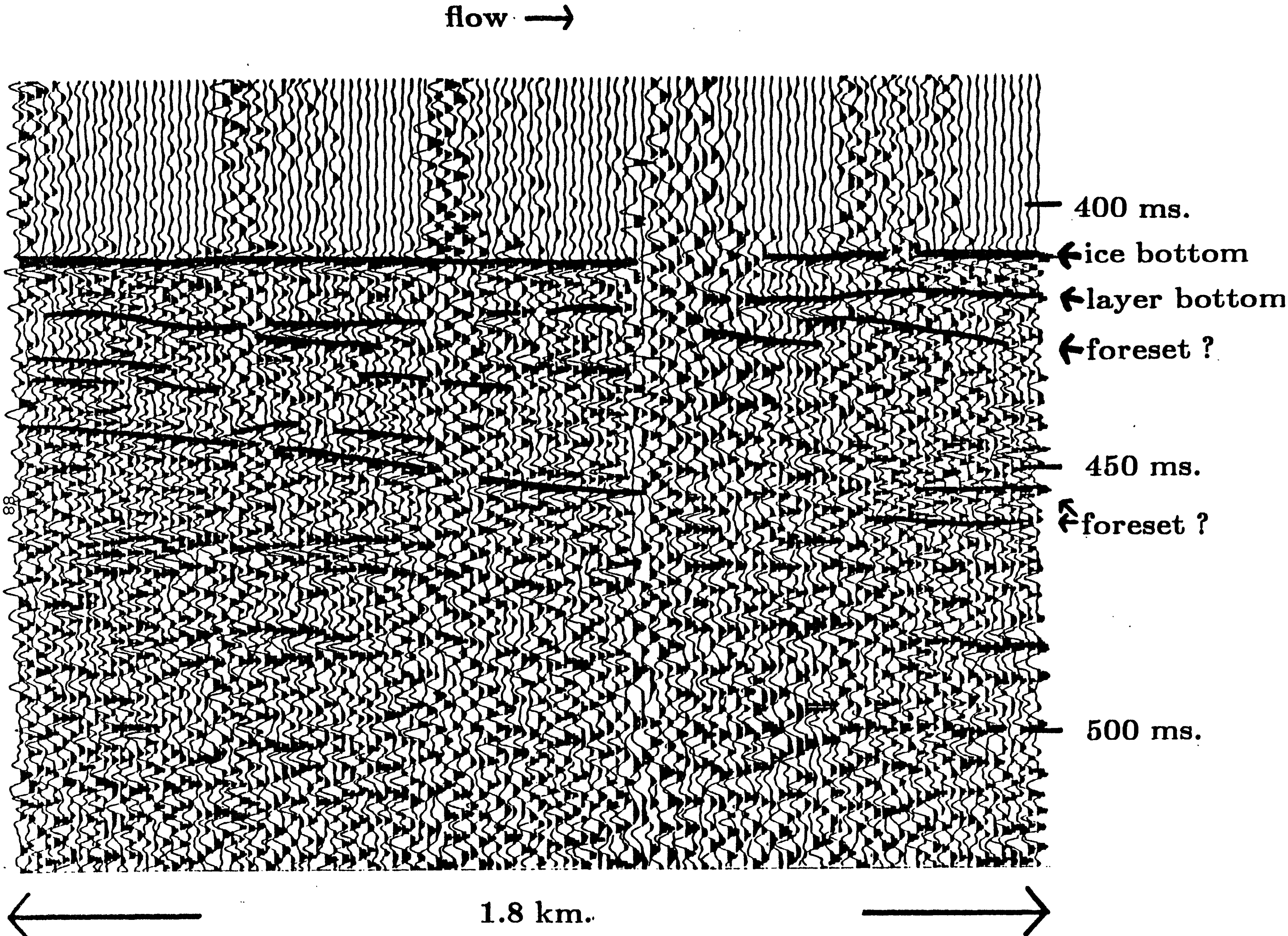

flow
400 ms.
ice bottom
layer bottom
foreset ?
450 ms.
foreset ?
500 ms.
1.8 km.

Figure 3

across flow

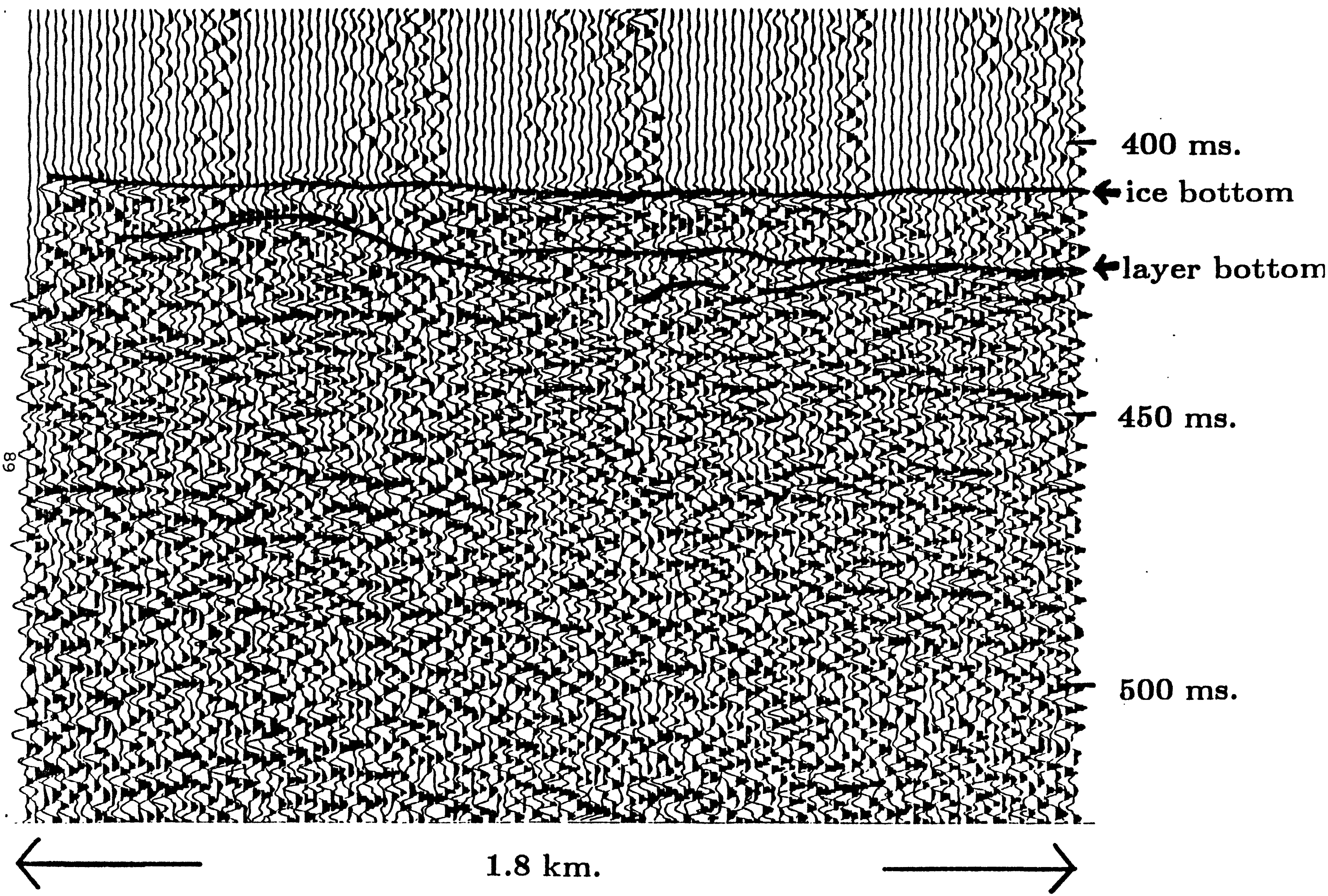


Figure 4

PRELIMINARY DESCRIPTION OF ITALIAN GEOPHYSICAL SURVEYS IN THE ROSS SEA AND ANTARCTIC PENINSULA AREAS: 1988 THROUGH 1990

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ROSS SEA PROGRAM

The Osservatorio Geofisico Sperimentale (O.G.S.) performed three geophysical surveys in the Ross Sea during the 1988, 1989 and 1990 Antarctic summers in the context of the National Antarctic Program. The ship employed was the OGS Explora and the characteristics of the surveys are as follows:

Energy source: 45 l air gun; 22.5 l for the site survey during the 1990 expedition

Seismic recorder: Sercel SN 358
Streamer length: 2400 m in 1988, 3000 m in 1989 and 1990
Number of traces: 96 in 1988, 120 in 1989 and 1990.
Traces interval: 25 m
Shot interval: 50 m
Coverage: 2400% in 1988, 3000% in 1989 and 1990.
Record length: 14 s
Sampling interval: 4 ms
Kilometres: 2393 in 1988, 4372 in 1989 and 2563 in 1990

The objective of the survey was to complete and to integrate the existing seismic grid in the Ross Sea and to study some specific sites in the Victoria Land Basin.

The processing of the seismic data was done in the OGS processing centre. Up to now, 80% of the first two surveys has been processed.

One of the main problems in the Antarctica data processing arose from the high reflectivity of the sea bottom which generates a strong sequence of multiple events. All the reflections detectable on the records are multiples.

For this reason, particular care was given to the individuation and attenuation of multiples:

The main steps in such attempt was:

- FK filtering for velocity analysis
- DBS operator length choosen taking into account the sea bottom depth whenever possible
- DAS with automatic sea bottom piking

The surveys cover all the main structural element known in the Ross Sea.

The Ross Sea is currently considered a passive margin in which two main rifting phases are known:

The first (early rifting) should be Late Mesozoic, Early Tertiary in age and responsable of the main structural elements already mentioned (Eastern Basin, Coulman High, Central Basin, Central High, Victoria Land Basin).The second one (late rifting) is Late Cenizoic and is related to the magmatic effusions in the Victoria Land Basin.

Basement tectonics clearly indicate the presence of distensive structures (half graben). The Tertiary sedimentary sequence is not affected by the basement faults thus indicating a post - tectonic deposition.

A first attempt to correlate structural elements of the basement between different seismic lines seems to indicate that East - West trends are prevalent, mainly in the Eastern Basin.
On the other hand, the Eastern Basin should properly be correlated to the Marie Byrd Land which was an active margin in the Mesozoic, as testify by the granitic intrusion during the Mesozoic. Is not, therefore, excluded that some of the tensional structures in the Eastern Basin represent the remnants of ancient baks - arc basins.
Next year's program will concentrate on the study of some sites where a set of geophysical surveys, included heat flow mesurements and sub - bottom sampling will be performed.
These sites, whose final position has not yet been decided, will investigate the Victoria Land Basin, the Eastern Basin and the Ross margin.

I would like to express our acknowledgments to Karl Hinz of BGR and Alan Cooper of USGS whose suggestions and contibutions have been very helpfull in planning and carring the program.

SCOTIA PLATE AND ANTARCTIC PENINSULA

The O.G.S. (Osservatorio Geofisico Sperimentale) performed a geophysical survey at the southern limit of the Scotia Sea and the Pacific Margin of the Antarctica Peninsula on behalf of the Italian Government and in the context of the National Antarctic Program.

About 3500 km of seismic, gravimetric and magnetic profiles were recorded.

The cruise started from Punta Arenas harbour on november 26 at 8:30 p.m. and finished at Ushuaia harbour on december 22 at 3 p.m.

The ship employed was the O.G.S. Explora; the caracteristics of the survey as follow:

ENERGY SOURCE:	45 l air gun (2500 cu. inch)
SEISMIC RECORDER:	Sercel SN 358
CABLE LENGTH:	3000 m
NUMBER OF TRACES:	120
TRACE INTERVAL:	25 m
SHOT INTERVAL:	50 m
COVERAGE:	3000%
RECORD LENGTH:	14 s
SAMPLING INTERVAL:	4 ms
SURFACE GRAVIMETER:	Bodenseewerk KSS31
GRADIOMETER:	Geometrics G81-813
POSITIONING SISTEM:	Navdata 3000

The objective of the survey was to investigate the Scotia Plate area and the Pacific border of the Anatrctica Peninsula.

The Scotia plate is a complex system of oceanic floor, spreading center, oceanic arc and continental fragments whose evolution is related mainly to evolution of the South Sandwich back arc system and to the westward motion of South America which caused the opening of the Drake passage during the Oligocene.

The Scotia Plate is borded south and north by two sinistral strike slip faults, east by an oceanic arc (the South Sandwich Arc) and west by the Sakleton Fracture Zone.

The program concentrated on three main areas:

1) The southern boundary of the Scotia Plate

2) The South Sandwich intra - oceanic arc

3) The Pacific margin of the Antarctica Peninsula

SOUTHERN BOUNDARY OF THE SCOTIA PLATE

The southern boundary of the Scotia Plate is marked by E - W sinistral stike-slip motion along which lie many continental fragments and oceanic basins. The origin of the continental fragments is Thought to be the Pacific margin of Gondwanaland were subduction and related accretion phenomena took place during the early Mesozoic. In fact, the South Orkney island are composed mainly of deformed and metamorphosed sedimentary and igneous rocks whose relationship with the Antarctic Peninsula have been recognized by various authors (Dalziel 1985). This old tectonic feature is probably reflected by the present E-W trends of structures such as the Newton Basin (King and Barker 198$)

The origin of the oceanic basins is thought to be related to tensional stress caused by back - arc extension of Tertiary (Oligocene) age. the Oligocene rifting also caused the opening of the Drake Passage and completed the separation and isolation of Antarctica from the other continental masses.

One of the most important consequences of the opening of the Drake Passage was the creation of the Circum - Antarctic Current

with significant influence on the Hearth' s climate.
South - North tensional feature like the half graben detected in the area, are related the Tertiary rifting.

Due to ice conditions, only a part of the program was done
in this area:

Line A38 264 km long trending NW - SE to investigate the South Orkney Plateau.

Line A39 704 km long trending NE - SW to investigate the Powell Basin, the Orkney Plateau and the Bruce Bank.

Line A41 412 km long trending NW - SE, and startingit starts from the Scotia Sea, it cuts the fracture zone at the Elephant Plateau and terminates in the Powell Basin.

The original plane was to investigate also the Jane Basin and the Discovery Bank, but Ice conditions didn't allow operation southern than line A39.

SOUTH SANDWICH ARC

This is currently an active volcanic arc; South Sandwich Island infact, consists wholly of oceanic lavas.

Two lines were scheduled for this area in order to investigate the relationships between the arc and oceanic area, both in the active zone (nothern) and in the southern portion of the arc where the seismicity is very low and many remnants of the arc are probably present. Due to ice conditions it was not possible to accomplish this part of the program.

PACIFIC MARGIN OF THE ANTARCTIC PENINSULA

The Antarctic Peninsula was an active margin of the megacontinent of Gondwana.

During the Cenozoic, a series of ridge crest - trench collisions took place which stopped the spreading and collision in the area 4 MA ago (Barker 1982). The opening of the Bransfield Strait and the active South Shetland subduction zone are not, therefore, related to a spreading centre but to some other mechanism of crust consumption.

The objective of the survey in the area was to complete the existing multichannel seismic data and to investigate the main structural elements. The correlation between the seismic stratigraphy of the continental shelf and the Ross Sea will allow the study of depositional mechanisms on a continental scale

The lines in the area are:

Line A42: 135 km long, connects with the South Scotia Sea program

Line A43: 230 km long and

Line A44: 237 km long, are for the investigation of the Bransfield Strait and the South Shetland Arc - Trench system

Line A45: 459 km long, ties and connects with the existing British Antarctic survey

Line A46: 44 km long, is a transferiment line.

Line A47: 310 km long, investigates the Pacific continental shelf and links with the British lines.

Line A48: 199 km long, starts from the continental shelf runs over the slope and onto the oceanic floor.

Line A49: 48 km long, connects the survey to DSDP site 325 which reached clastics sediments of Early Miocene age.

Next year OGS will complete the survey in the South Sandwich Arc and in the South boundary of the Scotia Plate.

In conclusion, I wish to express our apprecition to Peter Barker of the British Antarctic Survey, whose suggestions have been very helpfull in the planning of the survey.

Sonobuoy seismic data over the Ross Sea and Wilkes Land continental margins

by

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Although sonobuoy refraction and wide-angle reflection experiments are generally associated with studies of deep-crustal targets, sonobuoys are also useful in the investigation of shallower stratigraphy and structure. Sonobuoy data are especially useful when collected in conjunction with single-channel and high-resolution seismic profiles which do not inherently produce seismic velocity information, but also provide a useful constraint on shallow velocities derived from interpretation of multichannel seismic (MCS) data, especially in areas such as the Ross Sea where water-bottom multiples tend to obscure the reflection section.

In 1984, the U. S. Geological Survey (USGS) conducted sonobuoy experiments over the Wilkes Land margin and the western Ross Sea (WRS) (Figures 1 and 2) in conjunction with conventional MCS surveys. The results and interpretation of these surveys are to be found respectively in Childs and Stagg (1987) and Cooper and others (1987b). In 1989 and 1990, the USGS conducted further experiments throughout the Ross Sea, particularly the western Ross Sea, in conjunction with MCS surveys conducted by the Osservatorio Geofisico Sperimentale (OGS), as part of the Italian National Program of Research in Antarctica. Locations for the 1989 and 1990 sonobuoys are shown in Figure 2. The 1989 OGS survey was a regional survey which extended throughout the Ross Sea. The airgun source was a 28-gun, 44-liter array fired at a pressure of 140 bar and a shot spacing of 50-meters. The 1990 OGS survey concentrated over the Victoria Land Basin (VLB) of the Western Ross Sea, and was collected in a "high-resolution" configuration with a 14-gun, 22-liter source array fired at 25-meter intervals.

The primary objectives of the 1989-90 USGS sonobuoy program in the Ross Sea were:

Improve the geographical definition of known structural and sedimentary features, particularly in the Central and Eastern Ross Sea.

Investigate the the evolution of the Antarctic escarpment and its relationships with the abyssal plain.

Develop detailed velocity models over each of five sites proposed for drilling under the Ocean Drilling Program (Cooper and others, 1987a).

Clarify the velocity structure of the sedimentary section within the VLB, in particular the nature of the U6 discontinuity (Cooper and others, 1987b), velocity discontinuities due to glacial epoches, and the nature of the acoustic basement, including a possible low-velocity zone just above the acoustic basement.

Correlate stratigraphy from drill sites CIROS-1, MSSTS-1, and DVDP 15 in the southernmost VLB to the network of seismic lines starting some 30 miles to the north.

USGS sonobuoy results have been interpreted using two methods. The conventional slope/intercept and x-squared/t-squared methods as described by Childs and Cooper (1978), are used for first-order solutions. The more advanced ray-tracing method of McMechan and Mooney (1980), has been used on selected profiles characterized by lateral velocity and structural variations, and where higher resolution is desired. (See Cochrane and Cooper, this volume.) Preliminary refraction results of the 1989 and 1990 surveys are currently available, although considerable refinement of these measurements is yet required. These data will be used to determine depth versus travel-time relation above acoustic basement throughout the Ross Sea, and to construct contour surfaces of the coefficients of depth/travel-time polynomial regressions, which can be used to convert isopach surfaces directly to depth. Future work will include the interpretation of wide-angle reflection events, and reinterpretation of digitally enhanced records, as well as comparision of the sonobuoy records with the multichannel velocity analysis.

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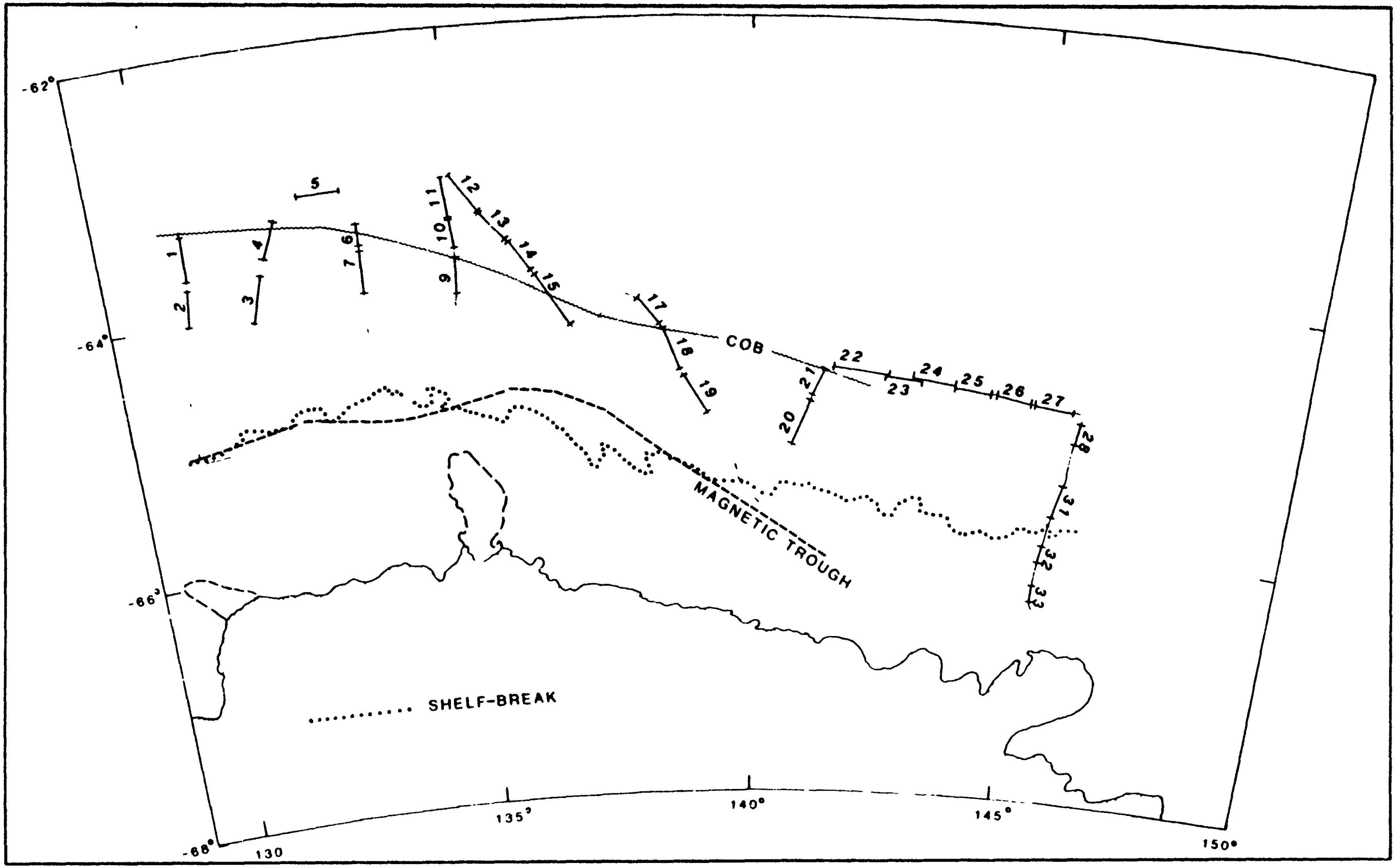
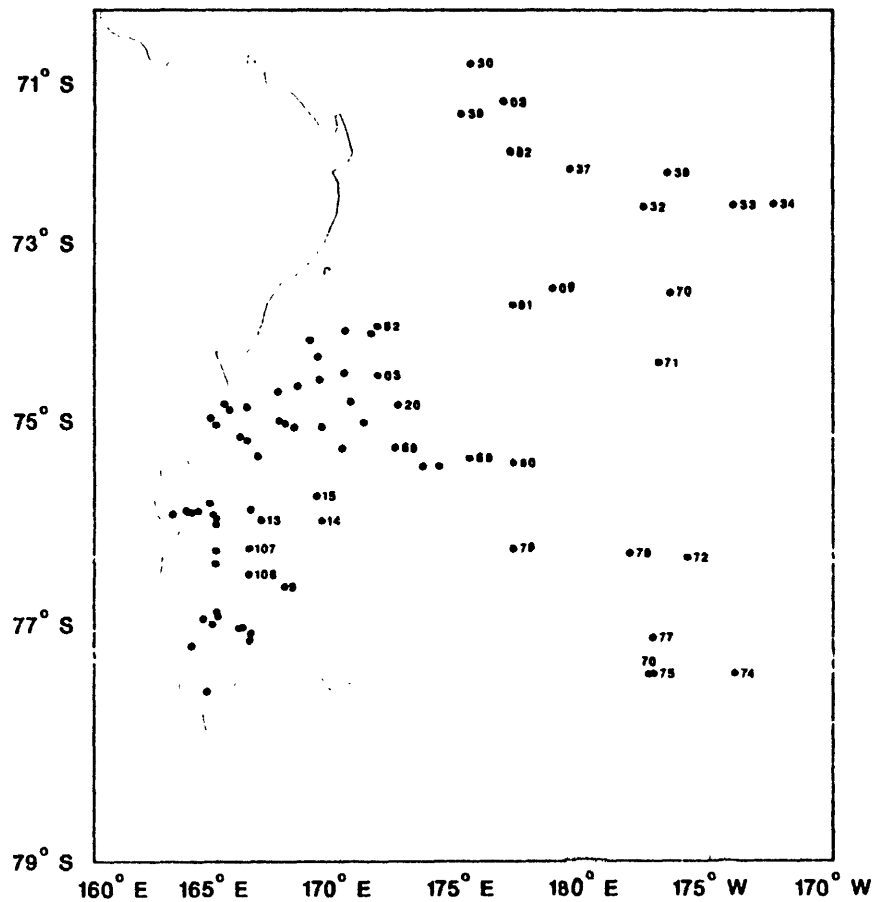


Figure 1. Locations of sonobuoys 1 thru 33 over the Wilkes Land margin collected by the USGS in 1984. Also shown are the shelf break (approximately 2000 m. contour), and the inferred continent-ocean boundary (COB). Polar stereographic projection. Taken from Childs and Stagg (1987).



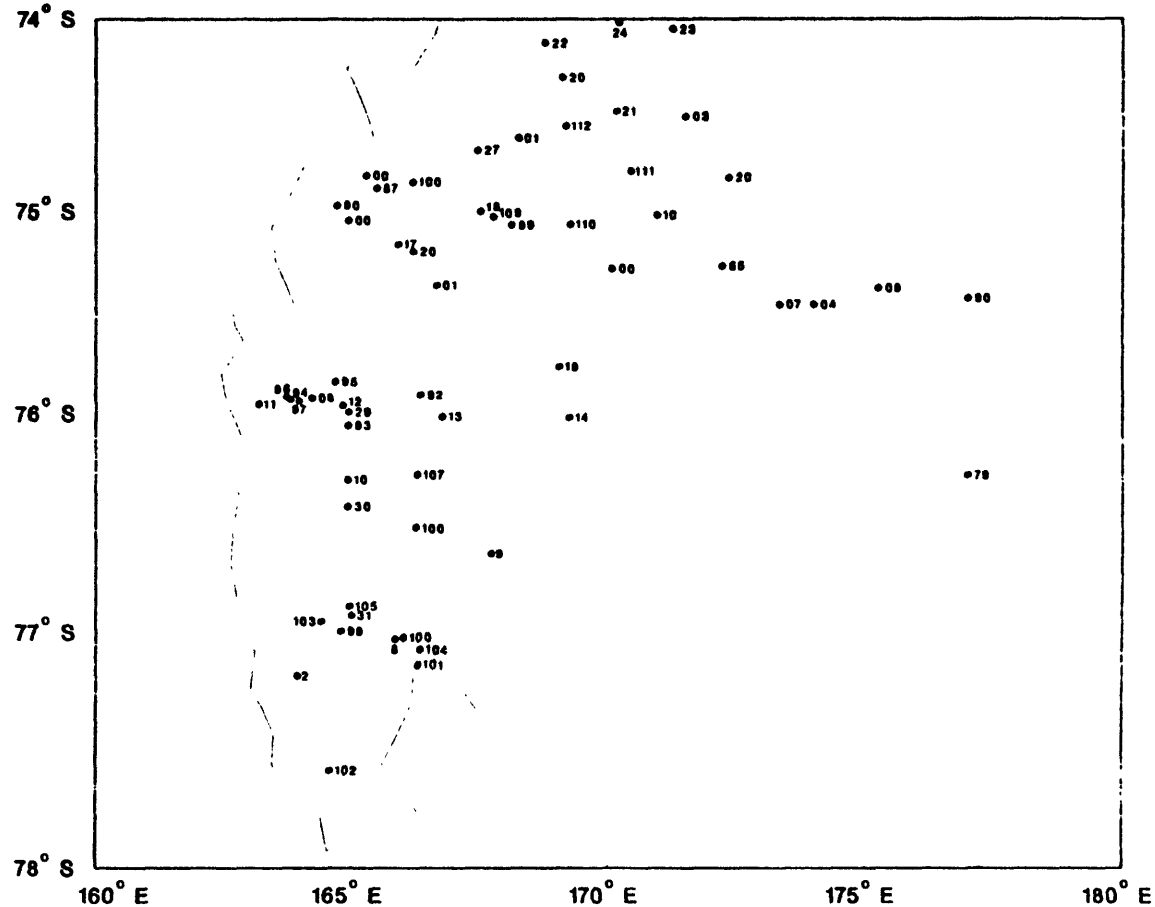


Figure 2. Locations of sonobuoys throughout the Ross Sea. Stations 2 thru 39 were collected by the USGS in 1984; 61 thru 83 were shot during the OGS 1989 survey; 85 thru 112 were shot during the OGS 1990 survey. Mercator projection. Low-resolution coastline is shown for reference only. Map on right is enlargement of western Ross Sea.

APPLICATION OF SONOBUOY SEISMIC DATA TO THE STUDY OF ANTARCTIC GLACIAL SEQUENCES

Guy R. Cochrane and Alan K. Cooper

Sonobuoy seismic-refraction data have been collected at many places around Antarctica (Childs and Cochrane, this volume). These data were initially used to delineate basement depths and sedimentary layer thickness at a scale on the order of 0.1 km. Cochrane and Cooper (in press) have shown that ray-trace modeling of sonobuoy data provides good estimates of the velocity-depth profiles on the order of 0.01 km when adjustments are made for navigational error and stratigraphic variation along the ships course. In this paper, we compare sonobuoy data and ray-trace models from the Prydz Bay and Ross Sea continental shelves. The implications of these models with respect to the study of Antarctic glacial sequences is also discussed.

Sonobuoy data were modeled using the ray-tracing method. In the ray-tracing method (McMechan and Mooney, 1980), a two-dimensional model with variable velocity and structure is designed using seismic reflection data and slope-intercept or x^2 vs. t^2 estimates of the velocities. The location of the sonobuoy is set at 0 km distance and 0.02 km depth. Rays are propagated through the model using the Cervany et al. (1977) algorithm. The traveltime-distance values obtained for rays that reflect off layer boundaries or refract through layers with a vertical gradient are plotted on the sonobuoy data. The model is modified and the calculation repeated iteratively until a fit between the calculated traveltime curves and the data is obtained.

Both sonobuoy and downhole logging velocities (Barron, Larsen et a., 1989) were recorded at Prydz Bay Sites 739 and 742 providing us with the opportunity to ground truth the sonobuoy data. For these two sites we constructed velocity-depth models based on the downhole logging data and generated refraction and wide-angle reflection traveltime curves for comparison to the sonobuoy seismic records.

Sonobuoy 4 (S4) was deployed over Site 739, about 30 km from the shelf edge (Fig. 1A). A near-surface refraction (R1) and a high-amplitude near surface reflection (RB) are observed at this site (Fig. 2A). The near surface refraction (R1) can be modeled by a layer with a velocity of 2.0 km/sec (Fig. 2B). Lithologic sampling at Sites 739 and 742 suggest that the near-surface refraction (R1) and the reflection (RB) off the top of the high velocity layer at the base of acoustic unit PS.1 (see Cooper et al., this volume for discussion of acoustic units) can be attributed to layers of massive diamictite (indurated diamicton) (Barron, Larsen, et al., 1989). The high velocities observed are consistent with glacially overconsolidated sediments, as described by Solheim (in press). Deeper reflections from layers within acoustic unit PS.2A were also modeled. RP and RQ are reflections off the top and bottom of a low-velocity layer that lies below the bottom of the downhole log. The velocity and thickness of this layer are based entirely on the curvature and zero range vertical two-way traveltime of the wide-angle reflection. Thinner layering within this section is not precluded by the modeling and may well be present. The velocity of the layer is lower than that of the overlying layer but is not necessarily indicative of undercompaction. The velocity of the layer is comparable to a normally compacted abyssal plain terrigenous sedimentary rock with approximately with a approximately equal thickness of overburden (Hamilton, 1978). Overconsolidation and resulting high velocity of the overlying layer probably accounts for the apparent low-velocity of this interbedded layer.

Sonobuoy 29 in the Ross Sea is an example of sonobuoy data modeled without the aid of downhole velocity logs. Sonobuoy 29 was deployed over the central region of the Victoria Land Basin (Fig. 1B) where the thickness of the sedimentary section may exceed 10 to 12 km (Cooper et al., 1987a). Unconformities have been identified in seismic reflection data in the upper 6 km of the section (Cooper et al., 1987b). The model (Fig. 3B) was constructed initially using slope-intercept velocities that were based on straight-line segment estimates of the first arrival refractions and on the seismic reflection data (Fig. 3C).

The sonobuoy data show clear refracted arrivals from shots at near range to shots in excess of 30 km (Fig. 3A). The clarity, continuity, and curvature of these refractions, suggest that velocity gradients within the sedimentary section are controlled more strongly by sediment overburden than by isolated high velocity layers within the section. These refractions can be modeled using layers about 1 km thick with a slight velocity increase between the layers and with an increase in velocity within each layer.

Because the traveltime curve of a deep reflection or refraction is affected by the velocity within overlying layers, the presence of velocity inversions and gradients must be considered in the modeling process. When downhole logs are not available, low velocity layers are not readily recognizable. The effect of interbedded low velocity layers is a slight lowering of the average vertical velocity of the layer in which the low velocity horizon occurs.

Sonobuoys are useful for determination of velocities in the near surface (i.e. the upper 50 to 100 m) where logging cannot be done, and for extending velocity estimates to depths below the bottom of the drillhole. However, ray-trace models cannot typically resolve velocity inversions for layers thinner than 0.01 km because reflections off the bottom of the layer cannot be resolved. Instead thicker layers with similar vertically averaged velocities must be used.

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FIGURE CAPTIONS

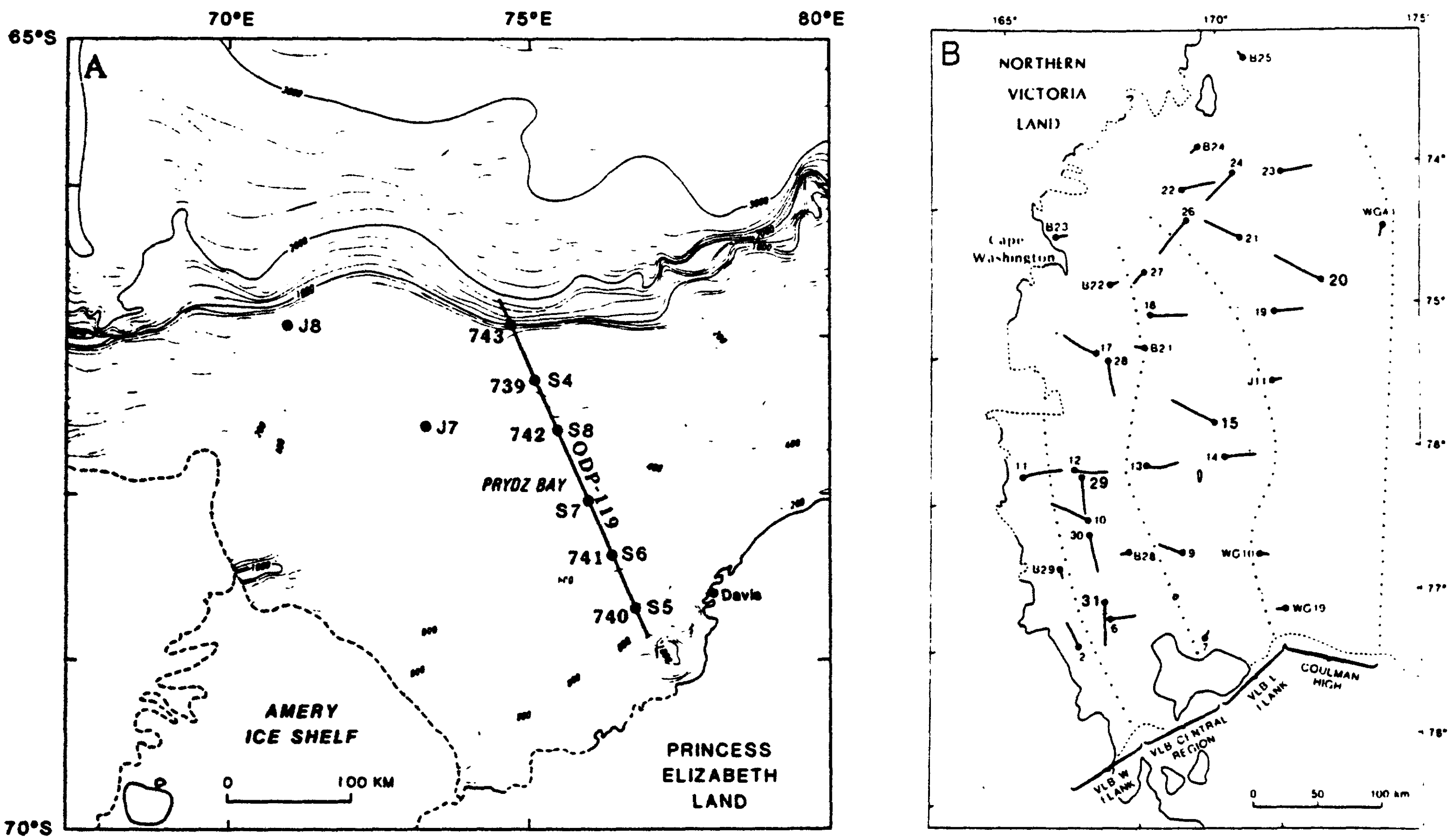
Figure 1. Maps showing locations of sonobuoys. A. Prydz Bay bathymetry (in meters) and locations of sonobuoy deployment sites (S4-S8, ODP Leg 119, J7-J8, Japanese), and ODP Leg 119 drill Sites 739-743. B. Location of sonobuoys in the Ross Sea. Dots are deployment site and lines emanating from dots are length of

sonobuoy line. Dotted lines show extent of structural regions in Victoria Land Basin.

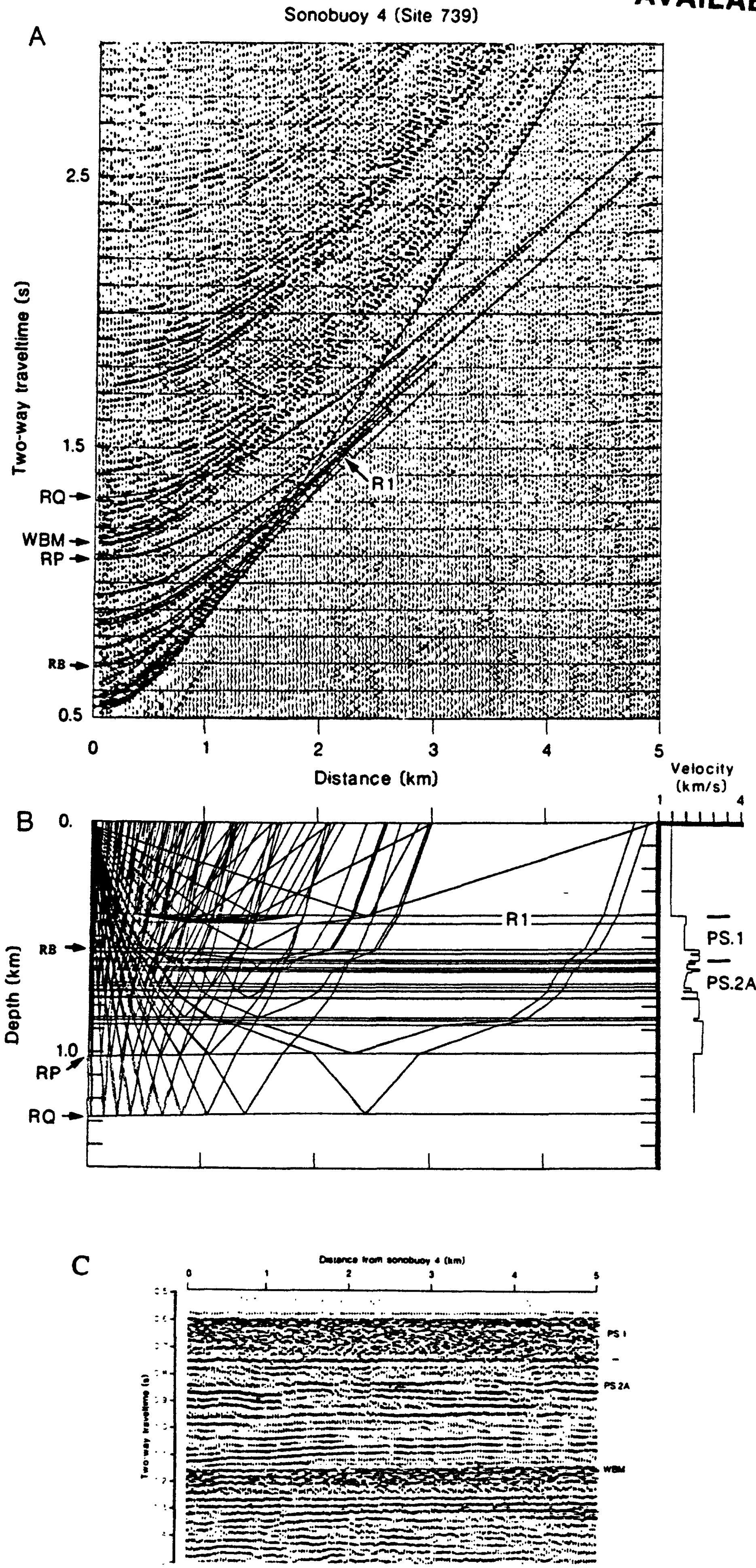
Figure 2. Ray-trace model for sonobuoy 4 data from Prydz Bay. WB = water bottom reflection; WBM = water bottom multiple; R1 = refraction through the near surface; RB = reflection from the top of a high velocity layer at the base of unit PS.1. A. Digitized sonobuoy data and ray-tracing arrival times. B. Velocity-depth model for ray-tracing generated from Site 739 downhole log. Velocity profile shown at right. C. Seismic reflection data.

Figure 3. Ray-trace model for sonobuoy 29 data in the VLB. A. Digitized sonobuoy data and ray-tracing arrival times. B. Velocity-depth model for ray-tracing. Velocity profile shown at right. C. Seismic reflection data.

Figure 4. Velocity-depth curves from ray-trace modeling in Prydz Bay and Victoria Land Basin and from downhole velocity log at Site 742 in Prydz Bay. Sonobuoy 29 is in the VLB, Sonobuoy 4 and Site 739 are in Prydz Bay.



70°E
75°E
80°E
65°S
70°S
A
J8
743
739
S4
J7
742
S8
ODP-119
PRYDZ BAY
S7
741
S6
740
S5
Davis
AMERY ICE SHELF
0
100 KM
PRINCESS ELIZABETH LAND
165°
170°
175°
B
NORTHERN VICTORIA LAND
Cape Washington
B25
B24
B23
B22
B21
B28
B29
J11
WG10
WG19
20
15
29
31
COULMAN HIGH
VLB CENTRAL REGION
VLB W FLANK
VLB E FLANK
0
50
100 km
74°
75°
76°
77°
78°


Sonobuoy 4 (Site 739)
A
Two-way traveltime (s)
2.5
1.5
0.5
RQ
WBM
RP
RB
R1
0
1
2
3
4
5
Distance (km)
B
0.
Depth (km)
RB
1.0
RP
RQ
R1
Velocity (km/s)
1
4
PS.1
PS.2A
C
Distance from sonobuoy 4 (km)
0
1
2
3
4
5
Two-way traveltime (s)
PS 1
PS 2A
WBM

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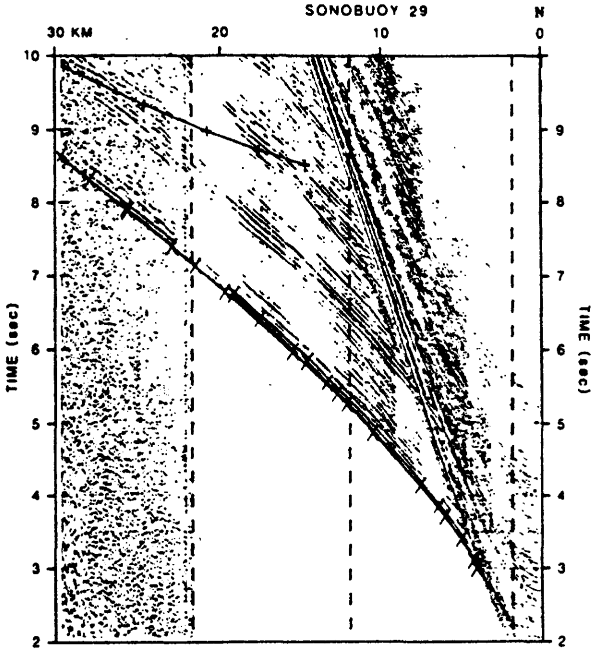
A)



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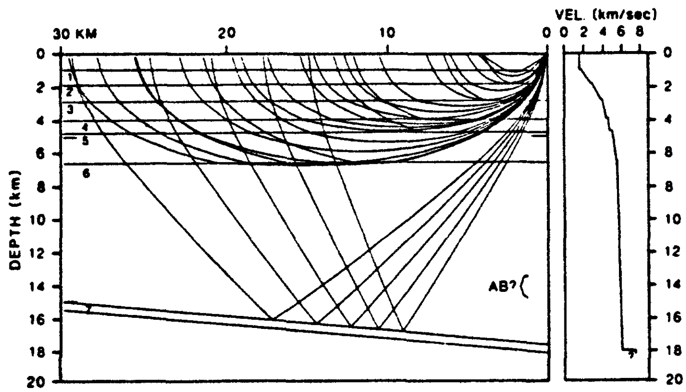
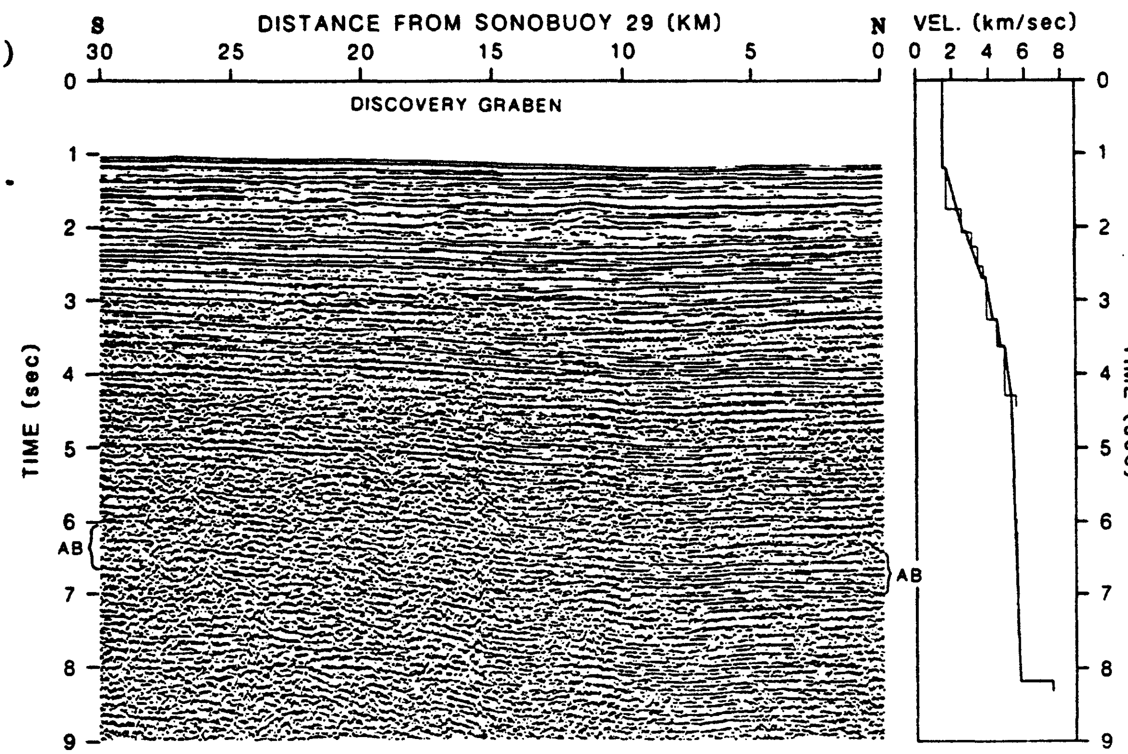
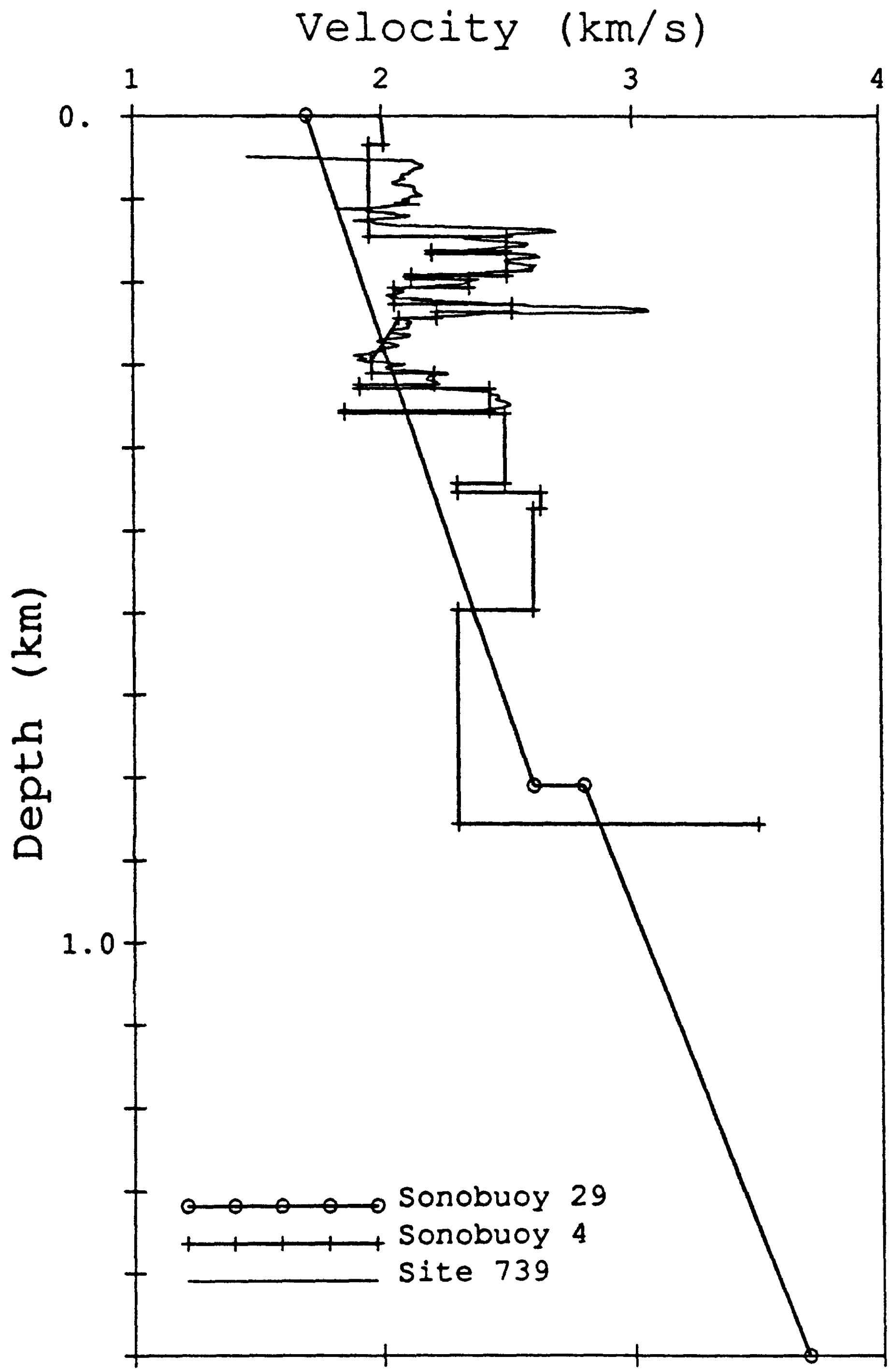


C)





Velocity (km/s)
1
2
3
4
0.
1.0
Depth (km)
Sonobuoy 29
Sonobuoy 4
Site 739

PROGRADING CENOZOIC SEDIMENTARY SEQUENCES OF THE ANTARCTIC CONTINENTAL MARGIN

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Peter J. Barrett, Victoria University, Wellington, New Zealand
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The outer continental shelf of Antarctica is commonly underlain by sedimentary sequences of probable Cenozoic age that are up to 6 km thick and have prograded as much as 80 km (Figure 1). These sequences overlie Mesozoic and Paleozoic (?) sedimentary sections that, in places, are up to 8 km thick beneath the shelf. The pre-Cenozoic sediments were deposited in expansive continental rifts, some of which are now Antarctica's passive margins, and in basins along the formerly active Pacific margin of Antarctica.

Antarctic Cenozoic sequences have been described by numerous investigators and several classifications of regional unconformities have been proposed. However, the areal mapping of these acoustic sequence geometries in detail has not been possible because of limited data. We suggest that Antarctic shelf sequences for the Cenozoic can be described largely by two geometries (Figure 2):

1) Antarctic type I sequences, which have steeply dipping well-defined foresets, truncated by sharp angular unconformities and strong topset reflections. These sequences are common beneath all parts of the Antarctic continental shelf, where they can be seen to represent extensive episodic prograding of the paleo shelf edges.

2) Antarctic type II sequences, which are gently dipping, and largely aggradational, are typical of the sequences described by Vail et al. (1977) from low- and mid-latitude continental margins. These sequences are uncommon, and where observed they lie stratigraphically below the type I sequences.

Differences between Antarctic type I and type II sequences are sometimes not clearly defined, especially in the transition between the two sequence types, such as directly below U4A in Figure 2.

Our present view is that Antarctic type I sequences were deposited by grounded ice, with gross geometry controlled by continental shelf subsidence, principally by ice loading, during advance of large ice sheets to the shelf edge on many occasions. Whereas, Antarctic type II sequences were deposited by normal wave and current processes, with gross geometry controlled by continental shelf subsidence, principally by thermal processes, and sea level change.

The age and composition of sedimentary sequences of the Antarctic margin is poorly known because drilling on the shelf has been done only in the Ross Sea and Prydz Bay. In the Ross Sea, glacial marine rocks of early Oligocene and younger age have been recovered. Drilling in Prydz Bay has sampled only type I sequences (Figure 2), which are massive to stratified overcompacted glacial marine rocks of late Eocene(?) to early Oligocene and younger ages.

Prydz Bay drilling on Leg 119 indicates that the type I sequences are caused by erosion and deposition of sediments by, and in front of, grounded ice-sheets (see also Cooper et al., this volume). Sediments have been eroded principally from onshore and inner-shelf areas and have been carried to the shelf edge, where they have been deposited a) onto the outer shelf from the base of the ice sheet as nearly flat-lying topset beds and b) onto the upper continental slope as steeply dipping foreset beds. At times, the topset beds and the upper slope parts of the foreset beds have been eroded by the grounded ice sheet causing a sharp angular unconformity between the foreset and later-topset beds. Glacial sediments that were deposited on the the shelf before the first grounded ice sheet crossed Prydz Bay have shallower dips. These strata are transitional type I sequences. Type II sequences are missing in Prydz Bay.

In the eastern Ross Sea, where likely Cenozoic continental rifting and subsidence has preserved the Paleogene and younger glacial record, the prograding sequences that have been drilled at DSDP sites 270, 271, and 272 include both acoustic type I and II sequences (Figure 3). Type II sequences lie between unconformity U6 (Hinz and Block, 1984), a regional Paleogene-Mesozoic(?) unconformity (Cooper et al., in press) and an overlying unconformity U4A of likely early Miocene age. All sequences above U4A are type I. Near the present shelf edge in the Ross Sea, the high-amplitude topset reflections commonly terminate abruptly, they are overlain by local domed reflections, and they truncate underlying underlying strata. We associate these acoustic patterns, which are presently recognized only above unconformity U4A, with erosion-deposition processes of grounded ice sheets that have likely crossed the eastern Ross Sea continental shelf periodically since early Miocene time.

Acoustic sequences below U4A and near the paleo shelf edges do not have steeply-dipping and prograding strata of the type that we associate with grounded ice sheets. Based on acoustic geometries, unconformities below U4A, such as U6, may not have been cut by grounded ice-sheets, like those unconformities lying above U4A (Figure 2). Grounded ice sheets of mid-Oligocene age that are considered to have flowed through the Transantarctic Mountains (Barrett, 1989) probably did not reach the eastern Ross Sea at that time. Additionally, at U4A a subtle and important change occurs from underlying acoustic sequences with type II geometries, typical of normal water-depth continental margins, to overlying type I geometries, typical of the present overdeepened Antarctic continental margin. Thus, the eastern Ross Sea may have been initially overdeepened in the early Miocene, as it is today.

The available continental shelf drilling data and distribution of seismic sequences is consistent with a scenario in which a) the most reliable record of early glaciation is in Prydz Bay where the East Antarctic ice sheet reached the edge of the continental shelf edge, at normal depths, in the the late Eocene-early Oligocene; ice was also calving at sea level in the western Ross Sea at this time, but the first clear evidence of extensive grounding of ice is in the early late-Oligocene; b) glacial environments with open marine conditions and normal continental shelf water depths prevailed in the eastern Ross Sea from at least late Oligocene time (Site 270) until early Miocene time; c) after early to middle Miocene time, and especially since late Miocene time, grounded ice sheets frequently extended to the continental shelf edges in Prydz Bay, the eastern Ross Sea, the Antarctic Peninsula, and likely elsewhere around Antarctica.

The location of prograding sequences around Antarctica is determined largely by Cenozoic subsidence from lithospheric processes such as crustal rifting in the Ross Sea, thermal subsidence along the Antarctic Peninsula, and crustal flexure in Wilkes Land. The sequence locations are also controlled regionally, but not necessarily locally, by the orientations of Mesozoic and older structures, such as in Prydz Bay and the Weddell Sea. Glacial erosion of the continental shelf enhances depressions that are likely initiated by lithospheric process. Erosional troughs and banks commonly cross the trends of Mesozoic basin structures beneath the continental shelf, as in the Ross Sea (Figure 4) and Prydz Bay (Cooper et al., this volume). The overdeepening of the continental shelf is due partly to a) crustal loading by ice, b) little interglacial sedimentation on the shelf, and b) erosion of sediments from inner shelf areas, forming troughs, and deposition of sediments on mid to outer shelf areas, forming topset banks during glacial periods with grounded ice across the continental shelf.

Numerous changes in the size of the Antarctic ice sheet since at least early Miocene time are suggested by the acoustic stratigraphy of sedimentary sequences beneath the outer Antarctic continental shelf. The acoustic geometry of type I sequences is attributed to the action of ice-sheets that have episodically been grounded to the continental shelf edge (Figure 5). During glacial periods of expanded ice and lowered sea level, large volumes of sediment have been carried to the shelf edge by these ice sheets. During interglacial periods of sparse or no offshore ice, like today, only minor biogenic sediment may have been deposited on the continental shelf.

Our analysis of Antarctic Cenozoic sequences is a preliminary assessment, from limited data, of a complex glacial history that may have varied for different segments of the Antarctic margin. Further drilling and seismic studies are needed to provide a more accurate assessment of the proximal record of Antarctic ice volume and related sea level variations throughout the Cenozoic.

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FIGURE CAPTIONS

Figure 1: Index maps of Antarctica and cross sections showing the location of major features and Cenozoic prograding sequences of the continental margin.

Figure 2: Proposed nomenclature, characteristics and examples for Antarctic type I and II Cenozoic acoustic sequences beneath the Antarctic continental shelf and slope.

Figure 3: Seismic-reflection data and line drawings for profiles in the eastern Ross Sea showing regional geometry of unconformities U1-U6 (Hinz and Block, 1984), locations of DSDP sites 270, 271, and 272, and geometry of Antarctic type I and II sequences.

Figure 4: Index maps of the Ross Sea illustrating the difference between the orientations of pre-Cenozoic structures and late Cenozoic to Holocene ice-erosional features of the continental shelf. PSE-R1, which is the paleo-shelf edge for unconformity U5, parallels pre-Cenozoic structural trends, whereas PSE-R2, which is the paleo-shelf edge for unconformity U5, which parallels the present shelf edge. The divergence of PSE-R1 and PSE-R2 indicates a likely increase in glacial sedimentation here in early to middle Miocene time.

Figure 5: Model for deposition of Antarctic type I sequences beneath the outer continental shelf by grounded ice sheets during glacial periods of lowstand sea level. During interglacial periods of highstand sea level, like today, little sediment is deposited on the shelf.

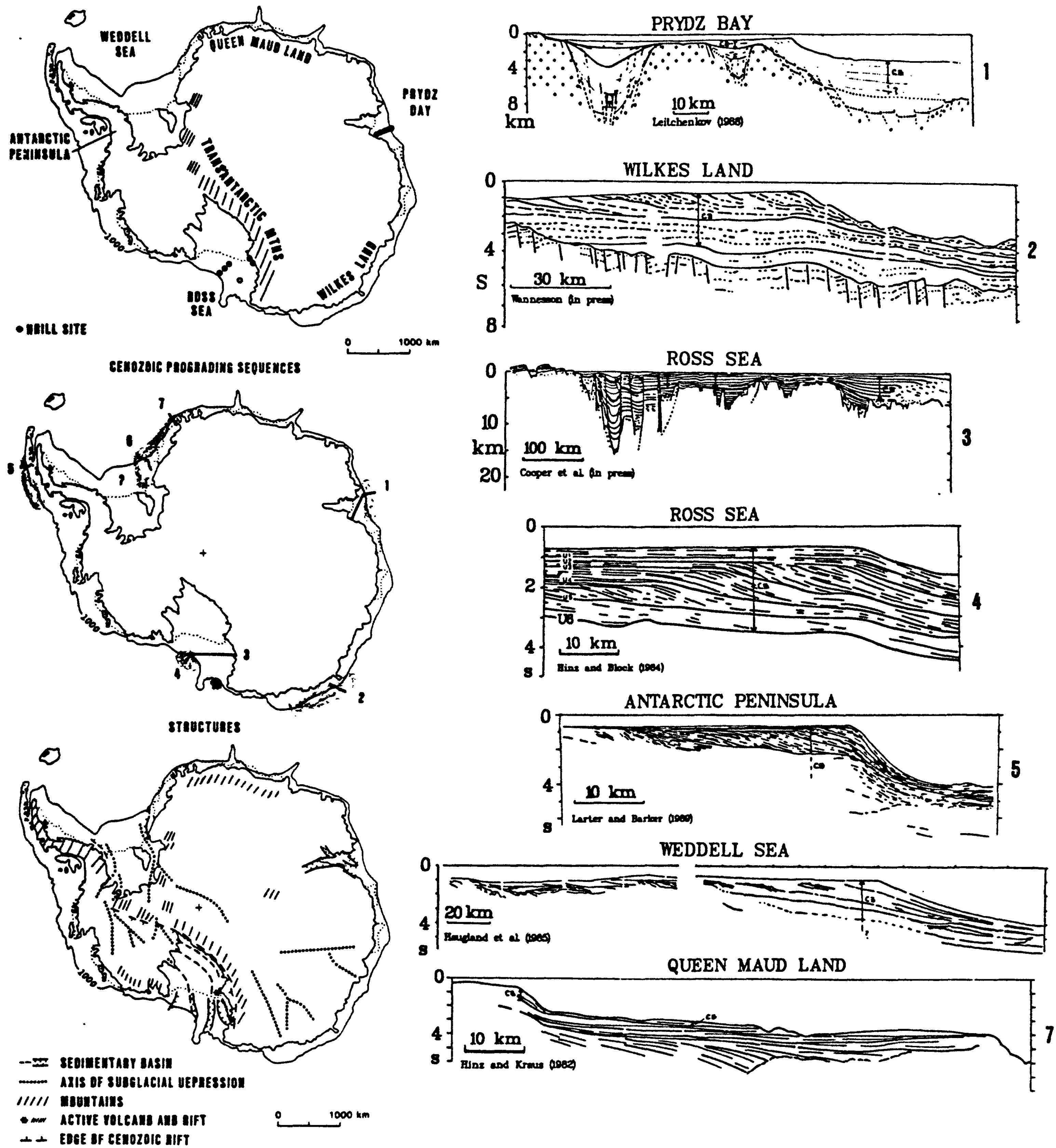
WEDDELL SEA
QUEEN MAUD LAND
PRYDZ BAY
ANTARCTIC PENINSULA
TRANSANTARCTIC MTNS
ROSS SEA
WILKES LAND
DRILL SITE
0 1000 km
CENOZOIC PROGRADING SEQUENCES
STRUCTURES
SEDIMENTARY BASIN
AXIS OF SUBGLACIAL DEPRESSION
MOUNTAINS
ACTIVE VOLCANO AND RIFT
EDGE OF CENOZOIC RIFT
0 1000 km
PRYDZ BAY
10 km
Leitchenkov (1988)
1
WILKES LAND
30 km
Wannesson (in press)
2
ROSS SEA
100 km
Cooper et al. (in press)
3
ROSS SEA
10 km
Hinz and Block (1984)
4
ANTARCTIC PENINSULA
10 km
Larter and Barker (1989)
5
WEDDELL SEA
20 km
Haugland et al. (1985)
QUEEN MAUD LAND
10 km
Hinz and Kraus (1982)
7

Figure 1

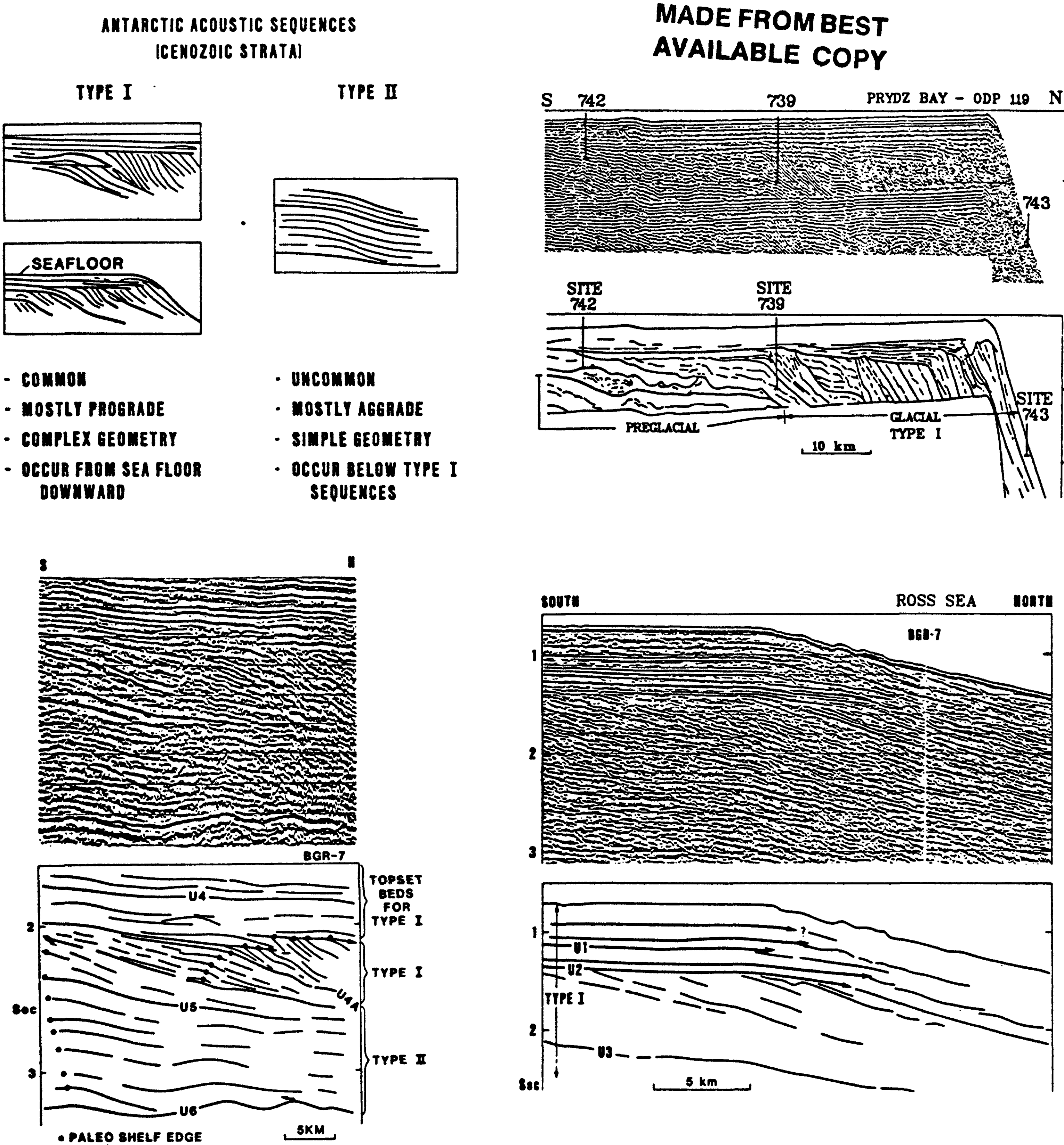
ANTARCTIC ACOUSTIC SEQUENCES
(CENOZOIC STRATA)
TYPE I
TYPE II
SEAFLOOR
- COMMON
- MOSTLY PROGRADE
- COMPLEX GEOMETRY
- OCCUR FROM SEA FLOOR DOWNWARD
- UNCOMMON
- MOSTLY AGGRADE
- SIMPLE GEOMETRY
- OCCUR BELOW TYPE I SEQUENCES
S 742 739 PRYDZ BAY - ODP 119 N
743
SITE 742
SITE 739
SITE 743
PREGLACIAL
GLACIAL TYPE I
10 km
S
N
BGR-7
U4
TOPSET BEDS FOR TYPE I
TYPE I
U4A
U5
TYPE II
U6
Sec
• PALEO SHELF EDGE
5KM
SOUTH
ROSS SEA
NORTH
U1
U2
TYPE I
U3
5 km

Figure 2

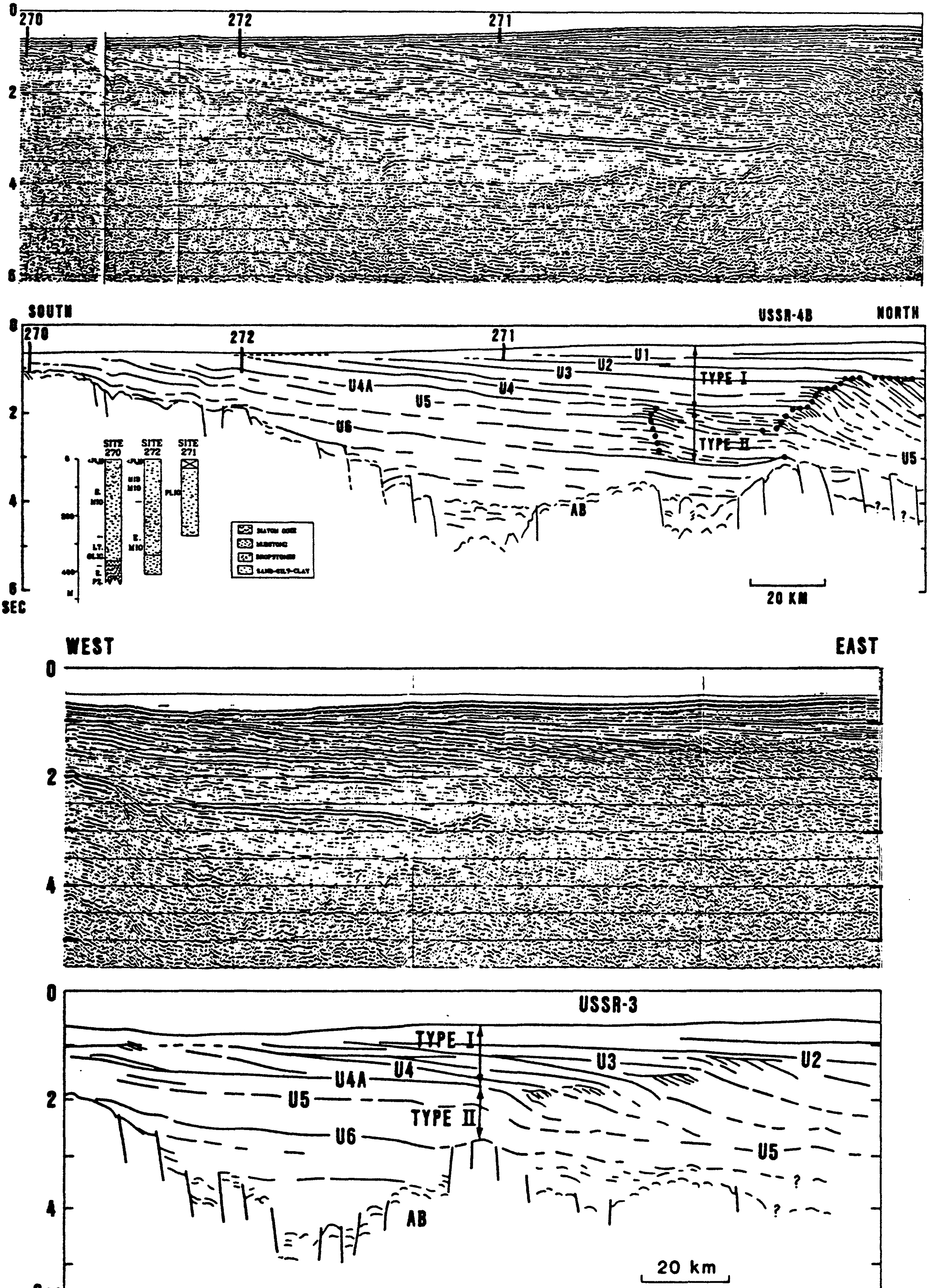
270
272
271
SOUTH
USSR-4B
NORTH
U1
U2
U3
TYPE I
U4A
U4
U5
U6
TYPE II
AB
SITE 270
SITE 272
SITE 271
20 KM
SEC
WEST
EAST
USSR-3
TYPE I
U4A
U4
U3
U2
U5
TYPE II
U6
U5
AB
20 km
Sec

Figure 3

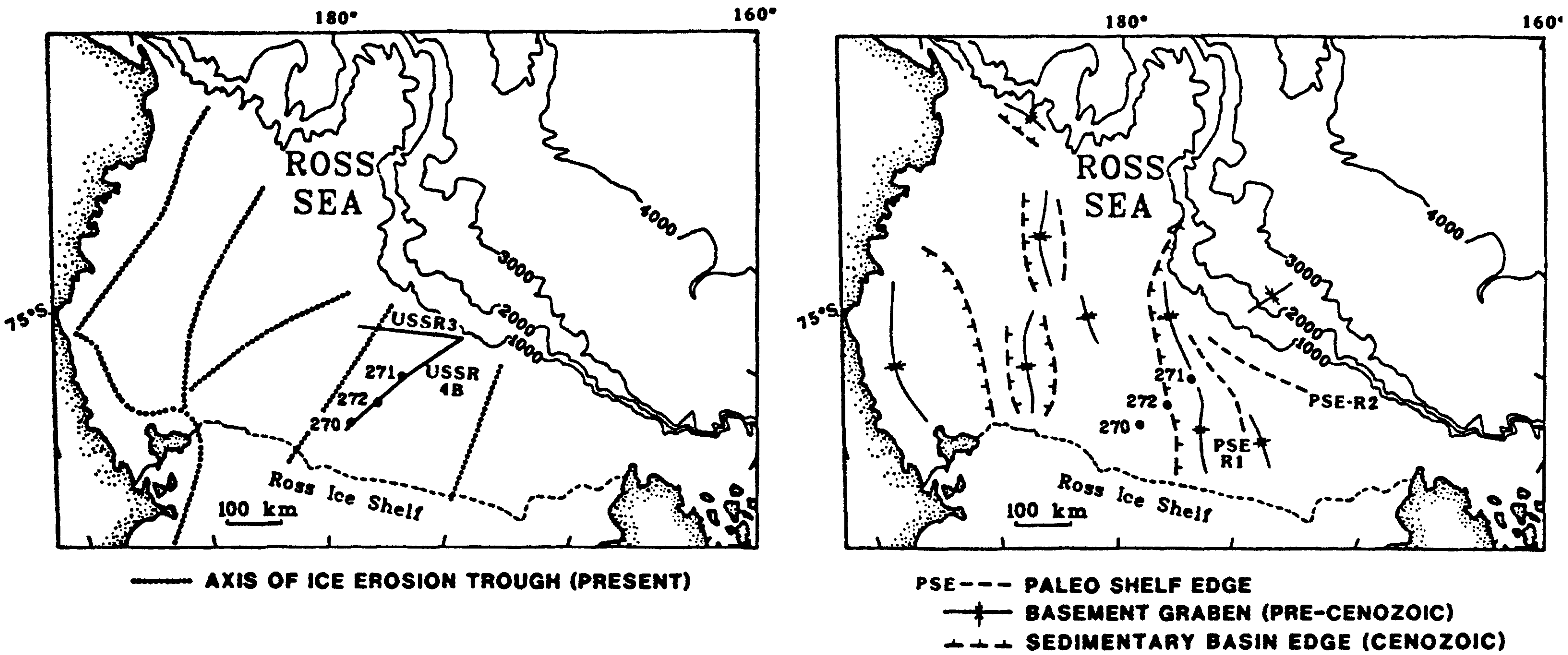
180°
160°
ROSS SEA
4000
3000
2000
1000
75°S
USSR3
USSR 4B
271
272
270
Ross Ice Shelf
100 km
AXIS OF ICE EROSION TROUGH (PRESENT)
180°
160°
ROSS SEA
4000
3000
2000
1000
75°S
271
272
270
PSE-R2
PSE R1
Ross Ice Shelf
100 km
PSE PALEO SHELF EDGE
BASEMENT GRABEN (PRE-CENOZOIC)
SEDIMENTARY BASIN EDGE (CENOZOIC)

Figure 4

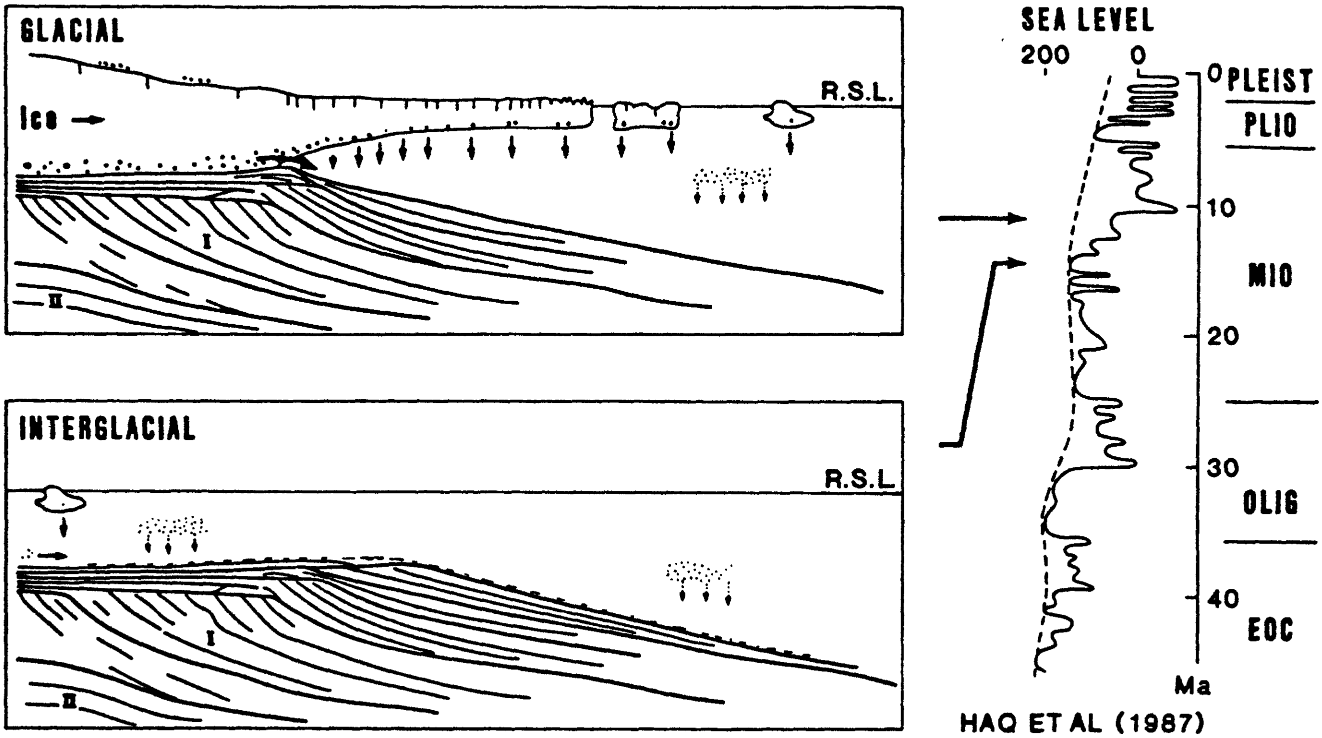
GLACIAL
Ice
R.S.L.
I
II
INTERGLACIAL
R.S.L.
I
II
SEA LEVEL
200
0
0
10
20
30
40
Ma
PLEIST
PLIO
MIO
OLIG
EOC
HAQ ET AL (1987)

Figure 5

CENOZOIC SEISMIC STRATIGRAPHY OF PRYDZ BAY, ANTARCTICA FROM SEISMIC-REFLECTION AND DOWNHOLE LOG DATA

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Jon R. Childs, U.S. Geological Survey, Menlo Park, CA, USA

Prydz Bay lies at the seaward end of the 700 km-long continental rift zone, the Lambert Rift. Offshore seismic-reflection data show that the inner half of Prydz Bay is underlain by a NE-SW trending basement horst-graben structure that is covered by up to 10 km of Mesozoic and Paleozoic(?) strata (Figure 1). These strata, which were sampled at ODP Leg 119 Sites 740 and 741, are covered by a seaward thickening sequence of glacial marine sediments that have prograded the shelf edge seaward 40 to 70 km from the likely Mesozoic preglacial position near Site 739. The Cenozoic glacial sequences, described herein, are those mapped as acoustic units PS.1 and PS.2A (Figure 2; Cooper et al., in press).

Acoustic unit PS.1 extends from the sea floor downward from a few m to as much as 300 m and is composed of chaotic, incoherent and some continuous flat lying reflections (Figures 2 and 3). The base of unit PS.1 is commonly a high-amplitude reflection that marks the unconformity between PS.1 and underlying PS.2A. On the outermost shelf unit PS.1 is composed of stacked, seaward thickening topset reflections for the steeply dipping foreset reflections of unit PS.2A. At Sites 739 and 742, unit PS.1 is composed of late Miocene and younger massive and overcompacted glacial diamictites with interbedded and diatomaceous strata.

Unit PS.2A comprises the bulk of glacial strata beneath the Prydz Bay continental shelf. Beneath the mid-shelf areas, the unit is relatively thin (up to 400 m) and dips gently seaward (Figure 2), but beneath the outer shelf, the unit is up to 4 kilometers thick and dips are steep, like those of the present continental slope. At ODP Sites 739 and 742 unit PS.2A contains massive, stratified marine glacial diamictites and diatomaceous sediments of late Eocene to early Oligocene and younger age. A disrupted layer at the base of Site 742 contains glacially deformed sands and carbonaceous shales that contain recycled late Cretaceous pollen and spores.

The base of the glacial sequence was not sampled and is believed to lie at the base of the disrupted layer about 100m below the bottom of Site 742 (Cooper et al., in press). The glacial to preglacial unconformity is difficult to trace beneath the 500 m thick glacial sequence covering the mid-shelf area because the reflections from overlying glacial rocks are typically discontinuous and disrupted. Early Cretaceous non-marine rocks were sampled about 200 m stratigraphically below the unconformity at Site 741.

Several acoustic sub-units can be distinguished within the glacial sequences of PS.1 and PS.2A based on the combined signatures of vertical-incidence seismic profiles and in-situ downhole velocity logs recorded at ODP Sites 739 and 742 (Figure 3). Velocities within PS.1 are highly variable ranging from 1.8 to 2.9 km/s. The velocities change systematically from near the seafloor downward to about 175 mbsf (meters below sea floor) where they abruptly increase nearly 1 km/s within an overcompacted layer(s) that is about 35-60 m thick (Solheim et al., in press). Less compacted diatomaceous sediments occur within the overcompacted layer as a distinct 3-m thick horizon. Synthetic seismic data show that the two high-amplitude reflections within PS.1 that can be traced from Sites 739 to 742 and beyond are caused by the abrupt velocity changes at the top and bottom of the overcompacted layer. Additionally, at Site 739 the 1-3-m-thick variations in velocity, and other downhole-log parameters, for PS.1 at 80-105 mbsf are believed due to alternating layers of diamictites and diatomaceous sediment (Barron, Larsen, et al., 1989).

In unit PS.2A, downhole logs show significant changes in velocity gradients for the steeply dipping strata at 175 to 320 mbsf and the more gently dipping reflections below 320 mbsf at Site 739. A change from diamictites containing more gravel above to more sand below has been noted (Barron, Larsen et al., 1989), but age control is inadequate to confirm an unconformity. The changes in seismic dip, downlap of reflectors, and changes in downhole velocity-log gradients indicate that this boundary is an unconformity and an acoustic sequence boundary (Figure 3).

Beneath the outer shelf, units PS.1 and PS.2A are composed of numerous acoustic sequences classified as Antarctic type I sequences by Cooper et al. (this volume; in press). The type I sequences are characterized by changes in dips at likely topset unconformities on the shelf and foreset unconformities on the continental slope. Erosion has removed topset strata for some sequences resulting in distinct angular unconformities (Figure 4). The regional extent and subsurface geometry of the Prydz Bay type I sequences is poorly known because of limited seismic profiles. Profiles across the margin (Figure 4; Stagg, 1985) show that some features, such as likely paleo shelf edges (PSE), and major dip changes can be traced at least 200 km along the outer shelf and upper continental slope.

The seaward dipping Cenozoic sedimentary units beneath Prydz Bay are exclusively of glacial origin where sampled at ODP Sites 742 and 739 on the mid to outer continental shelf. We infer that the origin of unsampled sequences lying seaward of Site 739 is also glacial based the lithology and acoustic stratigraphy at Site 739. However, the presence of thick non-glacial or interglacial strata beneath the outermost shelf cannot be precluded based solely on available seismic data.

Several investigators have suggested that extensive grounded ice sheets have episodically moved across Prydz Bay since late Eocene (?) to early Oligocene time (e.g. in Barron, Larsen et al., 1989, in press)(Figure 5). ODP drill site measurements of diamictites compaction and downhole velocity fluctuations strongly support numerous glacial and interglacial episodes with loading of near surface sediments by ice sheets (Solheim et al., in press). Seismic stratigraphy shows that the episodic glacial episodes inferred from ODP drilling have resulted in numerous thick prograding sedimentary sequences beneath the outer continental shelf (Figures 2 and 4). Most sediment are believed to be deposited during glacial periods and little sediment during interglacial times (Figure 5). The age of the sequences beneath the outermost shelf is unknown from drilling, but from seismic stratigraphy, sequences deposited stratigraphically above paleo-shelf edge 3 (PSE-3, Figure 4) are thought to be younger than late Miocene age (Cooper et al., in press).

Further scientific drilling of the sedimentary sequences beneath the outermost Prydz Bay continental shelf would provide a more complete glacial history of grounded-ice movements and related sea level changes.

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FIGURE CAPTIONS

Figure 1: Index maps and cross section of Prydz Bay, Antarctica, showing locations of major structures, sedimentary sequences and glacial features (see also Leitchenkov et al., this volume).

Figure 2: Seismic-reflection data and interpretation of line ODP-119 across Prydz Bay (modified from Cooper et al., in press).

Figure 3: Seismic-reflection data, synthetic seismic trace (S), downhole velocity log (I, km/s), lithology and age data for ODP Sites 739 and 742 in Prydz Bay.

Figure 4: Line drawings of seismic profiles across the outer Prydz Bay shelf. The approximate location of four different paleo shelf edges (PSE) are shown based on similarities in acoustic sequence geometries beneath the outer shelf.

Figure 5: Model for the evolution of the prograding glacial sequences beneath the Prydz Bay outer continental shelf.

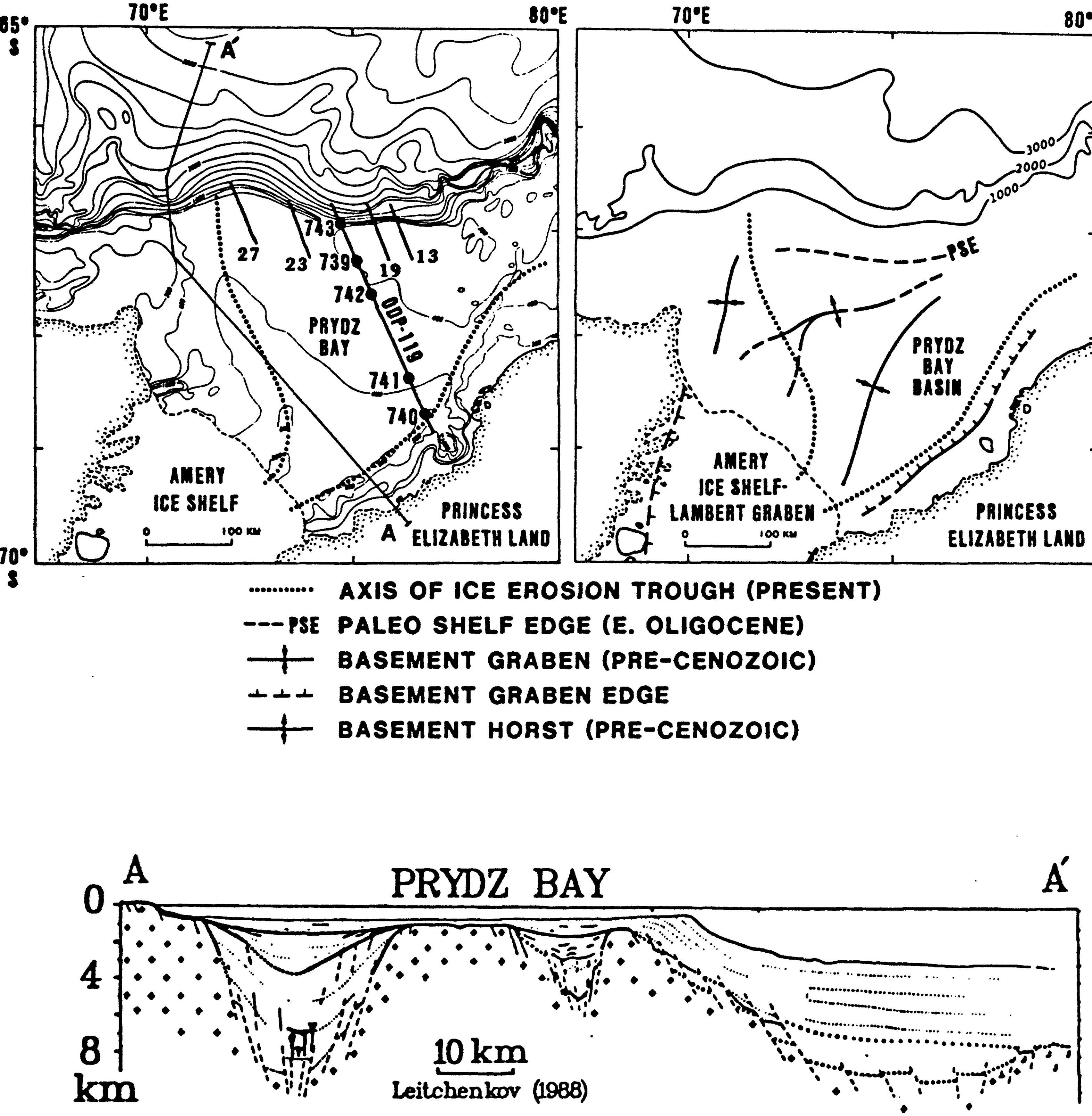
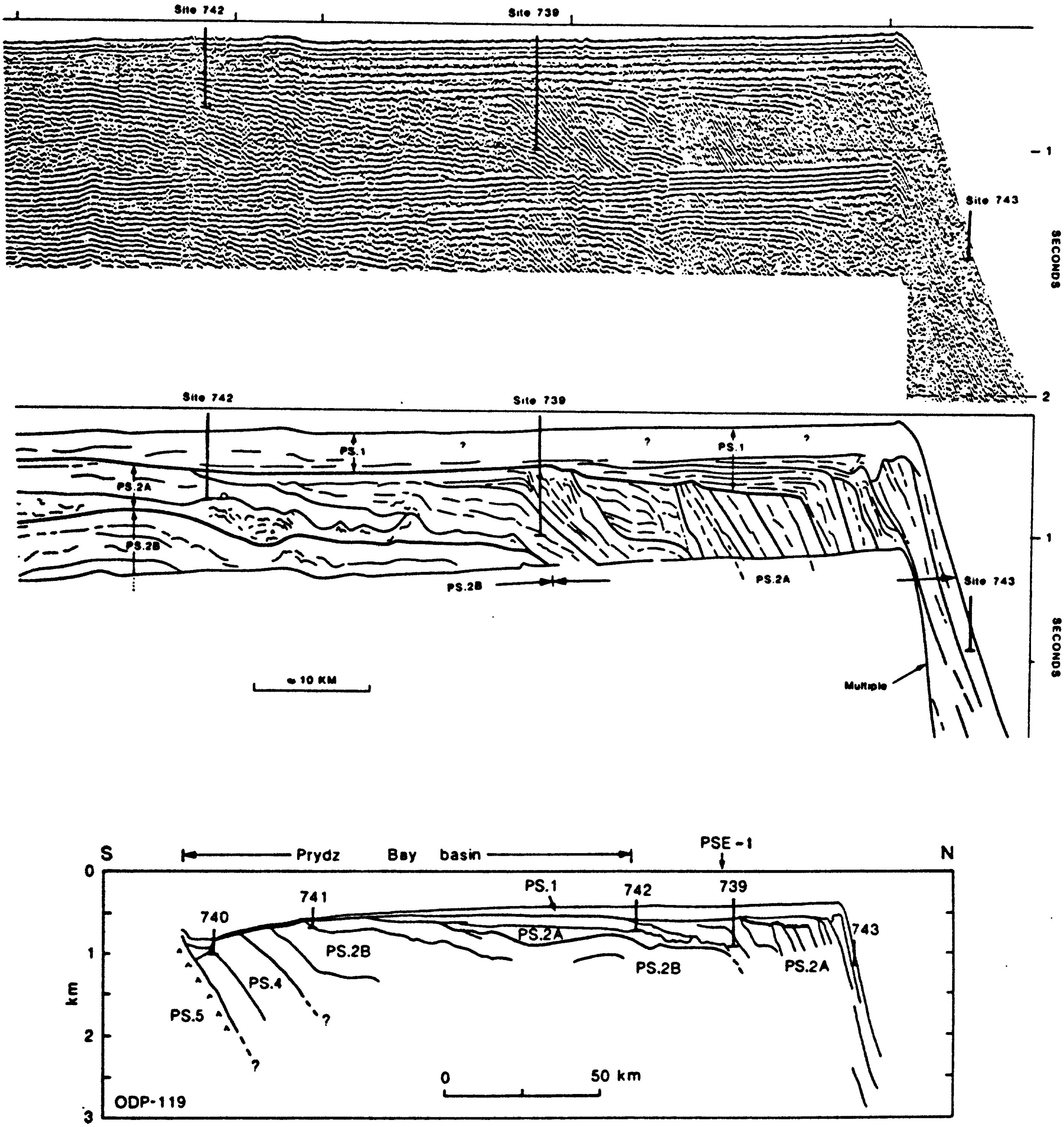
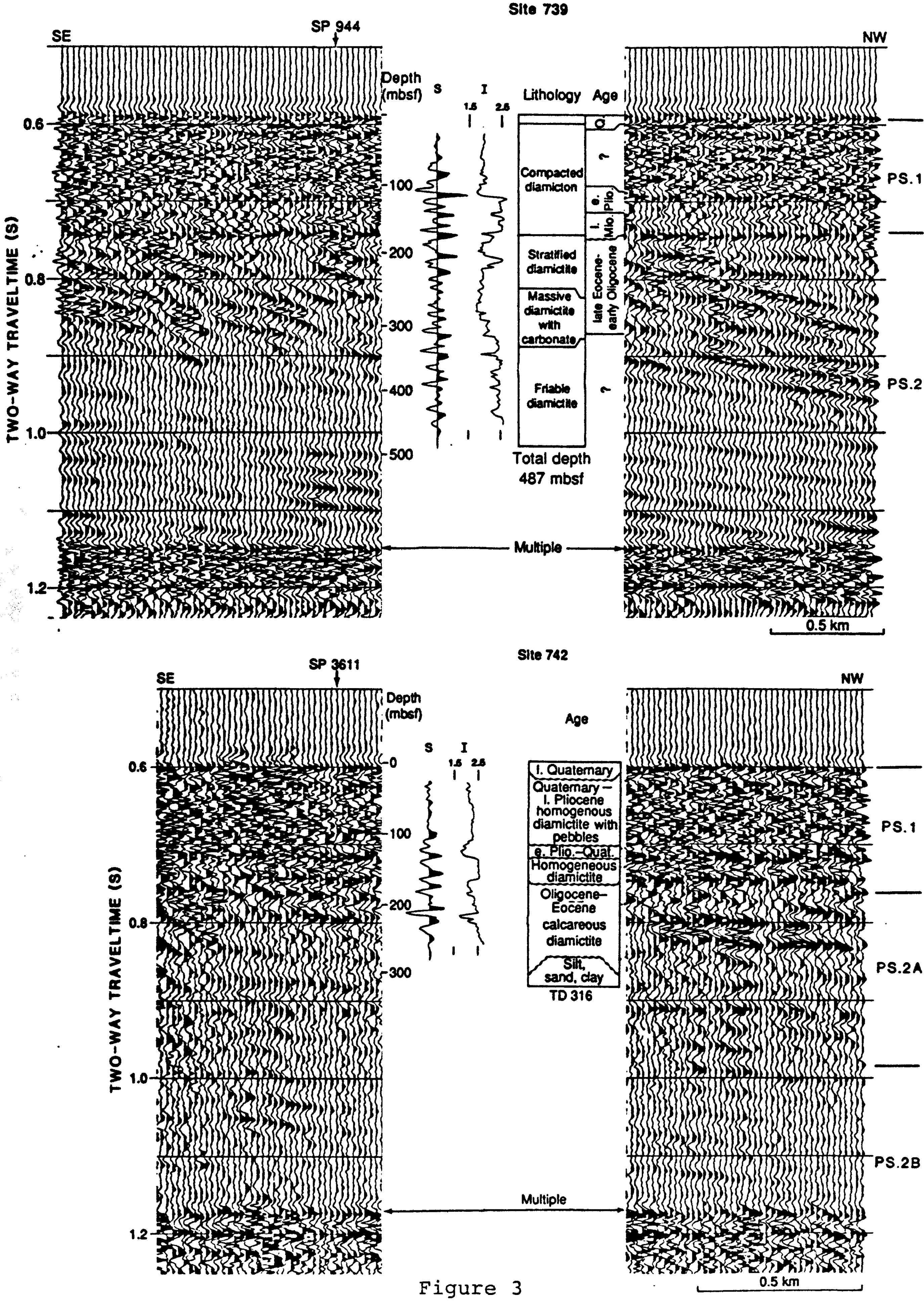

70°E
80°E
65° S
70° S
A′
A
27
23
739
743
19
13
742
ODP-119
741
740
PRYDZ BAY
AMERY ICE SHELF
PRINCESS ELIZABETH LAND
0 100 KM
3000
2000
1000
PSE
PRYDZ BAY BASIN
AMERY ICE SHELF-LAMBERT GRABEN
AXIS OF ICE EROSION TROUGH (PRESENT)
PSE PALEO SHELF EDGE (E. OLIGOCENE)
BASEMENT GRABEN (PRE-CENOZOIC)
BASEMENT GRABEN EDGE
BASEMENT HORST (PRE-CENOZOIC)
PRYDZ BAY
0
4
8
km
10 km
Leitchenkov (1988)

Figure 1



GLACIAL: PS.1 and PS.2A - late Eocene-early Oligocene through Holocene marine diamictite and diatomaceous sediment
NON-GLACIAL: PS.2B - Early Cretaceous nonmarine sandstone and siltstone
PS.4 - (?)Permian to Mesozoic red siltstone and sandstone
PS.5 - (?)Precambrian metamorphic rocks
PS.6 - (?)Mesozoic or Precambrian intrusive or metamorphic rocks

Figure 2



Site 739
SE
SP 944
NW
TWO-WAY TRAVELTIME (S)
0.6
0.8
1.0
1.2
Depth (mbsf)
S
I
1.5
2.5
100
200
300
400
500
Lithology
Age
Q.
?
Compacted diamicton
e. Plio.
l. Mio.
Stratified diamictite
late Eocene-early Oligocene
Massive diamictite with carbonate
Friable diamictite
?
Total depth 487 mbsf
PS.1
PS.2A
Multiple
0.5 km
Site 742
SE
SP 3611
NW
TWO-WAY TRAVELTIME (S)
Depth (mbsf)
0
100
200
300
S
I
1.5
2.5
Age
l. Quaternary
Quaternary – l. Pliocene homogenous diamictite with pebbles
e. Plio.–Quat.
Homogeneous diamictite
Oligocene–Eocene calcareous diamictite
Silt, sand, clay
TD 316
PS.1
PS.2A
PS.2B
Multiple
0.6
0.8
1.0
1.2
0.5 km

Figure 3

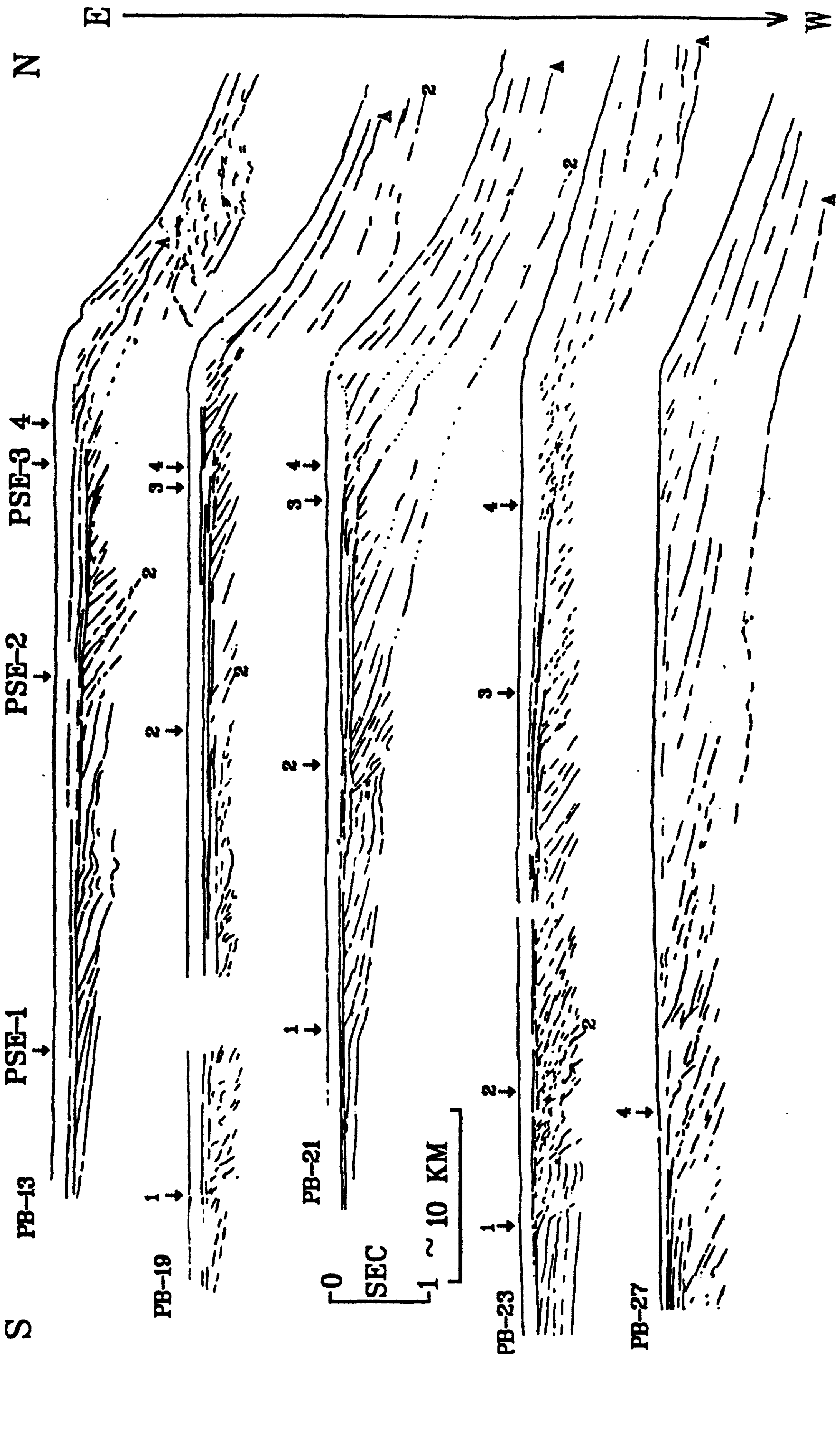


Figure 4

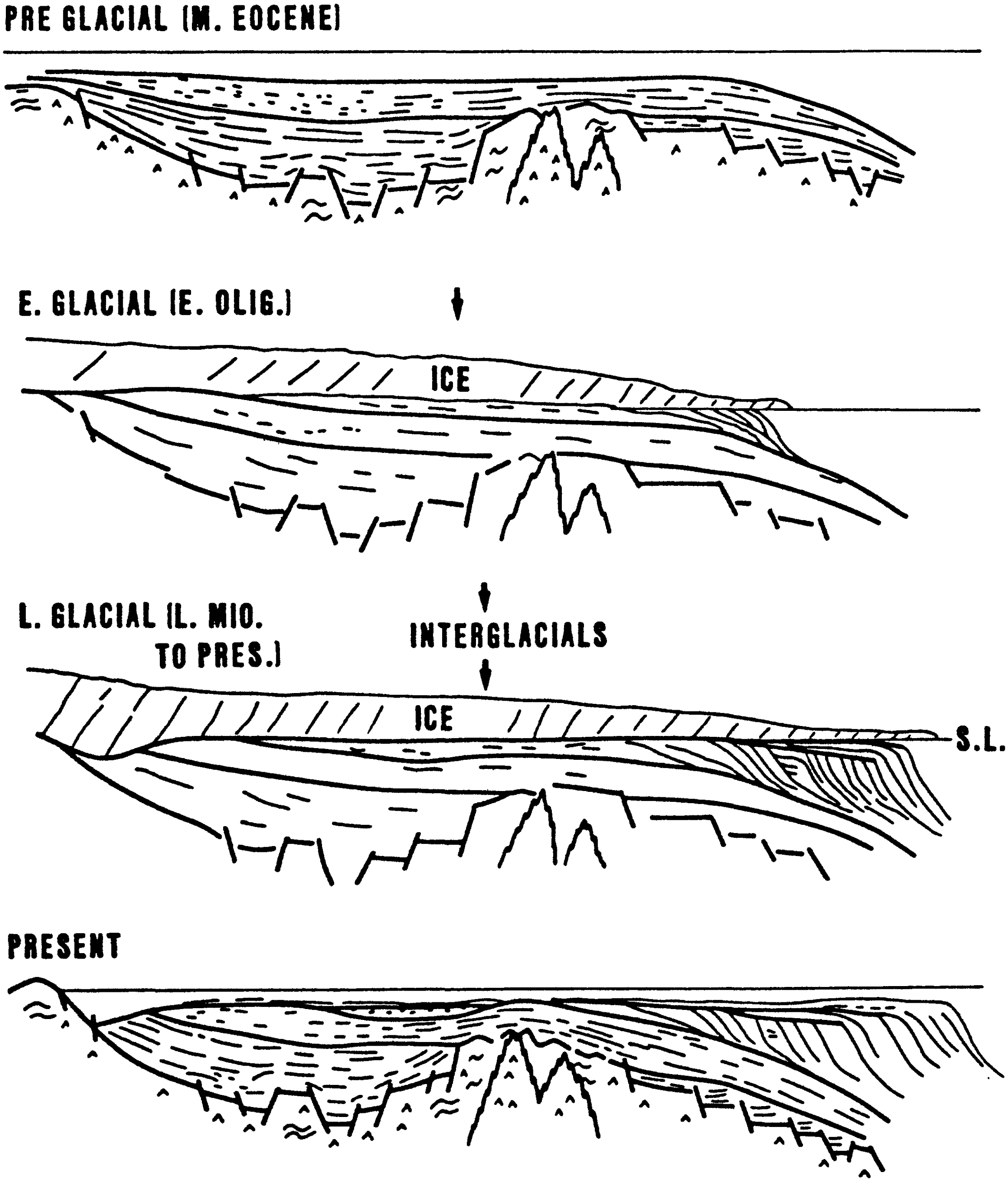

PRE GLACIAL (M. EOCENE)
E. GLACIAL (E. OLIG.)
ICE
L. GLACIAL (L. MIO.
TO PRES.)
INTERGLACIALS
ICE
S.L.
PRESENT

Figure 5

ROSS SEA SINGLE CHANNEL SEISMIC REFLECTION DATA (NZ AND EARLY USA)

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Geophysics Division, NZ DSIR, Wellington

ABSTRACT

Single channel seismic reflection data, sonobuoy seismic refraction data and bathymetry were recorded in 1981 along the western margin of Ross Sea, from Cape Hallett to McMurdo Sound, and across the eastern Ross Sea (Fig. 1). The former measurements were designed to extend the existing seismic coverage over the centre and western margin of the Victoria Land Basin to investigate this basin and its relationship to the Transantarctic Mountains. The latter measurements were focussed on the eastern margin of the Eastern Basin to define the eastern margin in more detail and to investigate the total thickness of sediments over basement in the Eastern Basin. A total of 3200 km of single channel seismic reflection profiles and 25 sonobuoy seismic refraction stations were recorded. The seismic data were of average quality and nowhere could reflections be traced below the seafloor multiple. Refraction data indicated sediment thicknesses of up to 4 km. These data supplement the USNS Eltanin data set (ELT 27, 32, 52). Together the data indicate several seismic sequences, particularly the prograding, (?) glacially eroded, sequences off the Eastern Basin and possibly off the western Ross Sea margin. Distinctive sequences interpreted to be subglacial deposits are noted along the western Ross Sea Margin.

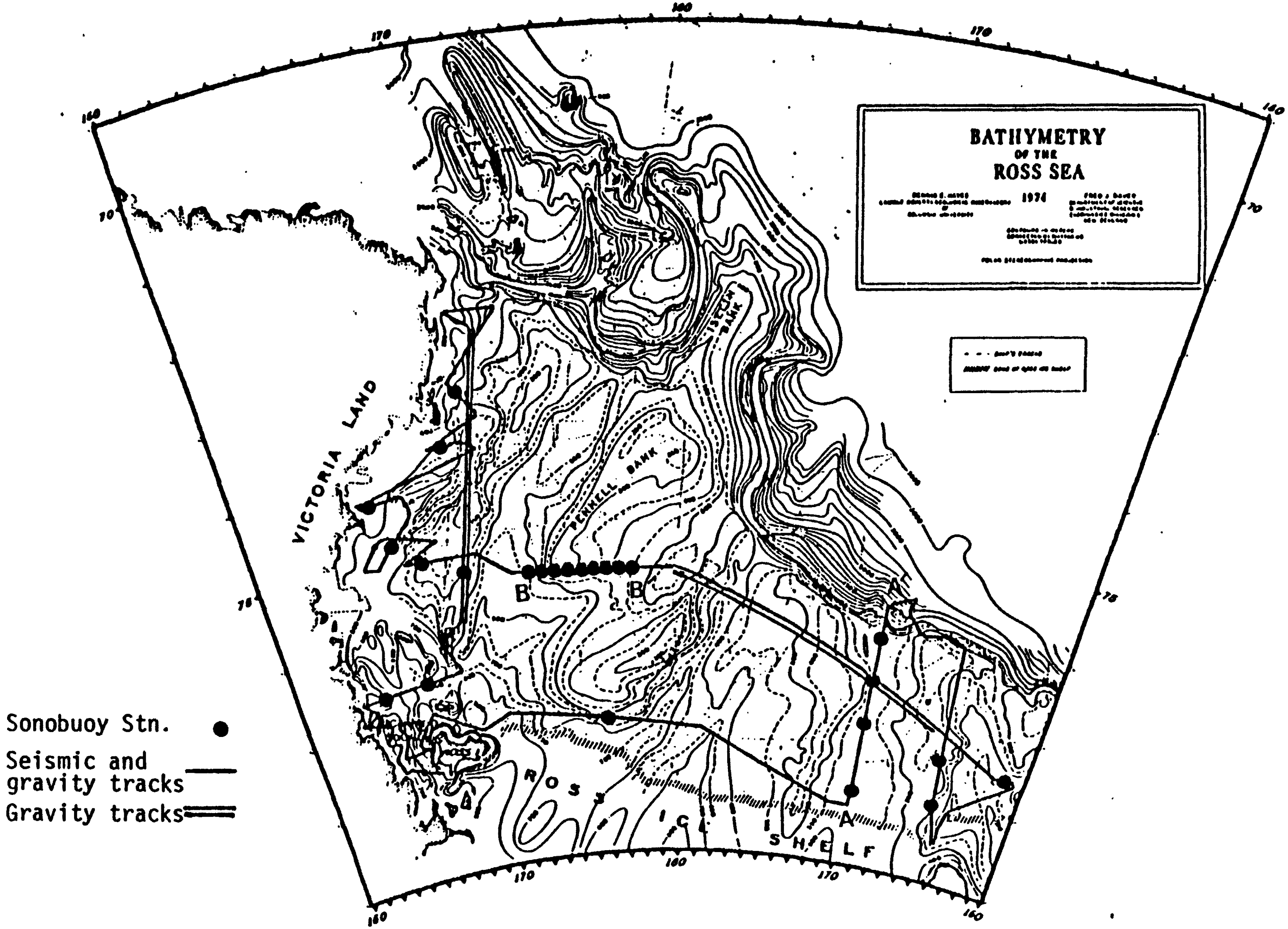

Fig. 1 Track Plot. Bathymetry after Hayes and Davey 1975.

LATE QUATERNARY AND PRE-GLACIAL STRATIGRAPHIC SEQUENCES ALONG THE EAST ANTARCTIC MARGIN: THE RECORD FROM INNER SHELF BASINS

by

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At least ten distinct depressions can be found along the inner continental shelf of the East Antarctic margin between 70° and 160° East Longitude (Figures 1 and 2). Individual depressions range in size from several hundred to several thousand km^2 and are more than 500 m to over 1000 m deep. The depressions are important because they mark the offshore boundary of Precambrian crystalline rocks (to the south) and prerift, synrift, or drift phase sedimentary sequences (to the north). The depressions developed due to preferential glacial erosion, as their bathymetric trends are aligned with major convergence of ice drainage on the continent. Piston cores collected from the seaward flank of the Mertz-Ninnis trough (Wilkes Land) consist of in-situ Lower Cretaceous siltstones which were deposited at a time of continental rifting between Antarctica and Australia (Domack and others, 1980). Shallow drilling (Sites 740 and 741; ODP Leg 119) in the Amery Depression of Prydz Bay recovered fluvial sediments of presumably rift-phase origin (Barron, Larsen et al., 1989). These results indicate that the seaward flanks of similar inner shelf basins are excellent sites for the recovery of pre-glacial or early glacial stratigraphic units by use of either conventional piston core methods or shallow drilling. High resolution seismic reflection studies along the trend of these features would thus help to delineate specific sites for future drilling.

These basins also contain an important record of Late Quaternary ice volume and oceanic productivity changes. The depressions serve as ideal sediment traps for both biogenic and glacial derived particle accumulations because:

1) they are widespread beneath regions of seasonally ice free waters,

2) lie adjacent to floating ice tongues or ice shelves, and

3) lie below the depth of iceberg scour (ie. 500 m; Barnes, 1987).

Both 3.5 and 12 kHz seismic reflection data indicate that approximately 23 m of normally consolidated sediment occurs above a pronounced angular unconformity in the Amery Depression (Barron, Larsen et al., 1989) and nearly 30 m is to be found within the Mertz-Ninnis Trough (Domack et al., 1989). Both sequences are characterized internally by a combination of on-lapping (ponded) reflectors in the lowermost intervals and a draping (horizontal) set of reflectors in the uppermost portions of the sequence. The cause of internal reflections within this package is unknown. Chronologic and sedimentologic studies based upon intervals recovered in the Amery Depression indicate alternating periods in the latest Pleistocene and Holocene of open water and sub-ice shelf conditions; reflected by diatom ooze and pebbly mud deposition respectively (Domack et al., in press). Reflectors may therefore correspond to the interbedding of these contrasting sediment types. The sedimentary package in the Mertz-Ninnis Trough appears to be somewhat more homogeneous. A meter thick transitional (sandy) interval marks the lithologic succession from diamicton (below) to siliceous ooze/mud above. This succession represents the transition from ice tongue to open marine conditions which took place some time in the mid-Holocene (ie. 9000 to 2500 years B. P.). The origin of internal reflectors in this sequence remains unknown. Further work using high resolution seismic (ie. deep towed uniboom systems) in combination with long piston cores could help to resolve the reflection character of similar sequences within the inner shelf basin system.

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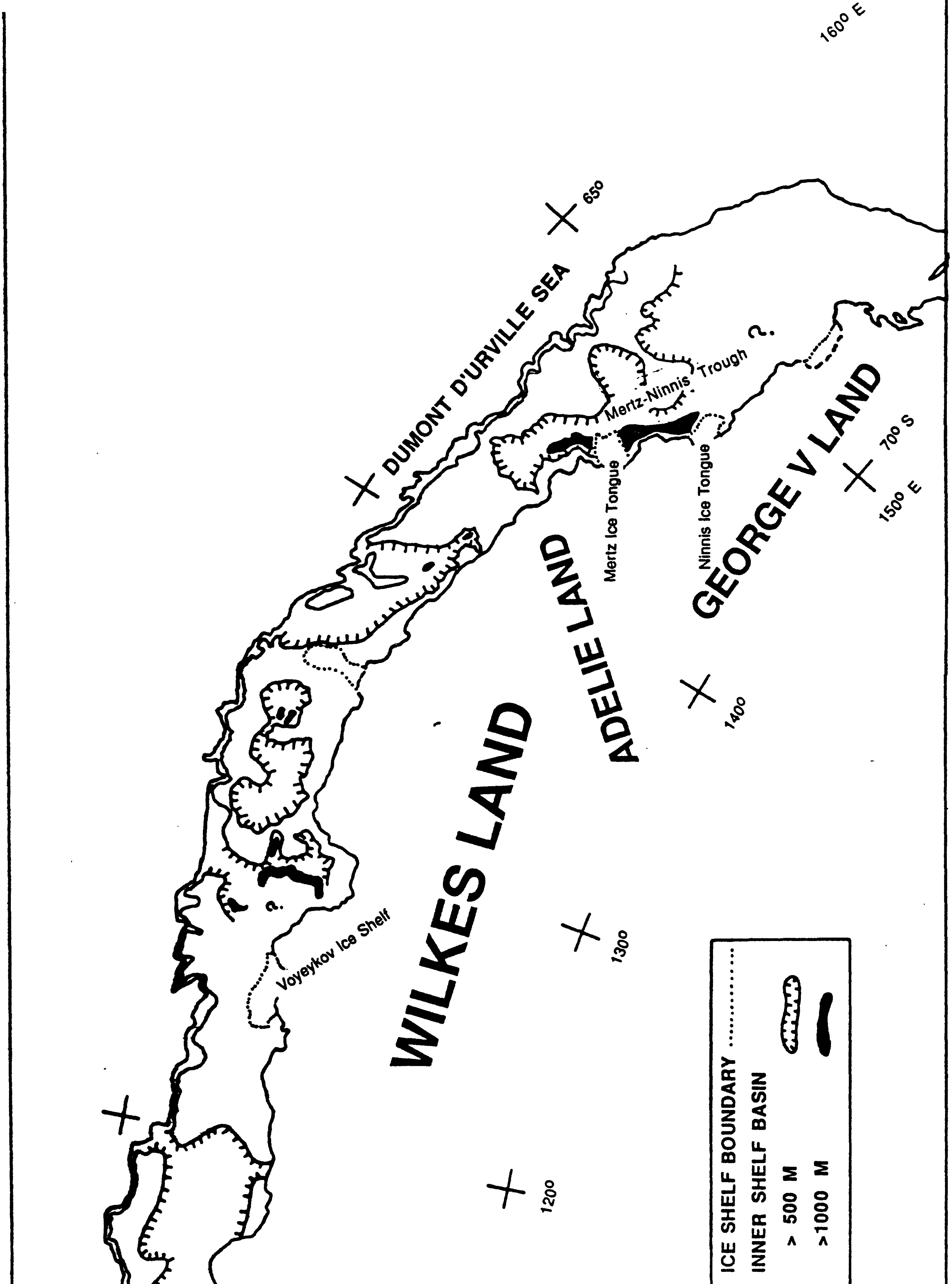
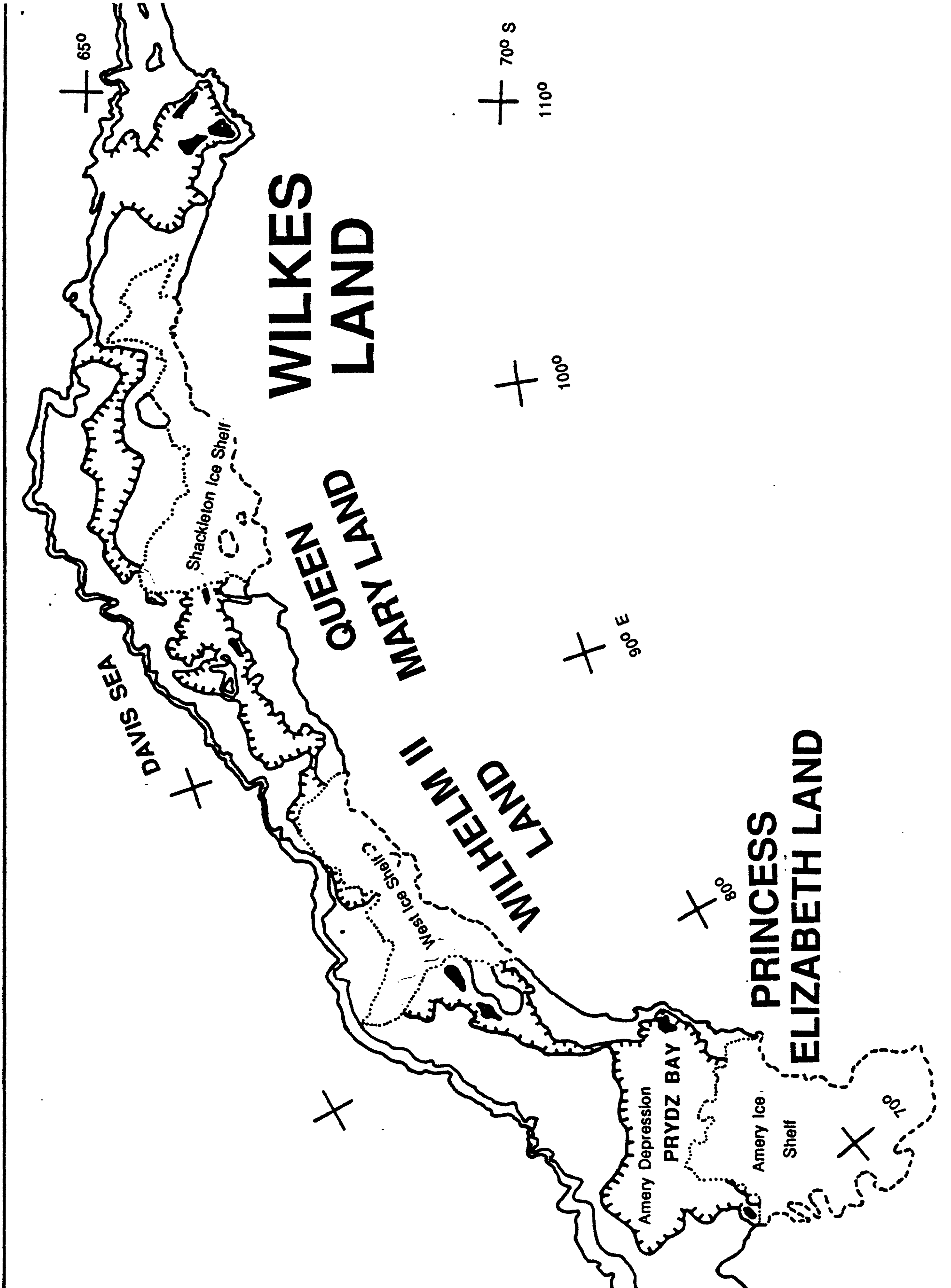
Figure 1. Physiographic map of East Antarctic margin between 160° and 115° E Longitude showing locations of major inner shelf basins. From GEBCO Antarctic sheet.

Figure 2. Physiographic map of East Antarctic margin between 115° and 65° E Longitude showing locations of major inner shelf basins. From GEBCO Antarctic sheet.


160° E
65°
DUMONT D'URVILLE SEA
Mertz-Ninnis Trough
?
GEORGE V LAND
70° S
150° E
Mertz Ice Tongue
Ninnis Ice Tongue
ADELIE LAND
140°
WILKES LAND
Voyeykov Ice Shelf
130°
120°
ICE SHELF BOUNDARY
INNER SHELF BASIN
> 500 M
>1000 M


65°
70° S
110°
WILKES LAND
100°
Shackleton Ice Shelf
QUEEN MARY LAND
90° E
DAVIS SEA
WILHELM II LAND
West Ice Shelf
80°
PRINCESS ELIZABETH LAND
PRYDZ BAY
Amery Depression
Amery Ice Shelf
70°

The Elusive Seismic Signature of the Ice-Sheet Onset; Wilkes Land Margin

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USGS, Menlo Park, CA

An inventory of the seismic stratigraphy on the Wilkes Land margin, from the 1800-km of multichannel seismic data collected by USGS in 1984 (Fig. 1), shows about 1-4 km of synrift and postrift sequences of sediment covering the continental margin. Postrift sediment consists of an early, poorly stratified sequence,"B", believed to be shelf, nearshore marine, or non-marine deposits that are overlain by a highly stratified sequence, "A", believed to be marine continental rise and slope deposits (Fig. 2). The unconformity between them, "T", is an extensive, flat, highly reflective horizon. T is onlapped from the seaward side by gently dipping beds of the upper stratified Sequence A that continue uninterrupted up to the present seafloor. Sequence A consists of generally parallel beds showing variations of dip and stratigraphic style usually associated with channeling, slump deposits, drifted and levee deposits of a continental rise environment. From the overall morphology of the rise, it appears to be a sequence of coalesced fans dissected by canyons. The onlapping of T by Sequence A appears to mark the innundation and drowning of a former continental shelf deposit and the onset of marine deposition on this margin. Assumung a normal history of thermal subsidence for the margin, this marine onset would be expected to have an age sometime in the upper Cretaceous, not too long after the age of breakup at 95 Ma, significantly predating the glacial onset in the mid-Tertiary.

Thus, Unconformity T, the most striking unconformity in terms of contrast in sequences across it and in reflection amplitude, seems to be ruled out as the signature of glacial onset. Underlying the outer shelf and slope and postdating Sequence A is an unconformity (labeled the shelf-slope unconformity in Fig. 3) that marks a shift from deposition on the continental rise to deposition on the shelf. Overlying it are prograding foreset beds of the outer shelf that appear to be responsible for the present shelf morphology. This unconformity marks the prograding of the continental slope out over Sequence A of the continental rise and is a likely candidate for the glacial-onset signature. If this is correct it suggests that very little sedimentation, at least in the western segment of the area of the USGS survey, has occurred on the continental rise since glacial onset.

Seismic and high-resolution acoustic data indeed suggest erosion in many places on the continental rise (Fig. 4).

The modern seafloor morphology on the rise is degradational, with modern canyon-cutting and outcropping rise strata, even in the non-canyon areas. Thus the rise deposits are the result of a sedimentary environment that no longer exists and it appears that selective piston coring or shallow drilling would recover mid-Tertiary or older sediment on the rise. The specific mechanism of this erosion and non-deposition may be the high-velocity flow of bottom water, flowing parallel to contours in this area, that has been documented by current meter and nephelometer measurements. In addition glacial-caused sediment starvation may have caused the shift from sediment accumulation on the rise to accumulation on the outer shelf and to result in the environment of erosion and non-deposition that prevails today on the rise. Thus both these factors, high-energy bottom water flow on the slope and rise, and cut-off of normal hemipelagic sedimentation over the slope and rise, are presumed to be due to the initiation of glacial conditions in Antarctica.

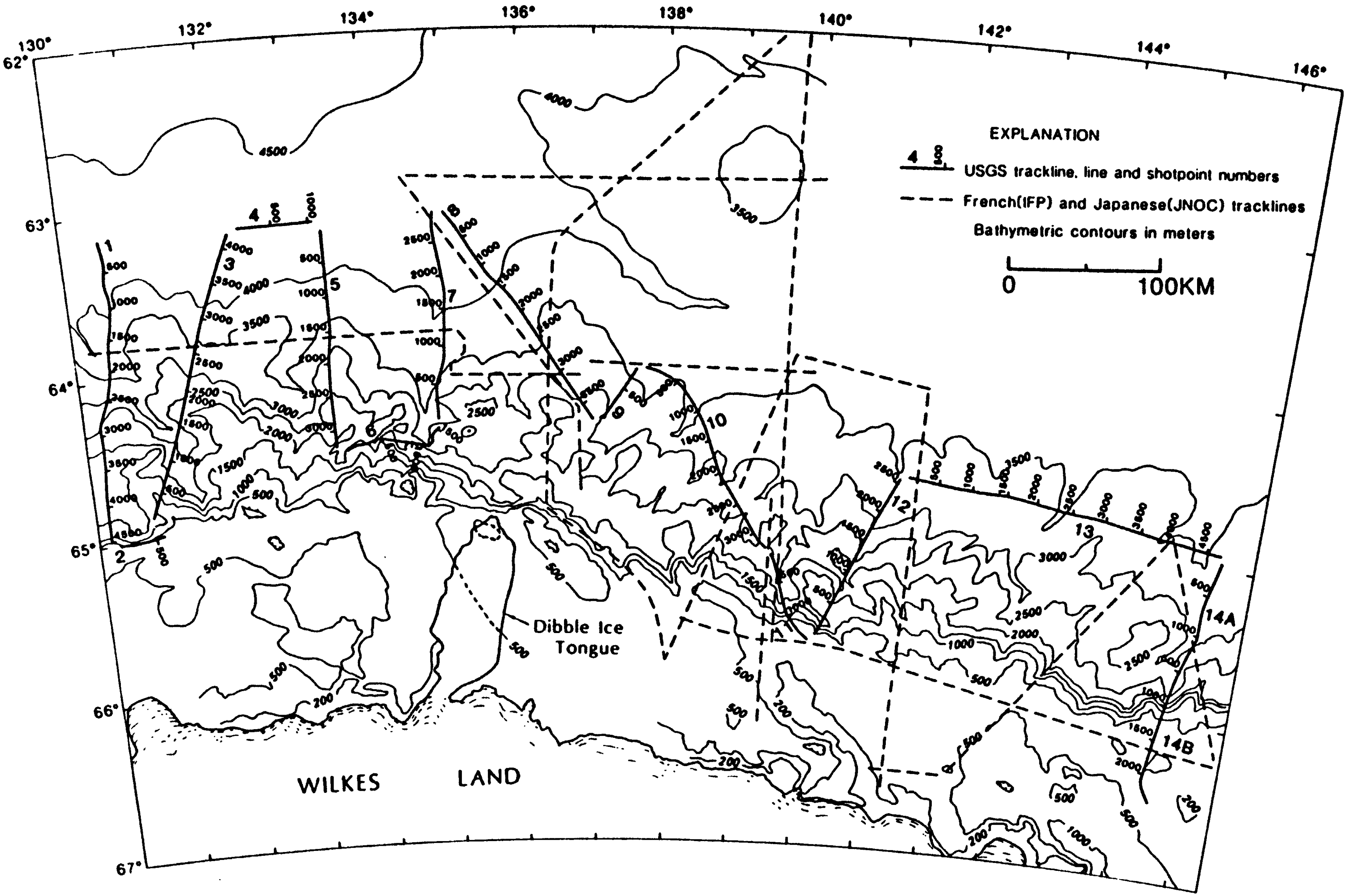

Figure 1 Tracklines of multichannel seismic data on the Wilkes Land margin.

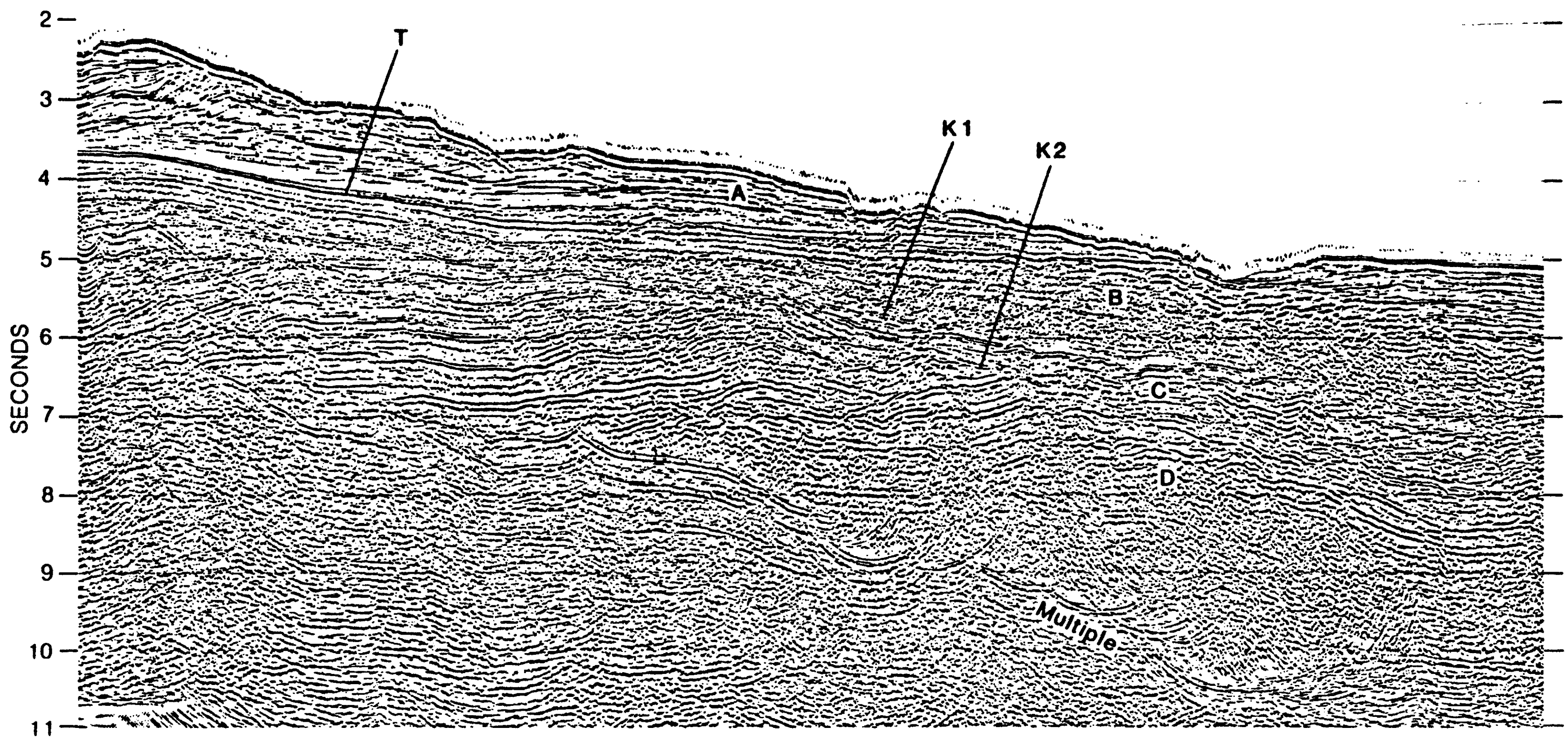

Figure 2 Line 1 stacked and migrated data illustrating the postrift sequences A and B separated by unconformity T.

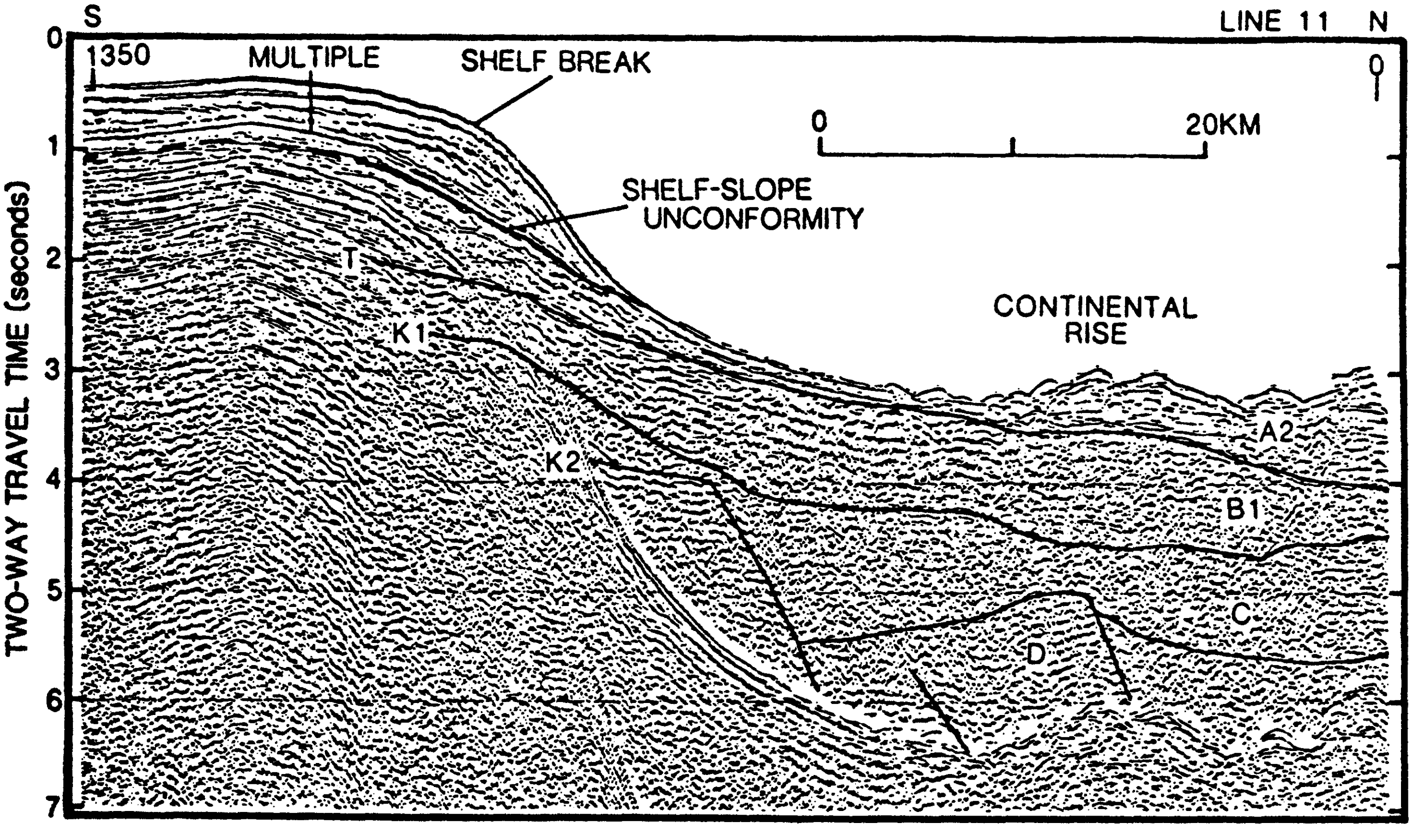

Figure 3 Line 11 stacked data on the outer shelf, slope and rise showing the prominent shelf-slope unconformity that postdates youngest Sequence A strata and is overlain by the outer-shelf progradational unit.

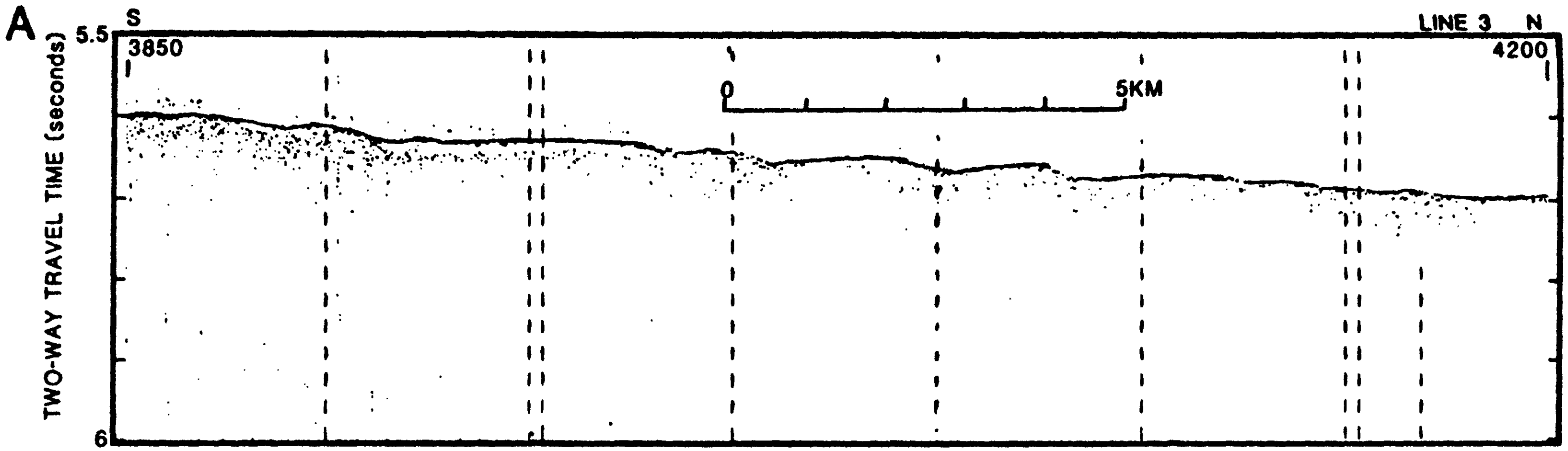

Figure 4 High-resolution 3.5 kHz acoustic record on the continental rise, Line 3, showing steps that correlate to truncated reflectors of Sequence A in the multichannel seismic data. Indicates present erosional regime on the rise.

GEOPHYSICAL INVESTIGATIONS IN THE BRANSFIELD STRAIT AND IN THE BELLINGSHAUSEN SEA-ANTARCTICA

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ABSTRACT

In 1987 and 1988 Brazil conducted marine geophysical investigations in Antarctica. The area covered extends from the Elephant to the Adelaide Islands, on the western side of the Antarctica Peninsula (Figure 1). The surveys were carried out aboard the research vessel Almirante Câmara of the Bazilian Navy. Five thousand and sixty hundred kilometers of seismic data were acquired using eight high-pressure air guns totaling 540 cubic inches and operating at 4500 PSI. The signals were received by a 72-channel streamer and recorded using a DFS_V. A Lacoste & Romberg gravimeter and a Geometrics nuclear precession magnetometer were used to acquire the pertinent data along the seismic profiles. Transit and GPS satellite systems were used to control navigation. These two field seasons allowed detailed investigation of the Bransfield Basin, an extremely well organized marginal basin and of the Bellingshausen Continental Margin, a region of fairly complex tectonic history.

The Bransfield Basin, within the Brasnfield Strait, has an asymmetrical profile with a steeper slope along its northern margin and a conspicuous spreading center closer to the South Shetland Islands. The tectonic setting of this basin is shown in Figure 2. A sedimentary wedge deposited along the southern margin of the basin forms the northern continental margin of the Antarctic Peninsula. Structural features and sedimentary sequences in this wedge show an Atlantic-type margin setting with an older rift sequence and a younger drift sequence separated by a regional unconformity (Figure 3). These main sequences occur at reasonable drilling depths and thus a good oportunity exists to understand not only the formation of the Bransfield Basin and the evolution of the northern Antarctic Peninsula, but also of older passive margins.

The Bellingshausen Continental Margin shows a well developed rise, including a deep-sea fan to the north of Adelaide Island, a steep continental slope and a broad continental shelf. At the outer shelf, clinoforms indicate a prograding shelf to slope environment similar to that of the continental shelf of an Atlantic-type margin. These sediments have prograded above an erosional unconformity, below which tilted and faulted layers are observed and appear to represent an earlier "active" margin setting (Figure 4). A basement high occurs at the eastern limit of the younger passive margin sedimentary wedge, and a closed and buried basin has been discovered to the east of the basement high. The basement high and the closed basin could represent an eroded island arc and a fossil back-arc basin, respectively. Several unconformities occur within the sequence deposited above the terrane interpreted as deposited and/or emplaced during the active phase of the margin. A sequence of wells from the shelf to the continental rise could test the hypothesis for the tectonic evolution of the basin as well as investigate the late sedimentary evolution of this margin.

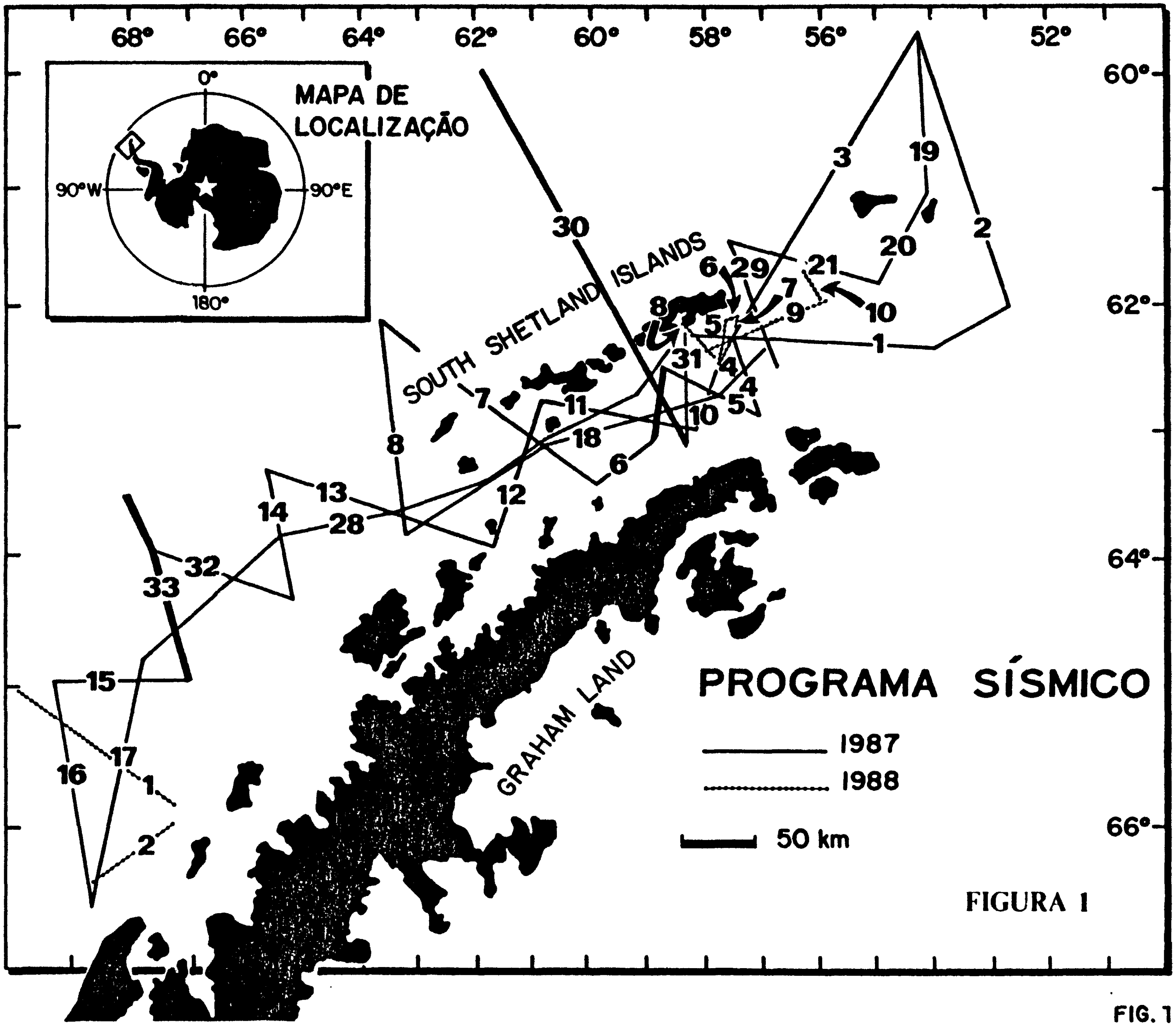

FIGURA 1

FIG. 1

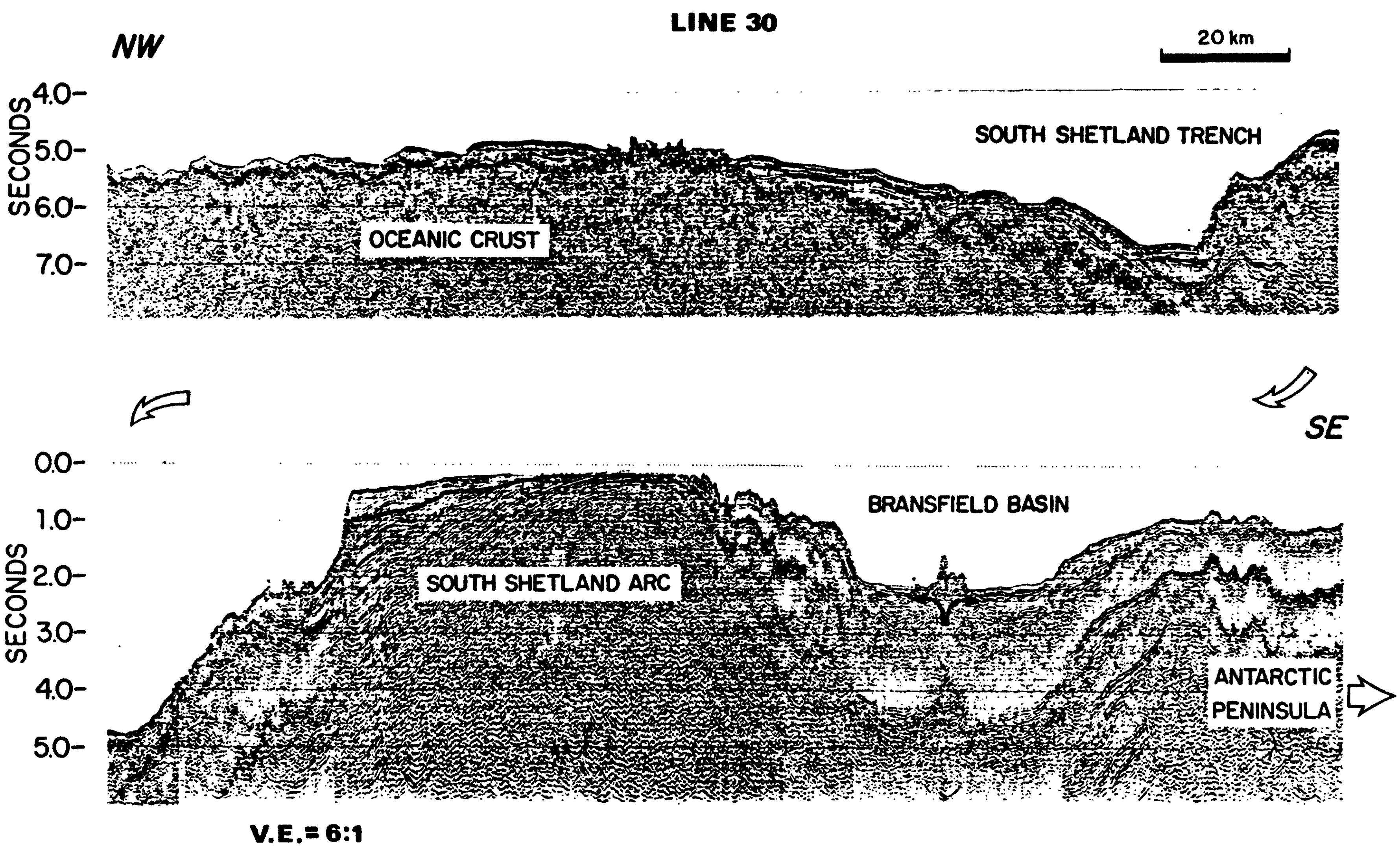
LINE 30
NW
20 km
SECONDS
4.0
5.0
6.0
7.0
SOUTH SHETLAND TRENCH
OCEANIC CRUST
SE
0.0
1.0
2.0
3.0
4.0
5.0
BRANSFIELD BASIN
SOUTH SHETLAND ARC
ANTARCTIC PENINSULA
V.E.= 6:1

FIG. 2

LINE 6

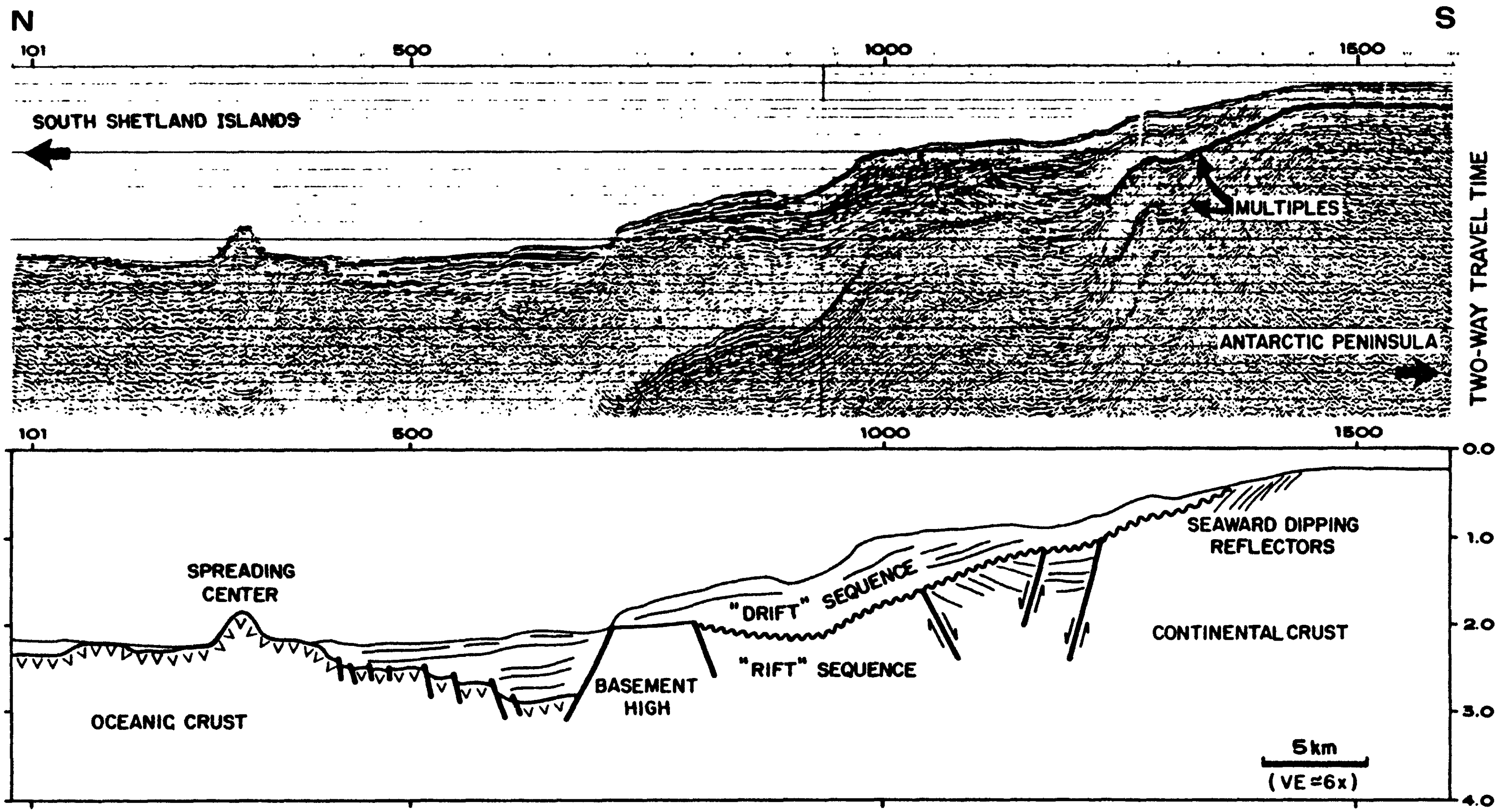
N
S
101
500
1000
1500
SOUTH SHETLAND ISLANDS
MULTIPLES
ANTARCTIC PENINSULA
TWO-WAY TRAVEL TIME
0.0
1.0
2.0
3.0
4.0
SPREADING CENTER
"DRIFT" SEQUENCE
SEAWARD DIPPING REFLECTORS
"RIFT" SEQUENCE
CONTINENTAL CRUST
BASEMENT HIGH
OCEANIC CRUST
5km
(VE ≈6x)

FIG. 3

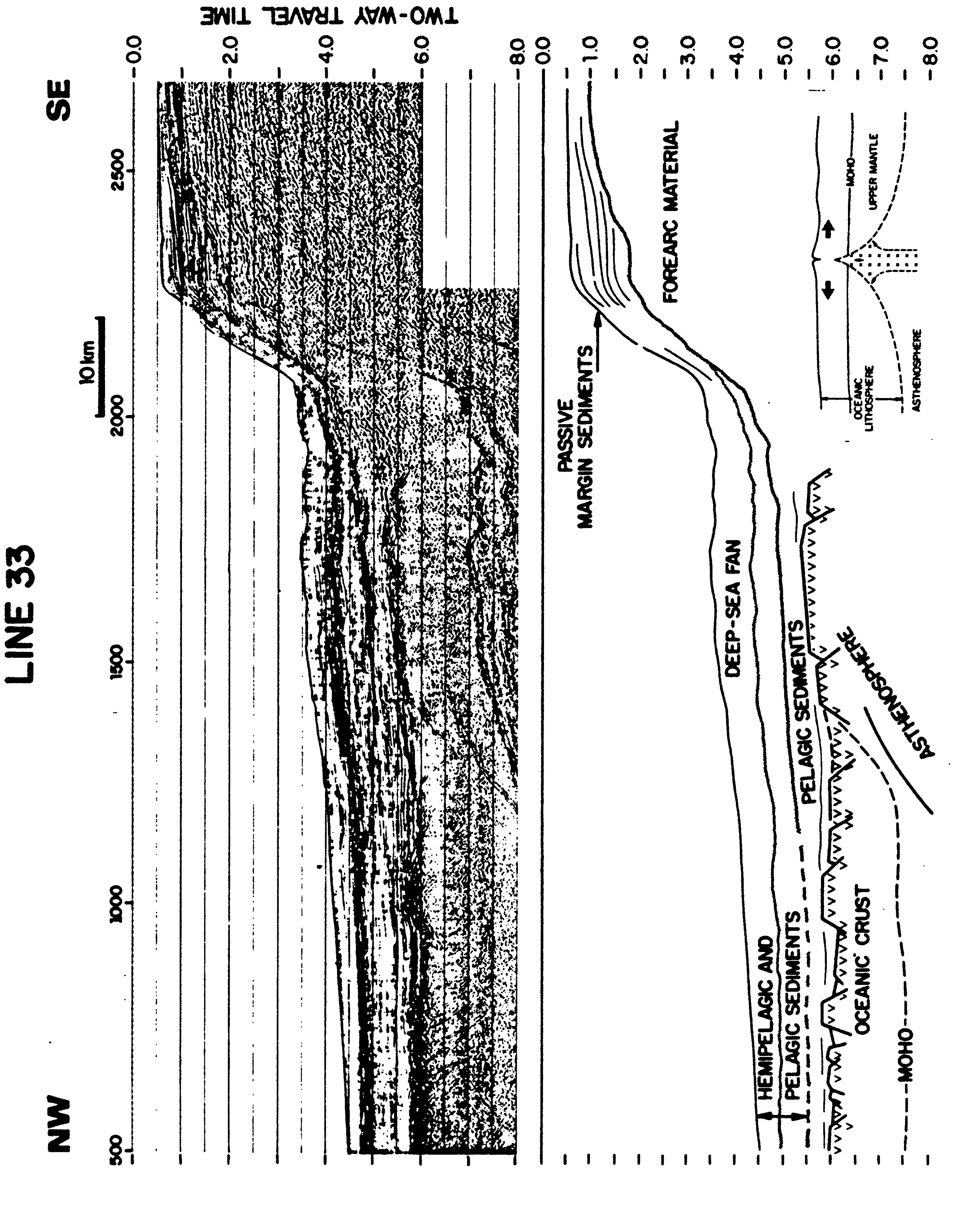
LINE 33
NW
SE
TWO-WAY TRAVEL TIME
10 km
500
1000
1500
2000
2500
0.0
2.0
4.0
6.0
8.0
1.0
3.0
5.0
7.0
PASSIVE MARGIN SEDIMENTS
FOREARC MATERIAL
DEEP-SEA FAN
PELAGIC SEDIMENTS
ASTHENOSPHERE
HEMIPELAGIC AND PELAGIC SEDIMENTS
OCEANIC CRUST
MOHO
OCEANIC LITHOSPHERE
UPPER MANTLE
ASTHENOSPHERE

FIG. 4

Hydrothermal Activities in the King George Basin, Antarctica

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The King George Basin is one of several morpho-tectonic depressions along the axis of the Bransfield Strait, Antarctica (Fig. 1). The strait was formed by back-arc spreading separating the South Shetland Islands chain in the north from the Antarctic Peninsula in the south. Spreading has been documented over the last 1.4 m.y. (Roach, 1978; Barker and Dalziel, 1983). Submarine volcanism, associated with the process of back-arc spreading, was only recently documented in the King George Basin. Two sea mounts were discovered during a survey by RV Polarstern in 1985. Fresh basalts and pillow basalts were dredged from the area.

Pieces of evidence for hydrothermal activities, gathered from the King George Basin, include anomalous porewater chemistry (Han and Suess, 1987) and injection of a ^{3}He-rich helium component into the deep basin water (Schlosser et al., 1988). These reports are interesting as they document the hydrothermal activities under polar environmental conditions as well as in the thickly-sedimented basin. Active hydrothermal activities in the King George Basin appear to be unique in polar marine environments.

Pinpointing the area of the hydrothermal activities, their signs were detected only from the eastern margin of the King George Basin where numerous submarine volcanoes are distributed. The smooth basin floor, covered with thick turbidites, is punctuated by submarine volcanoes and numerous dike intrusions (Fig. 2). There appear to be no signs of hydrothermal activities in the rest of the basin. The eastern margin of the basin is also characterized by a very puzzling zone of acoustic turbidity (i.e., no acoustic reflection in the 3.5 kHz records). It is from this zone that the porewater chemistry shows distinct hydrothermal characters. Migrating pore fluids associated with the hydrothermal activities may be responsible for the acoutic turbidity, disrupting seismic reflection layers.

Distribution of normal faults along the northern and the southern margins of the basin suggests an active rifting along the basin margins. Distributuion of the faults predominantly along the southern margin and the basin sediment cover, thickening southward, suggest the major sedimentation from the continental slope off Antarctic Peninsula by slumpings which are likely to be associated with rifting and faulting in the southern margin.

The porewater chemistry from the eastern basin differs greatly from that of the central basin: both chloride and the sum of the major cations (Σ Na, Mg, Ca, K), normally considered conservative constituents, show significant enrichments downcore at all hydrothermal stations in the eastern basin (Fig. 3). The distribution pattern of dissolved species in porewater of the hydrothermal stations appears to be controlled by the degree of mixing between fluid reservoirs consisting of unaltered seawater, diagenetically altered porewater and hydrothermal fluid. Chloride enrichment suggests low temperature hydrothermal reaction in the basin (70 to 150 °C). The low-temperature regime in the basin generates far less intense hydrothermal activities than observed at the Guaymas Basin; this results in a different mode of generation and expulsion of fluids, and a lack of substantial secondary reactions between hydrothermal waters and sediments.

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Han M. W. and Suess E., 1987, Lateral migration of pore fluids through sediments of an active back-arc basin: Bransfield Strait, Antractica, EOS 68:1768.

Roach P. J., 1978, The nature of back-arc extension in Bransfield Strait, Geophys. J. R. Astron. Soc. 53: 165.

Schlosser P., Suess E., Bayer R. and Rhein M., 1988, ^{3}He in the Bransfield Strait waters: indication for local injection from back-arc rifting, Deep Sea Research 35: 1919 - 1935.

Figure Captions

Figure 1

King George Basin in the Bransfield Strait, Antarctica (marked by a square) and regional tectonic map of the Scotia Sea (insert).

Figure 2

Bathymetry, sedimentary and tectonic features in the King George Basin; normal faults develop along the southern basin margins; the sediment cover thickens southeastward. Circular contours indicate submarine volcanoes. Note the area of acoustic turbidity adjacent to the submarine volcanoes. "Hydrothermal" stations, 1346, 1340, 1341 and 1343, are located within this area; a "reference" core station, 1327, is located in the central basin.

Figure 3a

Depth distribution of interstitial Cl; at all hydrothermal stations (1346, 1340, 1341 and 1343) Cl increases downcore; at the reference station, 1327, there is no significant change in Cl with depth; S.W. = seawater.

Figure 3b

Depth distribution of the sum of the interstitial major cations (Σ Na, Mg, Ca, K). The sum of the major cations at all hydrothermal stations increases downcore between 2 and 8%. At the reference station, 1327, there is no significant change in the cation sum; S.W. = seawater.

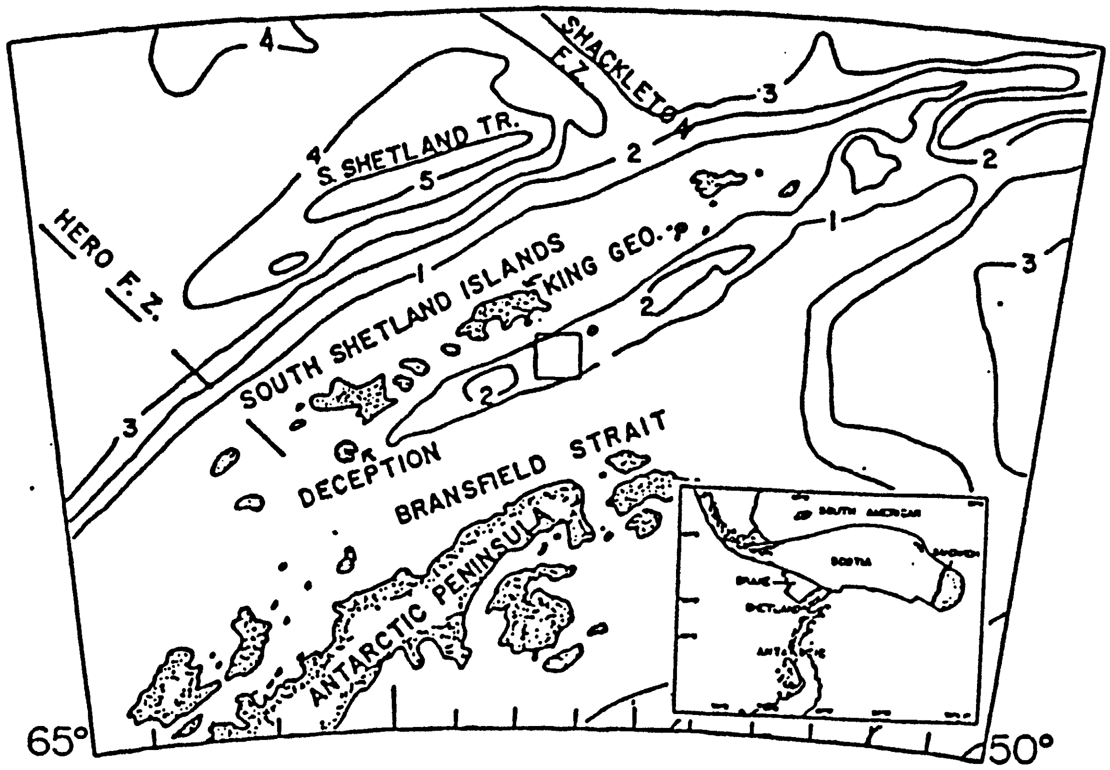
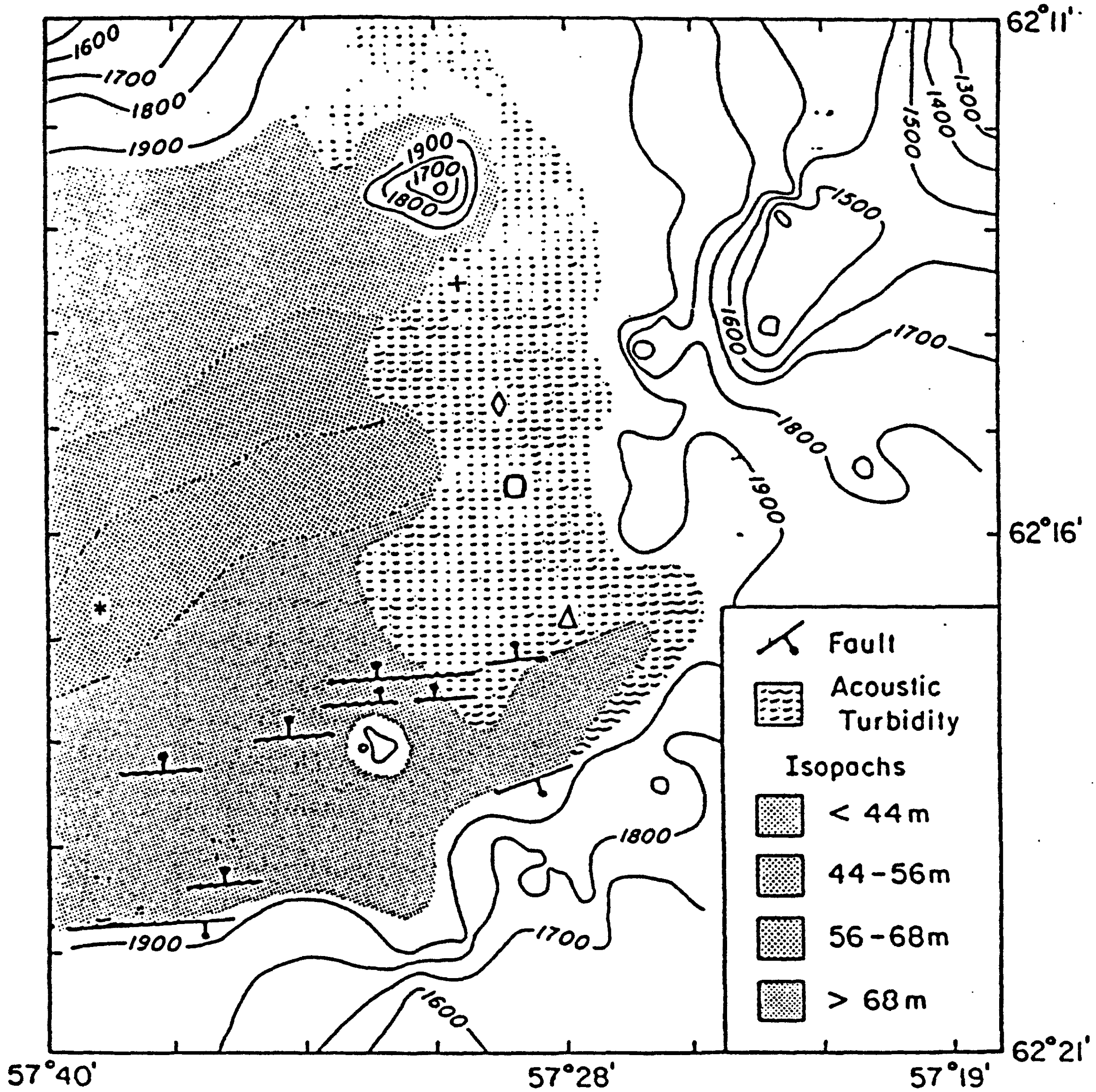
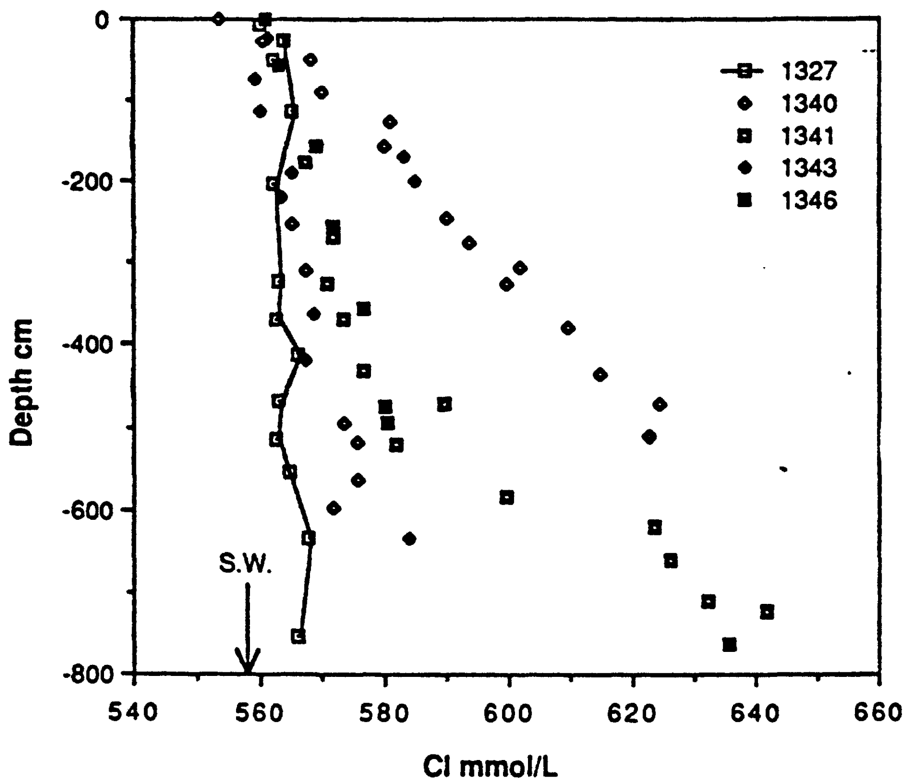

SHACKLETON F.Z.
HERO F.Z.
S. SHETLAND TR.
SOUTH SHETLAND ISLANDS
KING GEO.
DECEPTION
BRANSFIELD STRAIT
ANTARCTIC PENINSULA
65°
50°

Fig. 1



1600
1700
1800
1900
1900
1700
1800
1300
1400
1500
1500
1600
1700
1800
1900
1800
1900
1700
1600
62°11'
62°16'
62°21'
57°40'
57°28'
57°19'
Fault
Acoustic Turbidity
Isopachs
< 44 m
44-56m
56-68m
> 68 m

Fig. 2



1327
1340
1341
1343
1346
Depth cm
0
-200
-400
-600
-800
S.W.
540
560
580
600
620
640
660
Cl mmol/L

Fig. 3a.

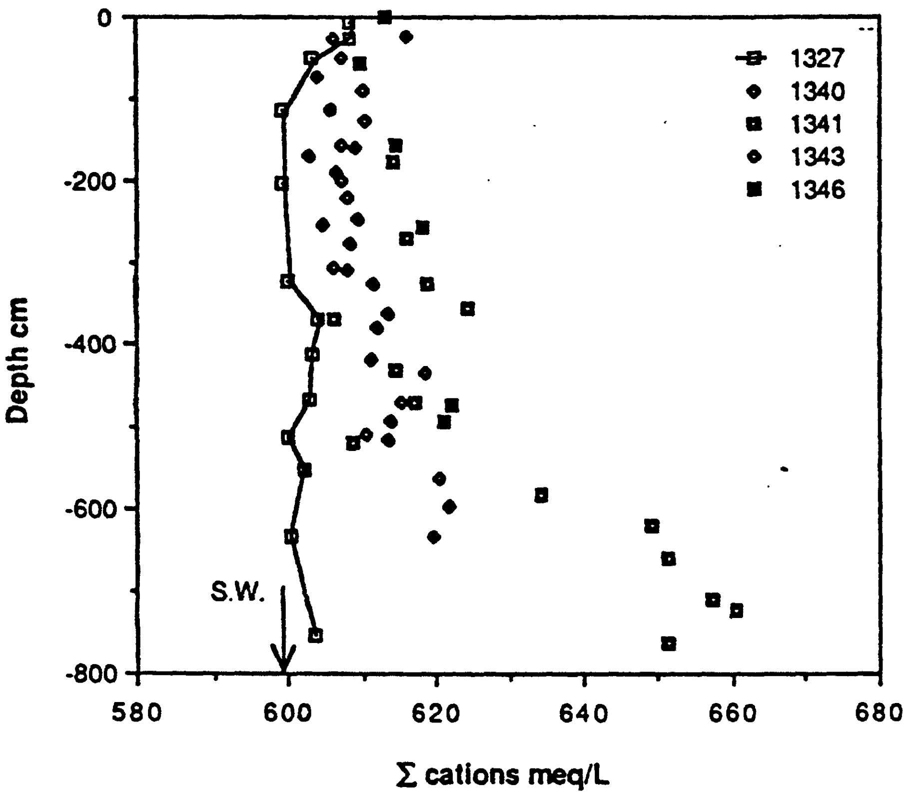

0
-200
-400
-600
-800
Depth cm
580
600
620
640
660
680
Σ cations meq/L
S.W.
1327
1340
1341
1343
1346

Fig. 3b

SEQUENCE-STRATIGRAPHIC GEOMETRIES AND RELATIVE CHANGE OF SEALEVEL

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ABSTRACT

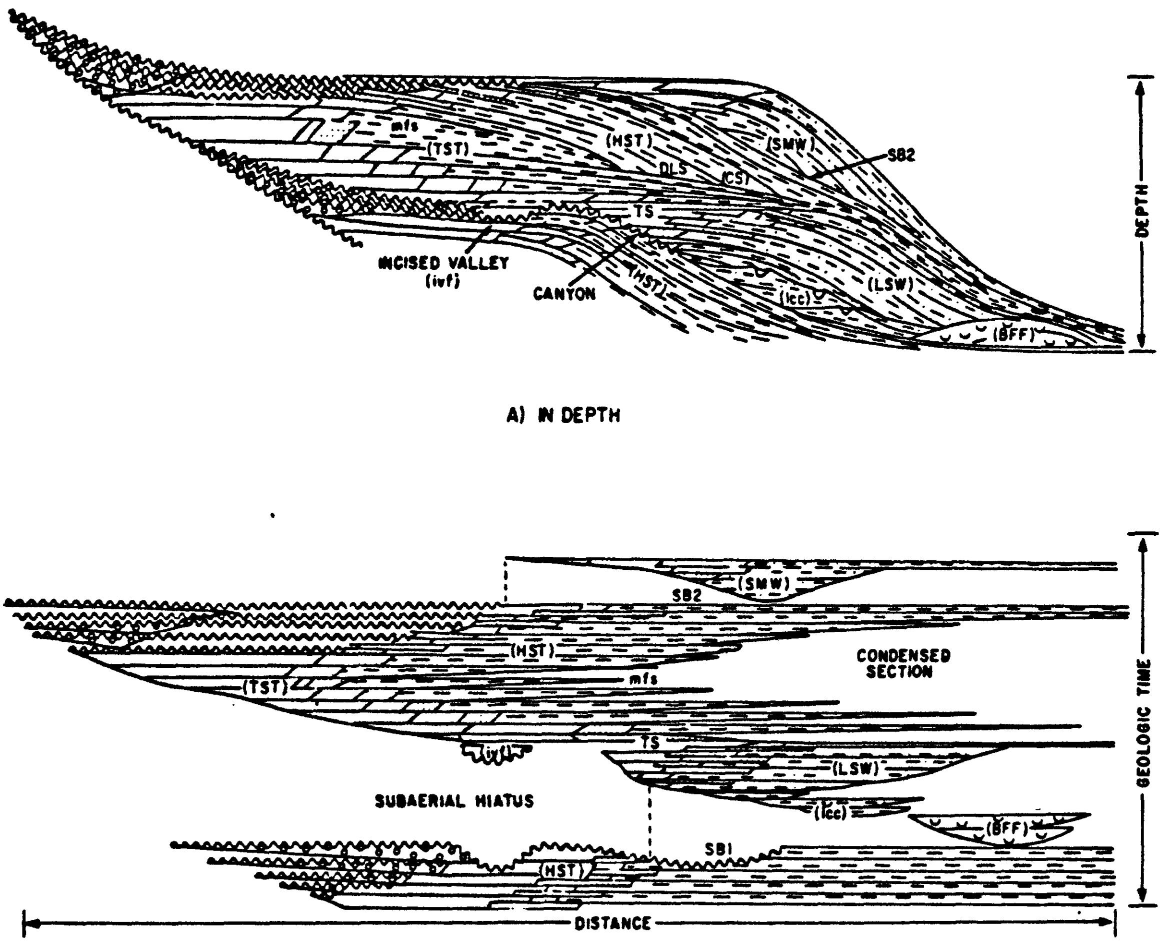
Sequence-stratigraphic models conceptualize the deposition of genetically-related sediment packages along continental margins as a response to various phases of the cycle of relative change of sea level. Regional tectonics (subsidence/uplift), eustasy, and rate of sediment supply interact to produce the measure of relative change of sea level. During a complete cycle of sea-level change characteristic stratal patterns resulting within siliciclastic systems comprise: a basal, basinward prograding wedge of lowstand (or shelf-margin) systems tract; an intermediate, retrogradational landward back-stepping, transgressive systems tract; and an upper, aggrading to prograding, highstand systems tract. In siliciclastic systems most of the terrigenous material is delivered to the basin during the lowstand. Stratal patterns in carbonate systems are comparable to those in the siliciclastic systems; much of the carbonate is transferred to the basin during lowstand progadation. But carbonate can also be exported off-bank during late highstand when productivity on banktop is high while accommodation is reduced. Both lowstand and late-highstand progradation contribute to lateral growth of the platform. In hybrid siliciclastic-carbonate systems, lowstands may be dominated by clastic deposition, while carbonate accumulation may occur both during lowstand and highstand times.

The history of the development of basic conceptual framework of sequence stratigraphy and efforts that led to the documentation of sea-level variations deciphered from sequence analysis of subsurface and outcrop data is outlined. The resulting history of sea-level change and its relationship to the sedimentary patterns of the deepsea are also discussed. A climatic feedback model of an alternating erosive/corrosive response to sea-level fall and rise is offered. Erosion on the seafloor is dominant during low seastands, and canyon incision on the margins during major falls of sea level. Carbonate dissolution on the seafloor is enhanced during times of maximum flooding of the shelves and during early highstand when carbonate is conserved on the inner shelves and nearshore. During the late highstand time following reduced accommodation on the banks, carbonate is again exported to the basins, abating the corrosive cycle. Distinction between early and late highstand phases, and between late highstand and lowstand progradation is, therefore, critical to understanding the response of the carbonate system and deep sea sedimentary patterns to sea-level change along continental margins.

Common Sequence Stratigraphy Terms

English	French	German	Spanish
Accomodation space	Espace disponible	Verfügbarer Platz	Espacio para acomodación
Basin floor fan	Cone sous-marin	Beckenboden Fächer	Abanico de fondo de cuenca
Coastal onlap	Biseau d'aggradation cotière	Küstenaggradationsüberlappung	Bisel de agradacion costera (traslapo costero)
Condensed section	Intervalle condensé	Kondensierter Abschnitt	Intervalo condensado
Conformity	Concordance	Konkordanz	Concordancia (conformidad)
Depositional sequence	Séquence de depot	Ablagerungssequenz	Secuencia deposicional
Downlap	Biseau de progradation	Progradationsüberlappung	Bisel de progradación
Downlap surface	Surface basale de progradation	Basale Progradationsüberlappungsfläche	Superficie basal de progradación
Downward shift	Déplacement vers le bassin	Beckenwärtige Verlagerung	Migracion centripeta
Eustatic sea level	Niveau eustatique	Eustatischer Meeresspiegel	Nivel marino eustático
Flooding surface	Surface d'inondation	Flutungsflache	Superficie de inundación
Highstand systems tract	Cortège de haut niveau	Hochstand System Bündel	Cortejo sedimentario de nivel alto
Lowstand wedge	Prisme de bas niveau	Tiefstand Keil	Cuña de nivel bajo

Lowstand wedge systems tract	Cortège de bas niveau	Tiefstand Keil System Bündel	Cortejo de cuña de nivel bajo
Onlap	Biseau d'aggradation	Aggradations-überlappung	Bisel de agradación (traslapo)
Parasequence	Paraséquence	Parasequenz	Parasecuencia
Sequence stratigraphy	Stratigraphie séquentielle	Sequenz Stratigraphie	Estratigrafia secuencial
Shelf margin wedge	Prisme de bordure de plate-forme	Schelfranden-keil	Cuña de borde de plataforma
Shelf margin wedge systems tract	Cortège de bordure de plate-forme	Schelfranden-keil System Bündel	Cortejo sedimentario de borde de plataforma
Systems tract	Cortège sédimentaire	System Bündel	Cortejo sedimentario
Transgressive surface	Surface de transgression	Transgressive Fläche	Superficio de transgresión
Transgressive systems tract	Cortège transgressif	Transgressives System Bündel	Cortejo sedimentario de transgresión
Unconformity	Discordance	Diskordanz	Discordancia



B) IN GEOLOGIC TIME

LEGEND

- ALLUVIAL
- COASTAL PLAIN
- ESTUARINE/FLUVIAL
- SHOREFACE/DELTAIC SANDS
- MARINE SILT, MUDSTONE
- MARINE SHALE
- DEEP WATER SANDS

SB1 = SEQUENCE BOUNDARY TYPE 1
SB2 = SEQUENCE BOUNDARY TYPE 2
(BFF) = BASIN FLOOR FAN
(LSW) = LOWSTAND WEDGE SYSTEMS TRACT
ivf = INCISED VALLEY FILL
lcc = LEVEED CHANNEL COMPLEX

TS = TRANGRESSIVE SURFACE
(TST) = TRANGRESSIVE SYSTEMS TRACT
mfs = MAXIMUM FLOODING SURFACE
(CS) = CONDENSED SECTION
DLS = DOWNLAP SURFACE
(HST) = HIGHSTAND SYSTEMS TRACT
(SMW) = SHELF MARGIN WEDGE SYSTEMS TRACT

Figure 1

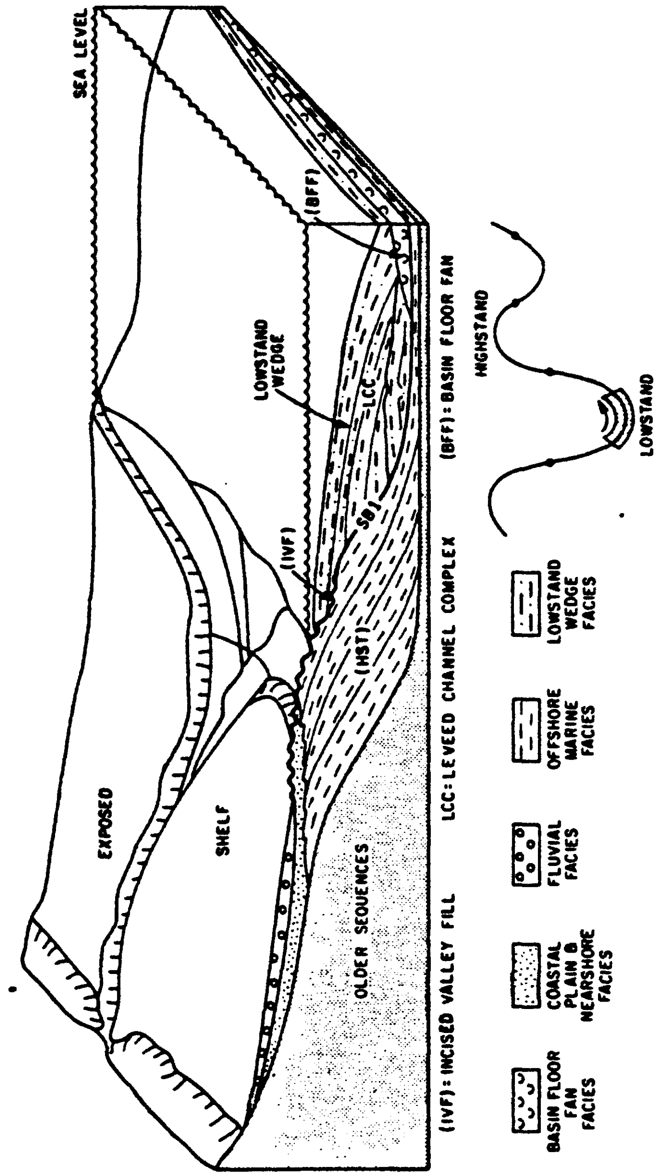

SEA LEVEL
(BFF)
LOWSTAND WEDGE
LCC
SB1
(IVF)
(HST)
EXPOSED
SHELF
OLDER SEQUENCES
(IVF): INCISED VALLEY FILL
LCC: LEVEED CHANNEL COMPLEX
(BFF): BASIN FLOOR FAN
HIGHSTAND
LOWSTAND
BASIN FLOOR FAN FACIES
COASTAL PLAIN & NEARSHORE FACIES
FLUVIAL FACIES
OFFSHORE MARINE FACIES
LOWSTAND WEDGE FACIES

Figure 2

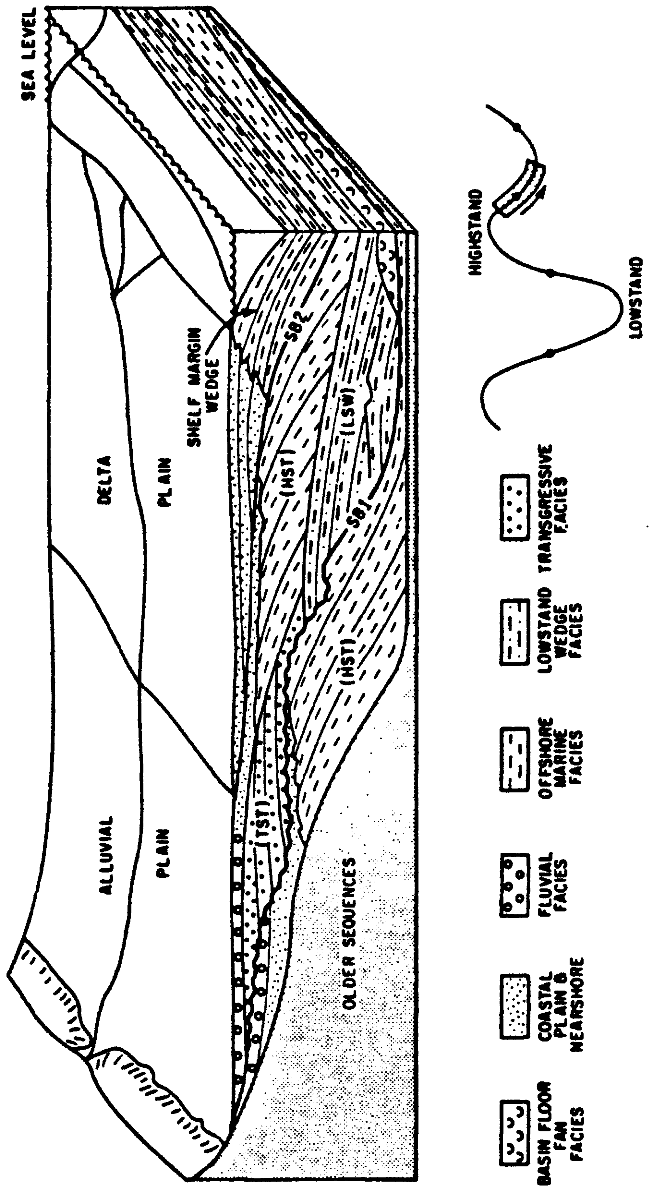

SEA LEVEL
DELTA
PLAIN
SHELF MARGIN
WEDGE
ALLUVIAL
PLAIN
SB2
(HST)
(LSW)
SB1
(HST)
(TST)
OLDER SEQUENCES
HIGHSTAND
LOWSTAND
BASIN FLOOR
FAN
FACIES
COASTAL
PLAIN &
NEARSHORE
FLUVIAL
FACIES
OFFSHORE
MARINE
FACIES
LOWSTAND
WEDGE
FACIES
TRANSGRESSIVE
FACIES

Figure 3

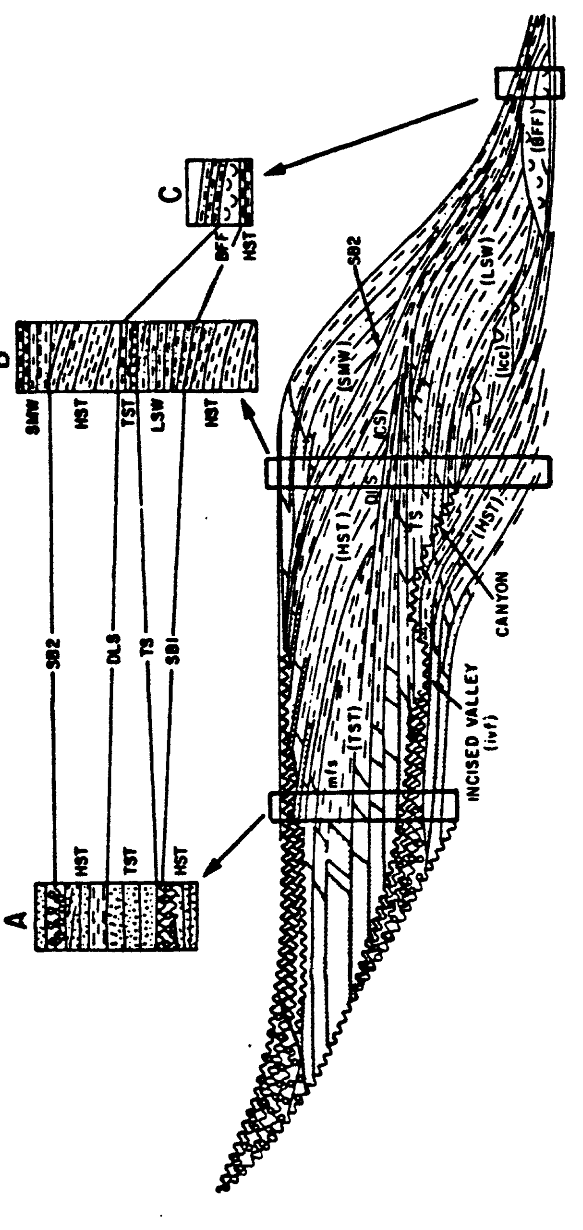

A
B
C
SMW
HST
TST
LSW
BFF
SB2
DLS
TS
SB1
(SMW)
(LSW)
(HST)
(TST)
(BFF)
(lcc)
mfs
INCISED VALLEY
(ivf)
CANYON

Figure 4

High Resolution Seismic Studies in Maxwell Bay, King George Island

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High resolution single channel seismic data were acquired in Maxwell Bay, King George Island during the 1987-88 Antarctic summer season. Maxwell Bay is an embayment which locates at southwest end of King George Island and surrounded by Fildes, Barton Peninsula, and Nelson Island (Fig. 1). The bay is open toward Bransfield Strait and the water depth is more than 500 m at the central part. Surface geology of King George Island consists mainly of the upper Jurassic volcanics and early Tertiary igneous rocks (Barton, 1965). The South Shetland Islands including King George lie on a continental crustal structure and this structure continues beneath the trough of Bransfield Strait. Gophysical studies suggest that the South Shetland Islands were a part of the Antarctic Peninsula and that Bransfield Strait extended and separated the two land masses after cessation of subduction along the South Shetland trench at 4 Ma (Barker, 1982). Normal faulting possibly related with Pliocene to recent volcanics continues from the South Shetland Islands to offshore into the northwestern margin of Bransfield Strait (Ashcroft, 1972).
Seismic profiles consist of five short lines running NE-SW and two lines of NW-SE direction which is parallel to the axis of the bay. Total length of profiles is about 77 km. Bathymetry of the bay shows that relatively flat bottom of deeper than 400 m lies at the center. The bottom area elongates southeasterly along the axis of the bay and may continue further out to Bransfield. Bathymetry changes rapidly toward coast with an average slope of 13° . Seismic profiles show the rugged topography above 200 m depth at nothwest margin of the bay. NE-SW profiles show an U shaped valley and the bottom tilts gently to southwest (Fig. 2).
Line 1 which runs from Marian Cove to a little bay near Nelson Island shows that Marian Cove is separated from Maxwell Bay by a prominent basement high. Irregular acoustic basement appears to be covered with thin sediments and a reflection free layer of 3-4 m thick trapped behind a basement high in Marian Cove. Bathymetry drops rapidly toward the central part of the bay and well laminated layers are seen at the bottom. The laminated layers are tilted southwesterly and a fault which breaks sediments all the way to the top is seen at figure 2. A trough of 18 m deep locates at the left end of figure 2 and this feature can be traced down from other profiles. This trough may represent a subglacial meltwater stream channel.
The flat lying well laminated layers of 50 ms thick can be seen in line 2 (Fig. 3). A piston core penetrated these layers consists of near pelagic sediments. However there is a possibility that thick glacial deposit underlies these laminated layers because the acoustic basement can not be discerned in the record. A prominent high which locates in the middle of bottom area looks like a submarine volcanic intrusion. The layers at SE side of intrusion are tilted whereas the layers at NW side are horizontal and bulged upward at the midpoint between the intrusion and NW margin of the bottom. This bulge formed

by compression at the time of intrusion and it must be a recent activity. Bathymetry goes up with several basement highs and U shaped small valleys in the northern part of the bay. The valleys filled with reflection free or chaotic layers and even big boulders can be identified in the profile. Depositional environment changes sharply from north to south where glacial deposit end behind a basement high and pelagic sediments occur in the bottom area.

A piston core penetrated the trapped sediments in Marian Cove consists of a pebbly mud layer of 1 m long at the top, rhythmic beds of 40 cm, and basal till at the bottom. Basal till may represent former grounding of the glacier in Marian Cove and the rhythmic beds indicate much warmer climate than now after the last glacial retreat. Paleontological study from the top 30 cm core suggests Holocene age and sediment rate was relatively slow. Sediment rate of the pebbly mud layer deduced from Pb-210 data is 0.75 mm/yr. The piston core at the flat bottom is all sandy mud with severe bioturbation but ice rafted debris are rare. Diatom study from the 2.6 m long piston core at the south of Maxwell Bay indicates that the core deposited last 7,000 years and the water temperature was warmer than now below 1 m depth. This suggests Antarctic Convergence may locate further south and sea level was higher than now.

Maxwell Bay is an embayment with a flat bottom at the central part and steeply rising margin in the northern and eastern part. Bathmetry in the northern part goes up with the step like pattern which consists of several basement highs and small valleys behind them. These basement highs may represent a series of normal faulting similar to those found in Admiralty Bay. The volcanic intrusion and fault that cuts the laminated layers indicate this area is tectonically still active.

Glacial once grounded whole bay and left meltwater channel at one side of flat bottom area. Probably a main glacial covered the central part and several vally glacials developed perpendicular to the axis of the bay. Core data shows that climate was warmer than now after the last glacial retreat in this area.

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Barton, C.M., 1965, The geology of the South Shetland Islands: Br. Antarct. Sci. Rep. 44, 33pp.

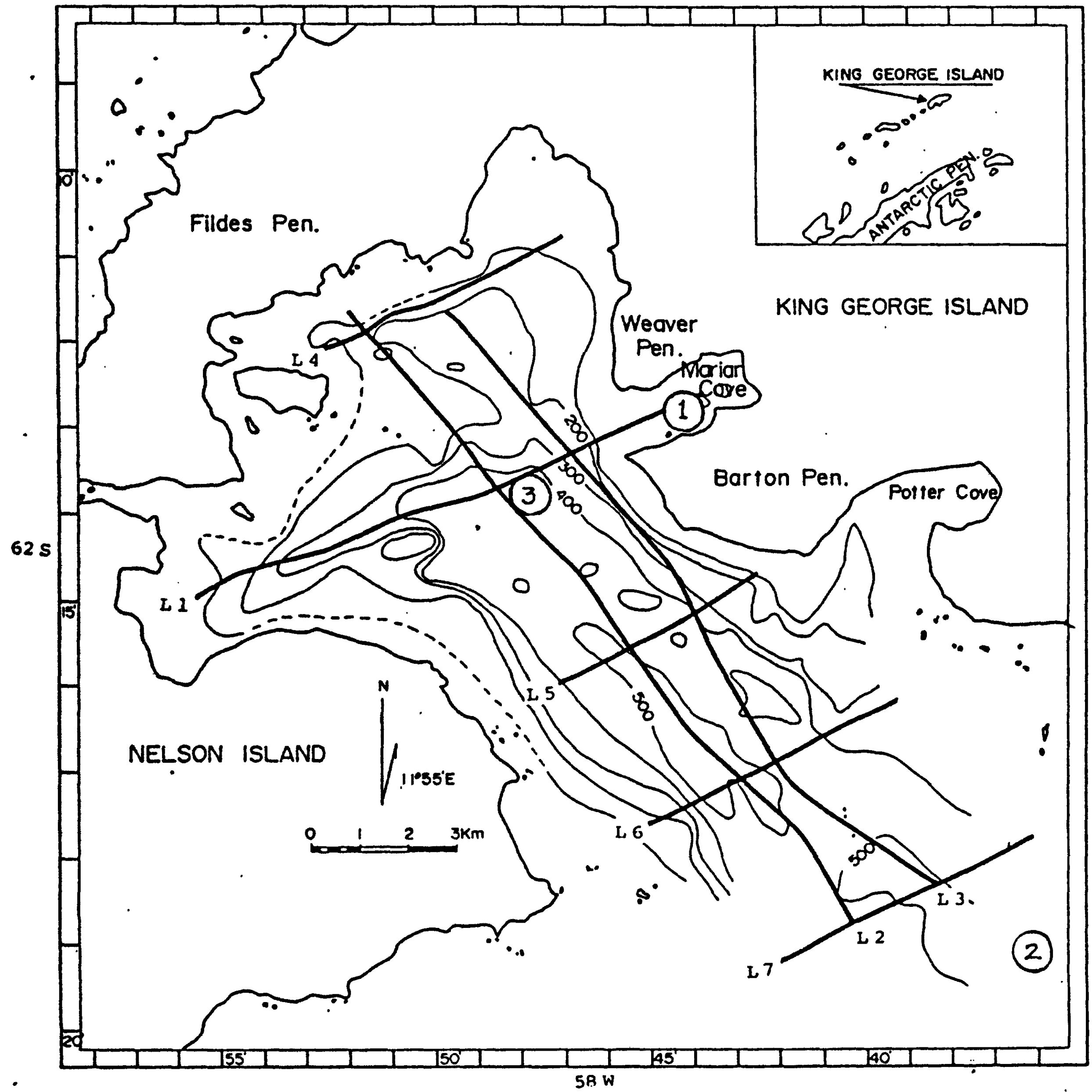

Fig. 1. Bathymetry of Maxwell Bay with the location of seismic lines. Circles with number represent the location of piston coring.

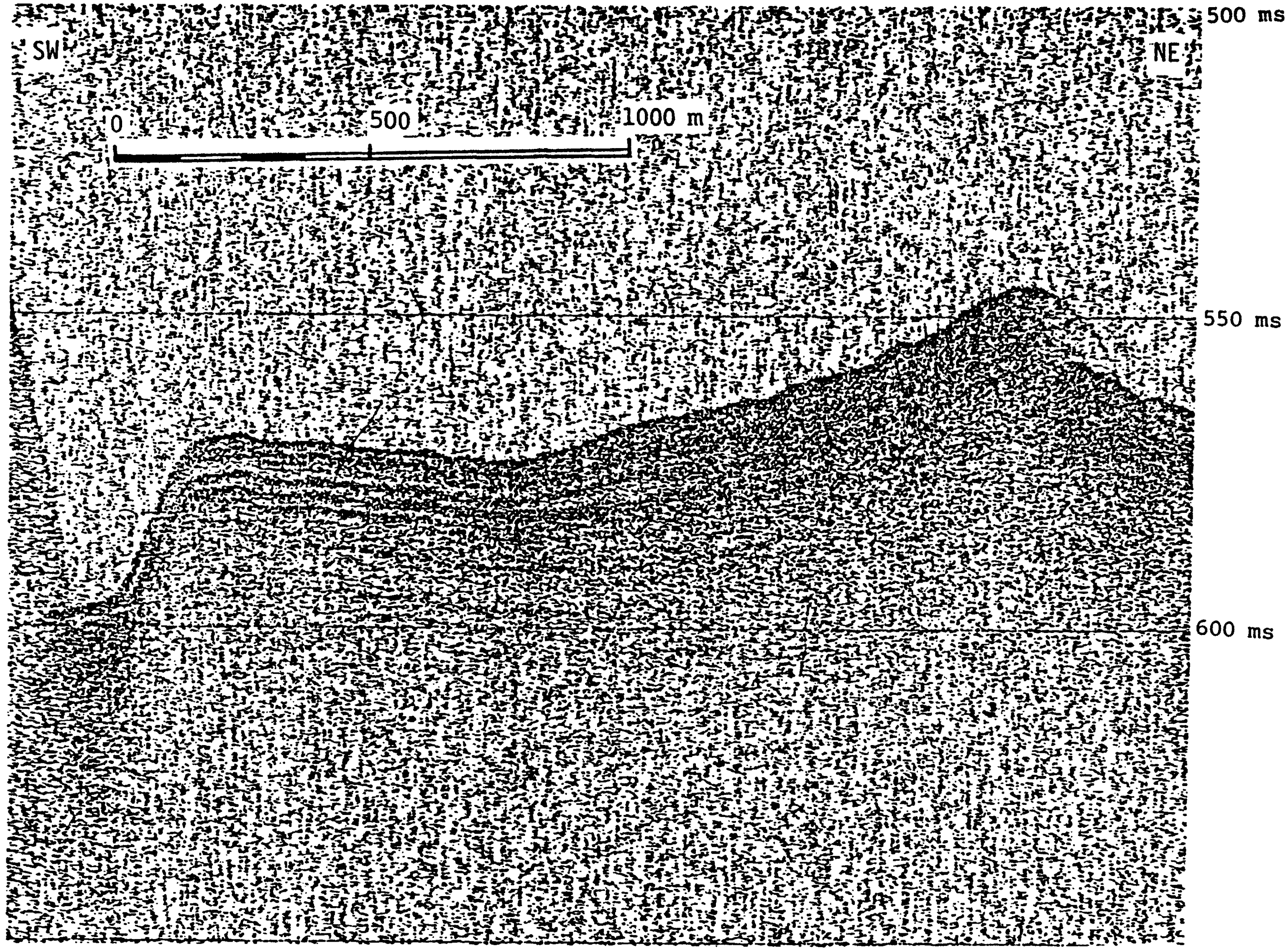

Fig. 2. A part of NE-SW profile of seismic line 1 which runs perpendicular to the axis of the bay. The central part of the bay with laminated layers, a trough at SW margin and a fault at NE end are shown. The trough is considered to be a subglacial meltwater channel.

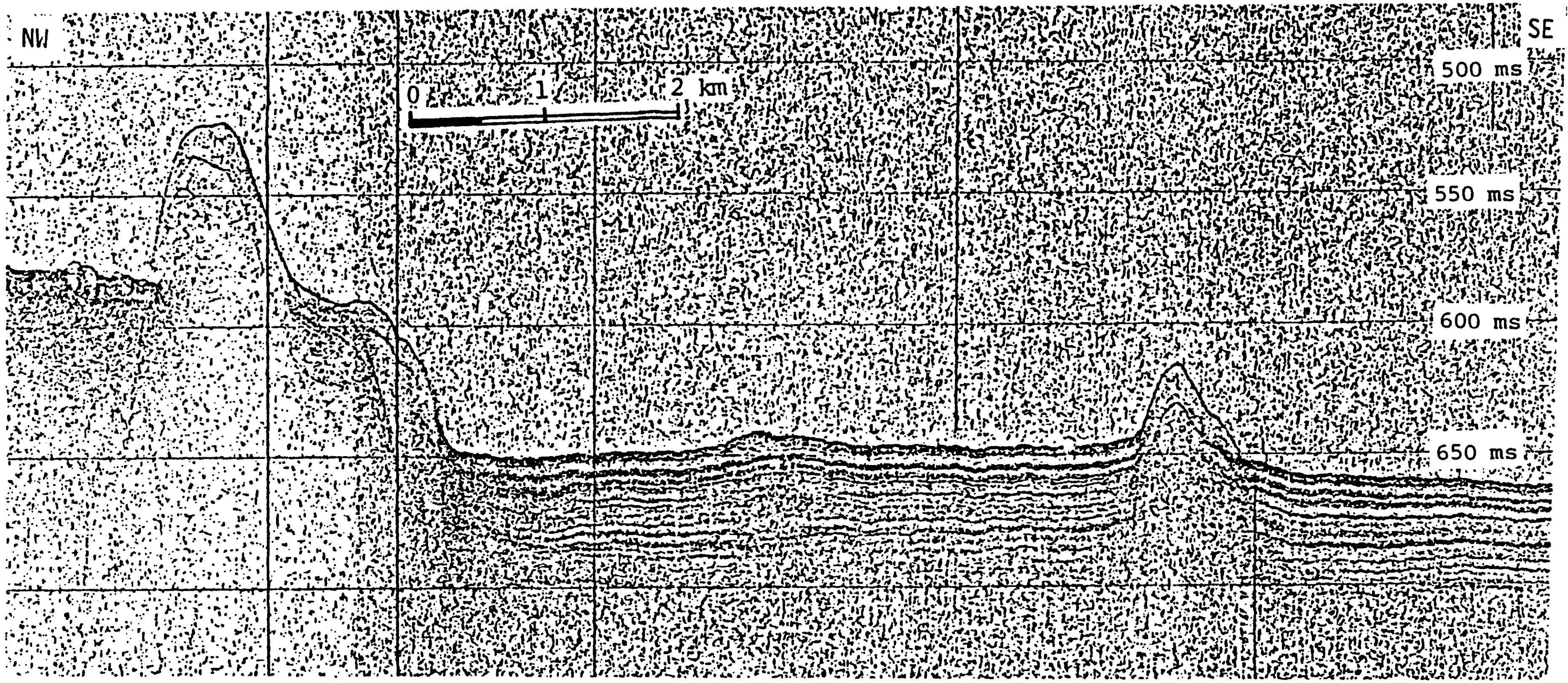

Fig. 3. A part of NW-SE profile of seismic line 2. A submarine volcanic intrusion is seen at the center of flat bottom. A basement high at NW side blocks ice rafted debris sliding down from marginal slope and glacial till deposits behind it.

Geoscientific studies of the southeastern Weddell Sea continental margin by Norwegian Antarctic Research Expeditions

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Anders Solheim
Norwegian Polar Research Institute, Oslo, Norway

Anders Elverhøi
Department of Geology, University of Oslo, Oslo, Norway

Berit Kuvaas
Seismological Observatory, University of Bergen, Bergen, Norway

The programs in marine geophysics and geology of the Norwegian expeditions in 1977, 1979 and 1985 to the Weddell Sea sector of Antarctica has acquired a data base of 4600 km of seismic multichannel data (Fig. 1), 2000 km of shallow seismic (sparker) data (Fig. 2), 55 gravity cores, 6 vibrocores, 10 dredge hauls, 20 camera stations, measurements of suspended matter and 2 heat flow measurements. Bathymetry has been collected routinely and the coverage of gravity and magnetic measurements is partial. A site survey for ODP leg 113 was carried out on the Maud Rise.

The seismic data base has been merged with the data of the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR) to define two sets of basement structures below the East Antarctic continental margin of the Weddell Sea, between 0^0 and 40^0 W. One set is formed by the Explora-Andenes Escarpment (EAE), trending 60^0-80^0E and bounded on the seaward side by oceanic crust. The other set lies landward of the EAE and represents a failed rift system (Weddell Rift) trending N50^0E with symmetrical volcanic wedges. The presence of the Weddell Rift demonstrates that the initial motion was rifting accompanied by prolific volcanism, and that a > 40 km wide area of oceanic crust may have been generated. Subsequently transtensional movements were initiated between South Africa and Antarctica and resulted in formation of the Explora-Andenes Escarpment as a new plate boundary and opening of the Weddell Sea by seafloor spreading.

Studies of the sediments have focussed on the glacially derived section as calibrated from ODP Site 693. The glacial sediments are characterized by a predominantly progradational pattern where the input along the margin is consentrated in two areas; at the mouth of the Crary Trough and outside the Stancomb Wills Ice Stream. During early Oligocene- middle Miocene, maximum sediment input was in the Crary Trough area, but later both areas received high input relative to the shelf to the northeast off Dronning Maud Land. A trough-mouth fan developed associated with the Crary Trough and its basic architecture is three generations of large channel-levee systems migrating in an eastward direction. The seismostratigraphy of the shelf and upper slope at the mouth of the Crary Trough interpreted in terms of the geometry of the deposits and the paleoshelf morphology provides strong evidence of multiple glacial advances at least after the middle Miocene. The main sediment input to the margin must be during glacial periods as the Ice Shelf Water flowing across the margin during the present inter-glacial has relatively low consentrations of suspended matter and erosion is taking place on the continental slope.

The shallow seismic data demonstrate that the Crary Trough is a depression carved out by glacial erosion at the edge of a large sedimentary basin bounded by the East Antarctic craton. We infer from the overconsolidated nature of the seafloor sediments on the shelf and a few C^{14} dates on shell fragments that the last advance of grounded ice to the shelf edge was during the late Wisconsin.

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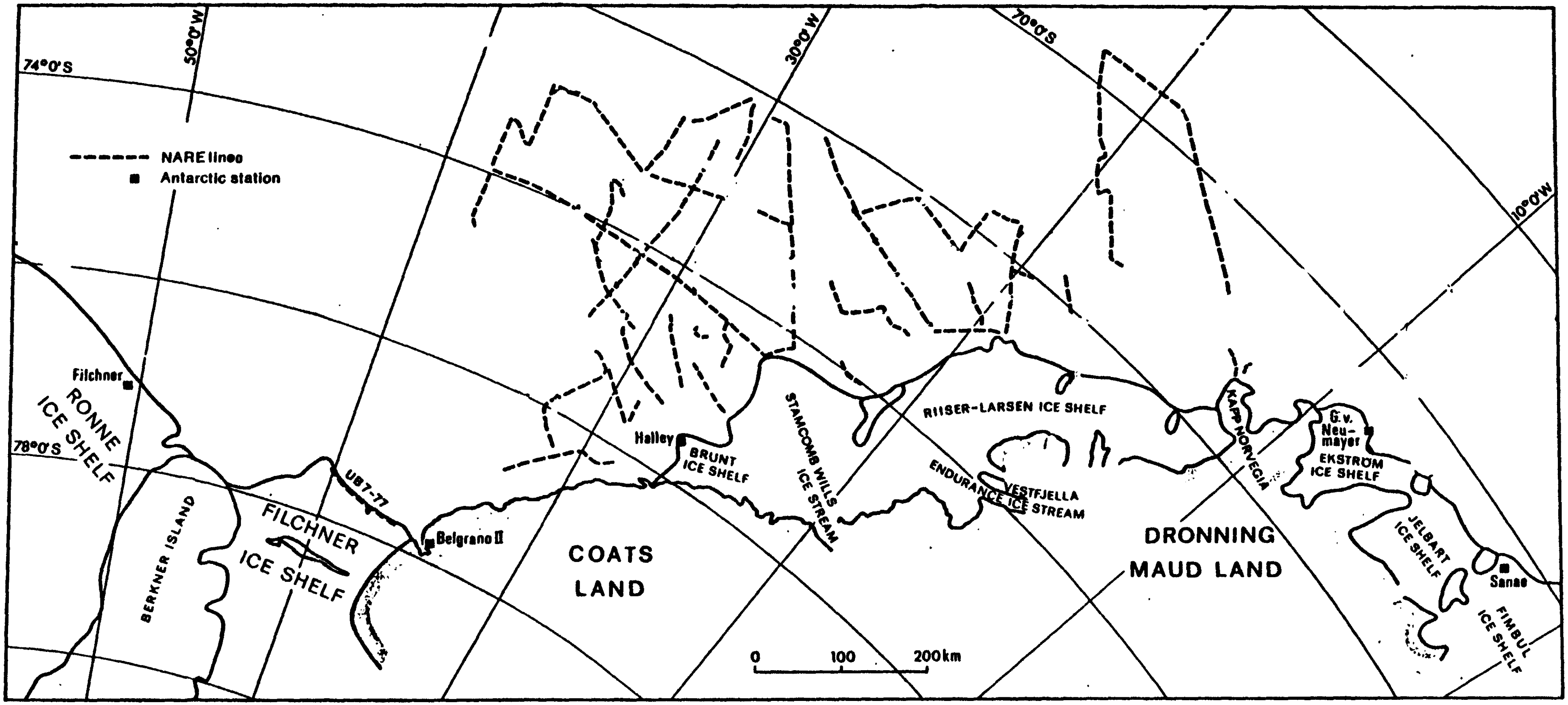

Fig. 1 Coverage of seismic multichannel data acquired by Norwegian Antarctic Research Expeditions 1976/77, 1978/79 and 1984/85.

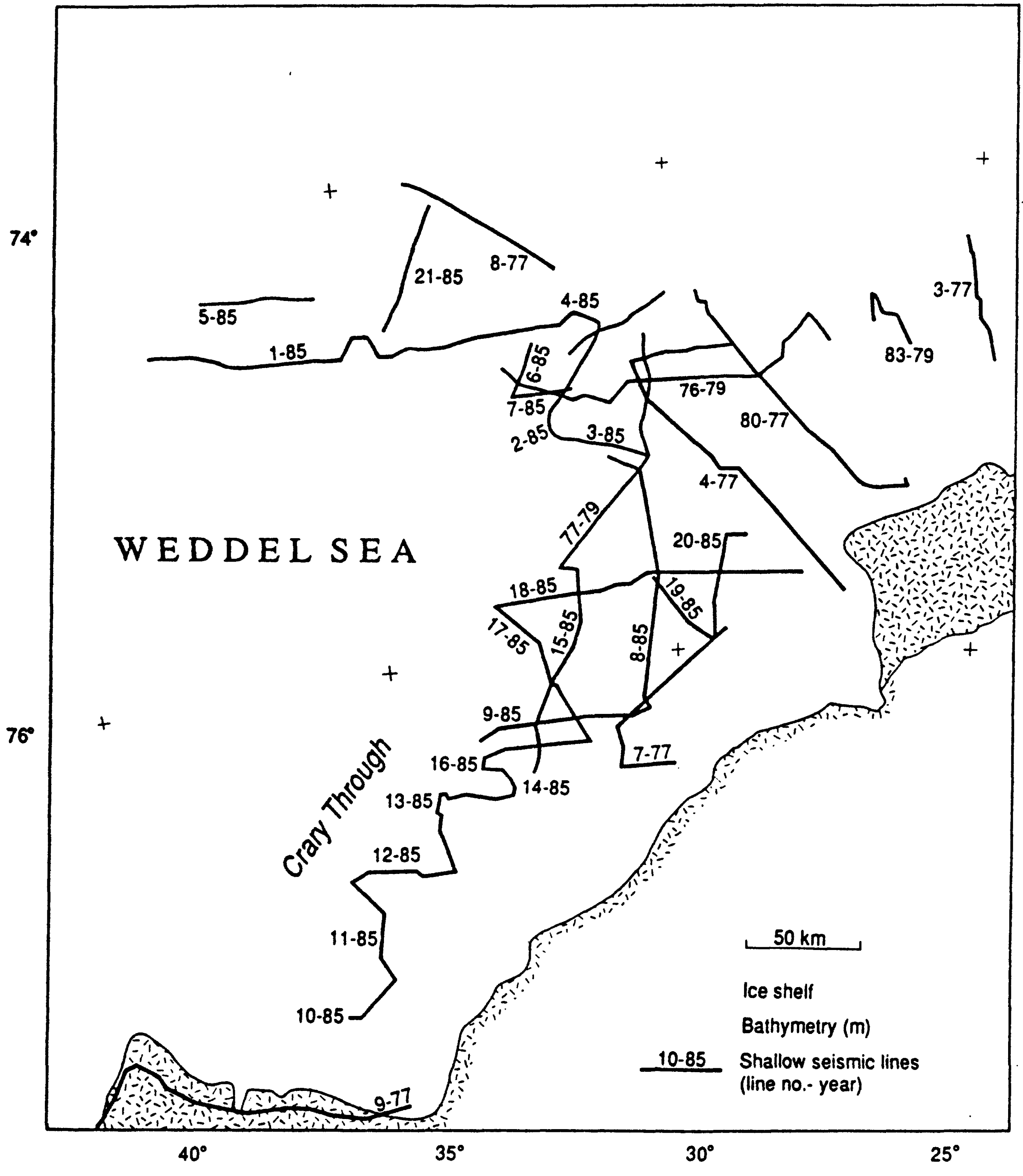

Fig. 2. Coverage of shallow seismic (sparker) data acquired by Norwegian Antarctic Research Expeditions 1976/77, 1978/79 and 1984/85.

THE SEISMIC STRATIGRAPHY OF GLACIGENIC SEDIMENTS ALONG THE WEDDELL SEA MARGIN

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Although the seismic stratigraphy on continental margins are commonly interpreted in terms of sea level changes, there is clear evidence from high latitude margins that processes related to advancing ice sheets are important.

Multichannel seismic profiles across the Weddell Sea shelf and upper slope (Fig.1) shows prograding sequences with a maximum of 70-80 km of shelf edge migration during the glacial history of the area as calibrated from ODP Site 693. From the middle Miocene and onwards the shelf edge has migrated up to 37 km. Reprocessing of seismic profiles from the shelf and upper slope environment has revealed features in the reflection pattern which we relate to multiple glacial advances to the shelf edge in the past. Profiles parallel to the shelf edge show large lense-shaped deposits, symmetrically arranged with respect to the longitudinal axis of a glacially eroded trough across the nargin (Crary Trough). The geometry of these deposits imply deposition from a line source, indicating sediment input from an advancing ice sheet. On dip profiles across the shelf and upper slope, we observe a characteristic morphology of both the present and ancient shelf edges in the form of lenses forming a "bulge" at the shelf break (Fig.2). The lenses are interpreted to represent coarse grained glacial material deposited at the grounding line (diamictite aprons). From a detailed study of the reflection pattern, we recognize four levels of glacial advances based on their capacity of erosion of the shelf sequences. This permits reconstruction of the glacial history of the area in relative terms. A correlation between the glacial history as derived from the seismostratigraphy and information of climatic variations from oxygen isotope studies and occurence of IRD is a future goal.

The main input of glacigenic sediments along the eastern Weddell Sea margin was north of the Crary Trough from early Oligocene to middle Miocene. From the middle Miocene and onwards, the main depot centre for glacigenic sediments was located north of the Stamcomb Wills Ice Stream and the western parts of the Riiser Larsen Ice Shelf. In the easternmost area, off Kapp Norvegia, sedimentation appears to have been low throughout the glacial history of the region.

A large trough-mouth fan deposit is present on the continental margin north of the Crary Trough. The seismostratigraphic evidence suggest that the submarine fan largely is composed of glacigenic sediments of early Oligocene and younger age. Three major channels and their associated levee complexes form the basic architecture of the fan (Fig.3). The channels are unusually large and appear to have been stable for long periods. Their associated levees may reach thicknesses of more than 1 km. The large amounts of fine material deposited in the levee complexes on the Crary TMF and the persistent loci of sediment supply require that meltwater transport must have been important during glacial periods in the Weddell Sea area. Meltwater transport further suggest that wet based glaciers have been predominant in the past. The growth of the Crary TMF is characterized by an eastward migration of the channel-levee complexes. The youngest complex is associated with the Deutschland Canyon/Channel. Preferential growth on the western levees are attributed to the influence of the Coriolis force on downslope currents, forcing channel migration towards the east. The channel levee systems and -complexes indicates different growth phases, apparently controlled by glacial/interglacial climate fluctuations. Glacial periods are believed to be characterized by advancing and eroding ice sheets, basal till deposition, deposition of waterlain till at the grounding line, and deposition of dropstone diamictons in regions of basal melting. When the ice sheet was grounded at the shelf edge, subglacial meltwater streams must have supplied sediments directly to the channels. Once the ice sheet advanced to the shelf edge, large amounts of sediments were deposited on the upper slope. Slumping of rapidly deposited sediments at the grounding line generated mass flow and turbidite sedimentation represented by the lense-shaped deposits in front of the Crary Trough. Also, turbidite sedimentation, characterized by the occurence coarse channel floors and finer grained levee deposits was fed by turbidity currents generated from glacial meltwater streams. During interglacial periods, sediment supply to the fan became strongly reduced. Vigorous downslope currents of cold and dense Ice Shelf Water, erode in the shelf and slope setting. Small amounts of sediments may have been supplied by winnowing from the shelf area and by resedimentation processes, triggered by the flow of Ice Shelf Water.

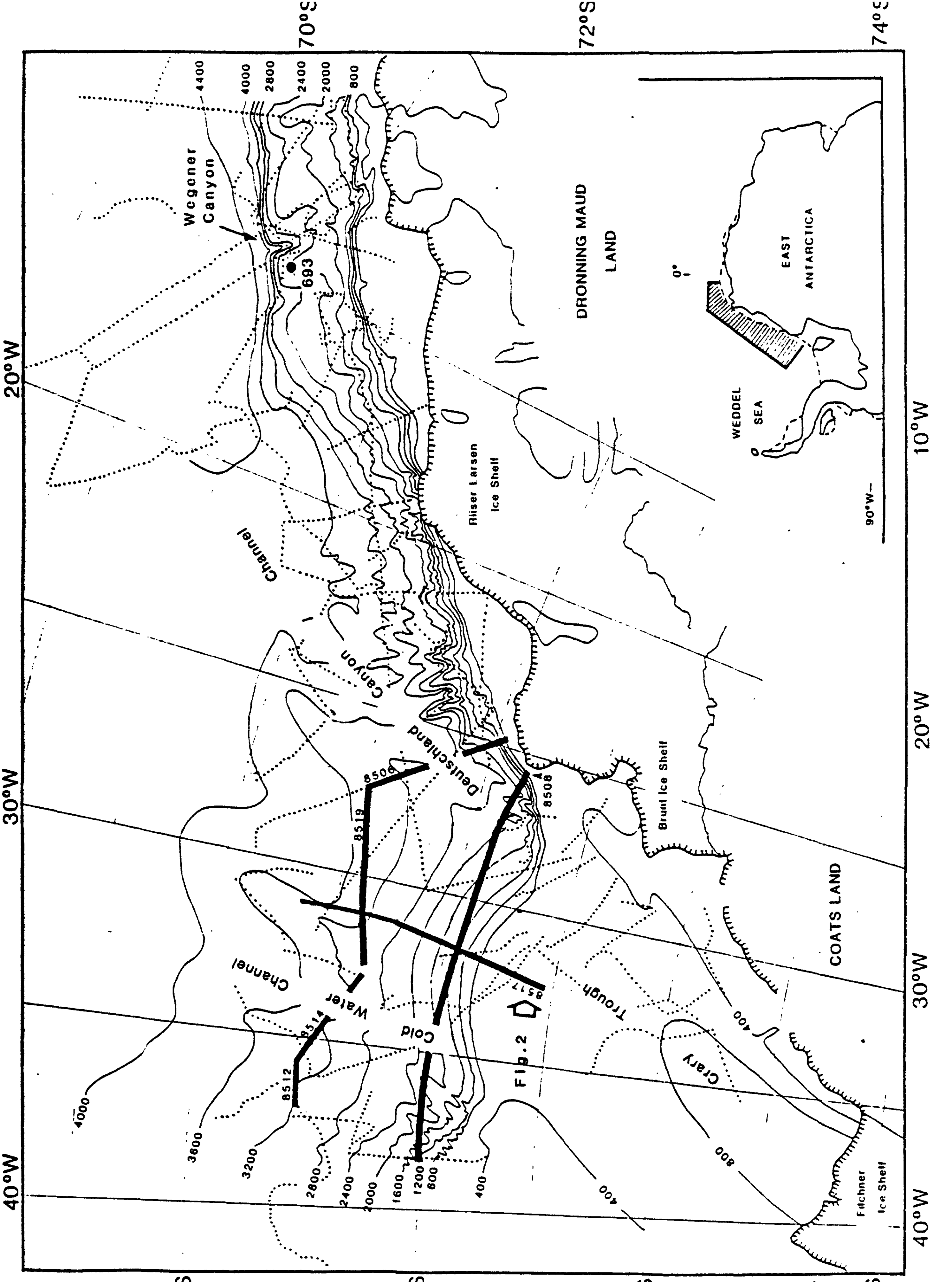
Through the exchange of data with the Russian group at VNI-IOKEANGEOLOGIA in Leningrad, we have also made a preliminary study of the deep sea sediments in Prydz Bay. The seismic profiles in this area suggest that a large, submarine fan also is deposited in this area. Comparison with the Weddell Sea data suggest that the Prydz Bay channels are similar sizes or maybe even larger. The seismic reflection pattern suggest large amounts of fine grained material and point to drainage from predominantly wet based glaciers.

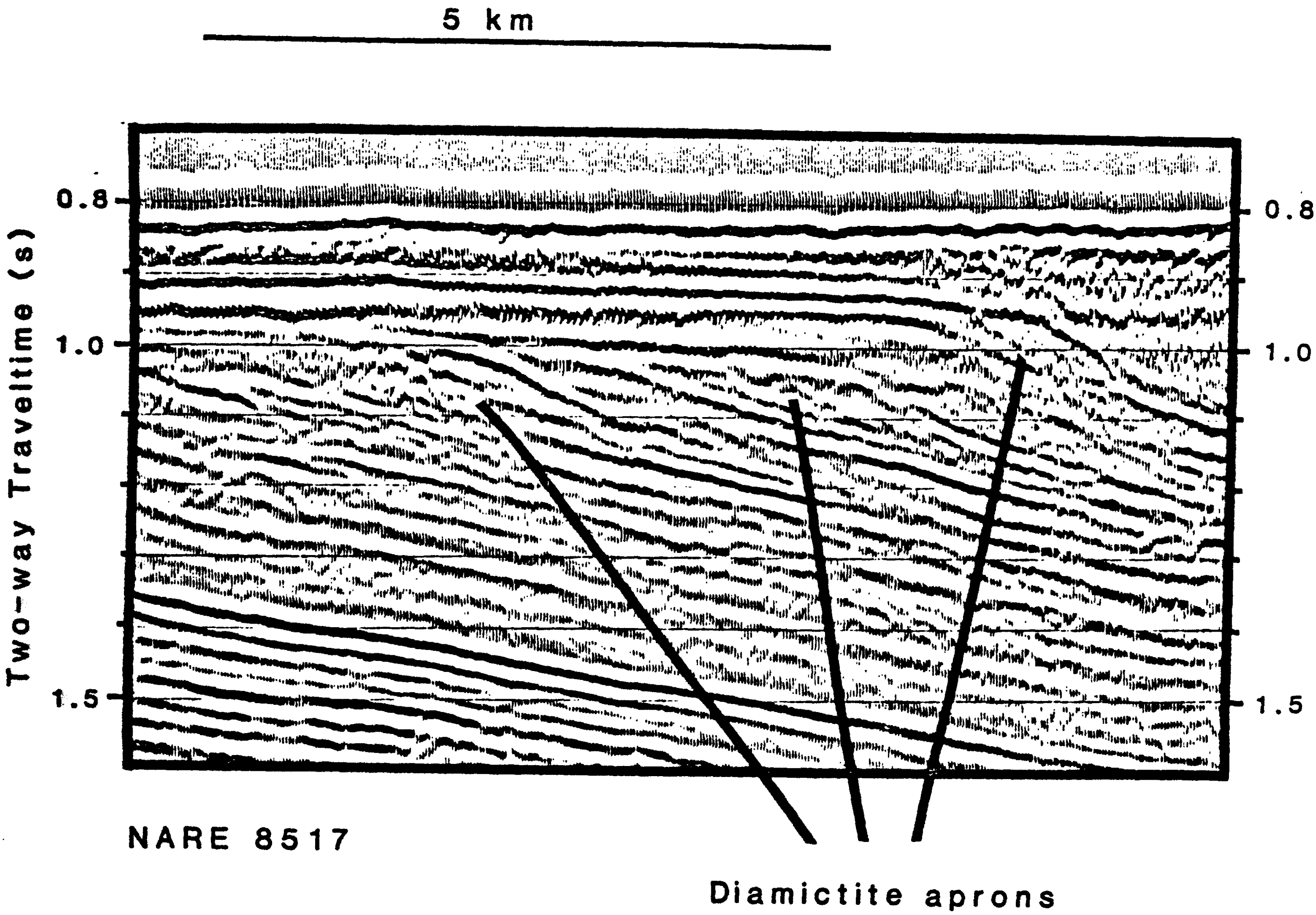
Figure captions:

Fig.1 Bathymetry of the southeastern Weddell Sea with locations of multichannel seismic lines (dotted and heavy lines). Heavy lines indicate profiles illustrated as line drawings in Fig.3.

Fig.2 Seismic profile NARE 8517 illustrating diamictite aprons located at the ancient shelf edges. Profile location is shown on Fig.1.

Fig.3 Cartoon showing interpreted hierarchy of channel-levee complexes forming the Crary TMF. Arrows indicate direction of levee outbuilding. Profile locations is shown in Fig.1.


Wegener Canyon
693
DRONNING MAUD LAND
EAST ANTARCTICA
WEDDEL SEA
0°
90°W
Riiser Larsen Ice Shelf
Deutschland Canyon Channel
Brunt Ice Shelf
COATS LAND
Cold Water Channel
Crary Trough
Fig. 2
Filchner Ice Shelf
8506
8519
8508
8517
8514
8512
4400
4000
3600
3200
2800
2600
2400
2000
1600
1200
800
600
400
70°S
72°S
74°S
76°S
78°S
10°W
20°W
30°W
40°W



5 km
0.8
1.0
1.5
Two-way Traveltime (s)
NARE 8517
Diamictite aprons

Fig. 2.

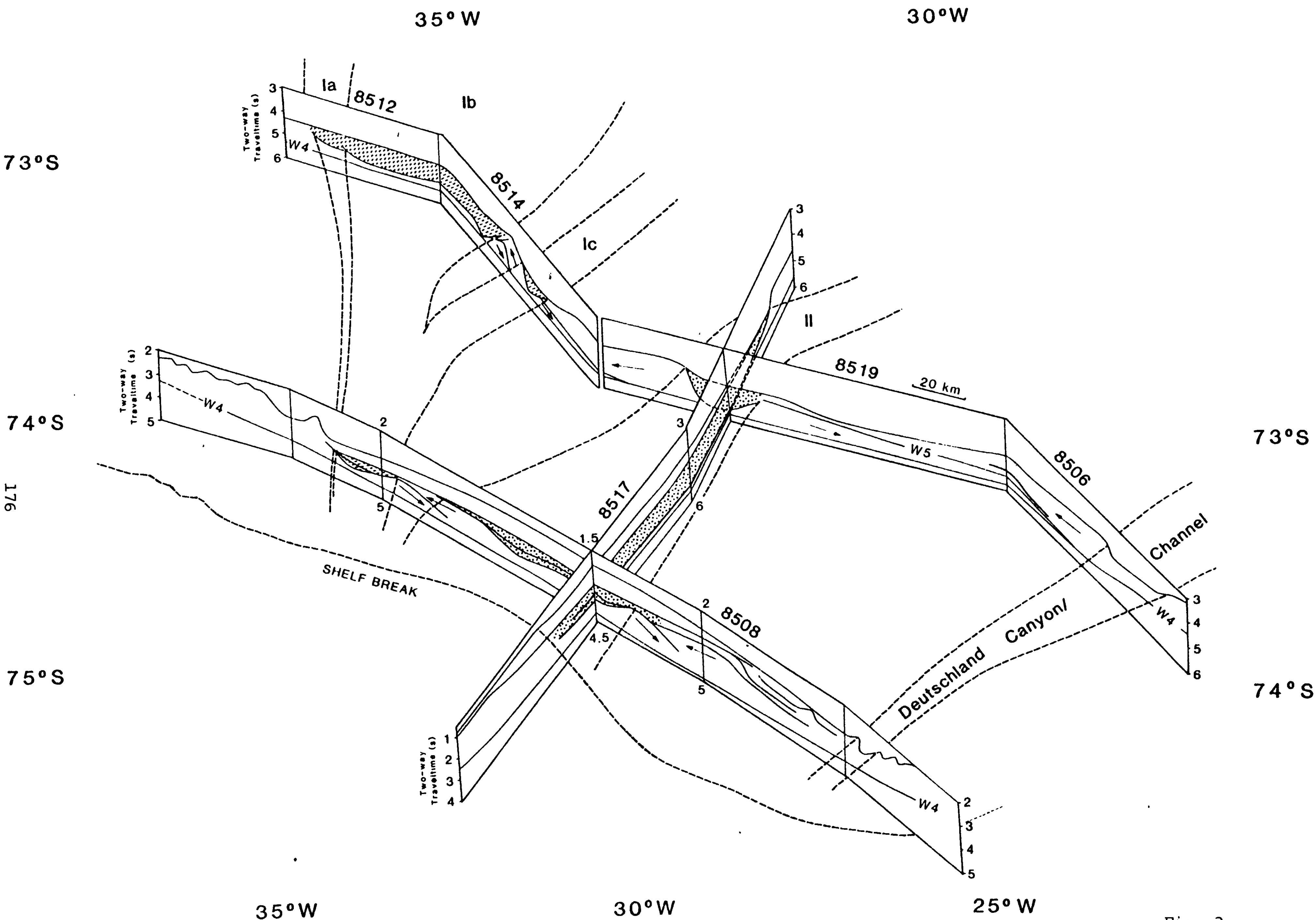

35°W
30°W
73°S
74°S
75°S
73°S
74°S
35°W
30°W
25°W
Ia
Ib
Ic
II
8512
8514
8519
8506
8517
8508
20 km
W4
W5
Two-way Traveltime (s)
SHELF BREAK
Deutschland Canyon/ Channel

Fig. 3.

Antarctic Peninsula Pacific margin: Neogene interaction of tectonic and glacial processes

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The Antarctic Peninsula was a magmatic arc subducting Pacific Ocean floor throughout the Mesozoic. During the Cenozoic, subduction ceased at each of a series of ridge crest-trench collisions which migrated NE along the margin. Multichannel seismic profiles across the Pacific margin of the Antarctic Peninsula show evidence of post-collision uplift, followed by subsidence. During Pliocene-Pleistocene time, ice sheets have grounded out to the shelf edge at times of glacial maximum, transporting sediment which has extended the outer shelf. Similar groundings have probably occurred on most Antarctic margins, but the depositional record is particularly well preserved at this margin because of syn-depositional subsidence. Hence there is an opportunity to examine in detail the hypothesised relationship between fluctuations in ice volume and the low-latitude record of global sea-level change.

Throughout the series of ridge crest-trench (RC-T) collisions (Barker, 1982), the trailing flank of the ridge crest and the overriding lithosphere at the trench were both part of the Antarctic plate (Fig. 1). Thus, in each collision zone, sea floor spreading and subduction both stopped at the time of collision, and the margin became passive. This makes it possible to determine collision ages fairly precisely, from marine magnetic anomaly identifications close to the margin (Fig. 2). Theoretical models predict that thermal uplift of the forearc, followed by subsidence, should result from RC-T collision (DeLong et al., 1978, 1979).

All multichannel seismic (MCS) reflection profiles crossing the continental margin between the Adelaide FZ and C FZ (Fig. 2) show the same 3 main geological provinces on the middle and outer shelf: a prograded outer shelf is separated from a mid-shelf sedimentary basin by a structural high (the 'Mid Shelf High' or 'MSH'). On all profiles the continental slope is unusually smooth and steep, and clearly has been constructed by depositional processes associated with progradation of the outer shelf (Larter & Barker, 1989 and in press). Mid-slope (1000 - 2000 m) angles range from 13° to 17°.

Beneath the outer shelf and slope between the projected lines of the South Anvers FZ and C FZ (Fig. 2), 6 major sequences or sequence groups (S1-S6) have been identified. In the same area 4 principal sequences (D1-D4) have been recognised within the sedimentary pile overlying oceanic basement on the continental rise. On 2 margin crossing profiles (Fig. 3a,b) changes in relative erosion level (REL) have been determined from the outer shelf sequences and crude chronostratigraphic control has been derived by correlation to oceanic basement of age known from marine magnetic anomalies.

MCS Profile AMG 845-08 (Fig. 3b) crosses the part of the margin where RC-T collision took place 10.0 Ma ago, whereas collision occurred only 5.6 Ma ago where Profile AMG 845-07 (Fig. 3a) crosses the margin. The seismic stratigraphy of each of these profiles reveals changes in REL after the local RC-T collisions which are much larger than the changes generally attributed to eustatic sea-level fluctuations. On Profile AMG 845-08 the S4/S3 sequence boundary represents a drop in REL of at least 350 m, and onlap at the base of S3 indicates a rise in REL of over 400 m during the deposition of the first part of this sequence. The S4/S3 sequence boundary can be followed beneath the continental slope and is interpreted to correlate with the D3/D2 boundary on the continental rise, indicating that sequences S3-S1 are younger than the oceanic basement near the margin which was generated at the time of RC-T collision (10.0 Ma). REL changes of similar magnitude are indicated by the interpretation of Profile AMG 845-07 (Fig. 3a), but in this case the major drop in REL occurred at the S3/S2 sequence boundary (MCS Profile AMG 845-10 intersects AMG 845-07 and AMG 845-08, and allows direct correlation between the outer shelf sequences on these two profiles). Once again, this sequence boundary can be followed beneath the continental slope into continental rise sediments, demonstrating that S2 and S1 are less than 5.6 Ma old. The magnitude of the drop and subsequent rise in REL on these 2 profiles, and the time of these changes relative to RC-T collision, suggest that they result from tectonic uplift and later subsidence, as predicted by theoretical models. In this usage the term 'tectonic' encompasses local vertical motion of a depositional surface due to a variety of causes (thermal effects, isostatic compensation, lithospheric flexure, compaction of underlying sequences etc.).

DSDP Site 325 was drilled on the central continental rise, opposite the part of the margin where RC-T collision took place about 16.5 Ma ago. The hole was spot cored, but the biostratigraphy of these cores adequately defines the major variations in sedimentation rate (Hollister, Craddock et al., 1976). The recovered sediments have a high terrigenous component (turbidite and ice-rafted), so the severely reduced sedimentation rate from 15 Ma ago until 8 Ma ago (or later) implies a reduction or cessation in the supply of terrigenous sediment.

MCS Profile BAS 878-19 (Fig. 3c) crosses the part of the margin where RC-T collision took place 16.5 Ma ago, and continues across the continental rise to DSDP Site 325 (Fig. 2). The period of low sedimentation rate identified at Site 325 is thought to correlate with the AD4/AD3 sequence boundary. This sequence boundary can be traced to the margin and is interpreted to correlate with the A4/A3 sequence boundary on the outer shelf. In terms of its position, its character, the character of the sequences above and below it, and the age of the youngest sediments below it relative to RC-T collision, the A4/A3 sequence boundary is similar to the post-collision uplift-related sequence boundaries identified on Profiles AMG 845-07 and AMG 845-08, and is interpreted to be of similar origin. The total REL rise since the start of deposition of A3 is estimated to be about 1.3 km, indicating that a large amount of subsidence has taken place since maximum uplift.

On every MCS profile crossing the margin SW of the C Fracture Zone, similar outer shelf and slope sequences which record similar, albeit diachronous, histories of vertical motion are observed. Following RC-T collision, uplift of the continental shelf, centred on the MSH, appears to cut off the supply of terrigenous sediment to the margin. A few million years after collision, uplift ends and a long period of subsidence begins.

This cycle of uplift and subsidence resulting from RC-T collision is of similar wavelength to the second order eustatic sea-level cycles proposed by Vail et al. (1977), but is of much greater amplitude (Fig. 4). The third order cycles of Vail et al. (1977), which were revised by Haq et al. (1987), are of similar amplitude to the second order ones, but of much shorter wavelength. Thus the steady subsidence following maximum uplift should preserve an excellent record of third order cycles and, perhaps, even shorter-period fluctuations.

On MCS Profiles AMG 845-07 and AMG 845-08 (Fig. 3a,b) 8 distinct oblique progradational sequences are identified within sequence groups S1 and S2. They are characterised by steeply dipping foresets and a depocentre on the upper continental slope, so that the slope has advanced oceanward and steepened with time. Several lines of evidence suggest that these sequences have been produced by the action of grounded ice sheets:

1. Water depth (~450 m) - too great for unconformities to have been produced by Pliocene-Pleistocene lowstands of sea-level.
2. The shelf becomes steadily shallower towards the shelf break (as would be expected from erosion beneath a grounded ice sheet that thickened inshore).
3. Steepness and stability of the continental slope. Deposition of typical low-latitude shelf and slope sediment facies would not generate or sustain such a uniformly steep continental slope, but deposition of glacial marine diamictons might.
4. Seismic velocities greater than 2000 m/s a few metres beneath the sea bed, suggesting overcompaction.

Supporting evidence of recent ice-sheet striation of the sea bed on the continental shelf comes from sidescan sonar and 3.5 kHz profiles.

The proposed model for the origin of these sequences is illustrated in Fig. 5 by four key stages in the development of a single sequence. During an interglacial, an intergrounding subsequence (IGS) of unconsolidated glacial marine and pelagic sediment would be deposited on the shelf and slope (Fig. 5a). At some stage during the next cooling an advancing ice sheet would ground on the shelf (Fig. 5b). The grounded ice sheet might erode part of the IGS or deposit (and consolidate) a basal till above it. More certainly, it would transport unsorted material in a basal debris zone to the shelf edge and upper slope to form the grounding subsequence (GS), steepening the slope (Fig. 5c). A sequence begins and ends at the start of a glacial recession with the floating of a previously grounded ice sheet (Fig. 5d).

Change in the volume of continental ice is the most popular explanation for the global sea-level fluctuations which have been deduced from sequence stratigraphy (Vail et al., 1977; Beard, et al., 1982). If this is correct, high-latitude and low-latitude sequences should be approximately in phase. The global cycle chart of Haq et al. (1987) shows 7 sequences in the last 6 Ma. On the Pacific margin of the Antarctic Peninsula we have identified 8 sequences that we are confident have been deposited in the last 6 Ma or less. Additionally, we recognise that the seismic evidence of some ice advances has probably been removed by later ice sheets which eroded all the intervening topset deposits, merging the adjacent sequences into one.

Oxygen isotope studies on deep sea cores indicate that major climatic fluctuations have occurred over much shorter periods than hypothesised by sequence stratigraphers, at least during the last 700 ka (e.g. Shackleton, 1987). It is most likely that seismic stratigraphic investigations on both high- and low-latitude margins have aliased a climatic signal which in part is beyond the resolution of the method. Support for this view comes from recent detailed studies of well logs, cores and outcrops in parts of the USA (e.g. Van Wagoner & Mitchum, 1989).

Direct correlation between the Antarctic Peninsula sequences and those on low latitude margins, or with the oxygen isotope curve (e.g. Miller et al., 1987), will require detailed stratigraphic data which can only be obtained by drilling. Drilling of the outer shelf sequences, together with high resolution seismic profiling, would make possible a detailed study of the interaction between ice volume fluctuations and global sea-level change.

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FIGURE CAPTIONS

Figure 1. Reconstruction of the SE Pacific 20 Ma ago, in the Antarctic reference frame. South American-Antarctic rotation parameters from Barker and Lawver (1988).

Figure 2. Tectonic interpretation of the area to the W of the Antarctic Peninsula based on marine magnetic and bathymetric data (Larter and Barker, in press). Locations of multichannel seismic reflections profiles discussed in text also shown, with parts of profiles used in Figure 3 shown by thicker lines.

Figure 3. Line drawings of multichannel seismic reflection profiles located in Figure 2. a: AMG 845-07. b: AMG 845-08. c: BAS 878-19.

Figure 4. Schematic diagram showing the interpreted temporal relations between ridge crest-trench collision, uplift and supply of terrigenous sediment to the margin. Portions of the 'long term' (second order) and 'short term' (third order) eustatic sea-level curves of Haq et al. (1987) are shown at the same scale for comparison, together with a crude representation of the much more rapid sea-level fluctuations proposed by oxygen isotope workers.

Figure 5. Model for development of a single glacial margin sequence. a: Early stage of ice sheet advance; intergrounding subsequence (IGS) is being deposited on shelf and slope. b: Initial grounding. c: Glacial maximum; ice sheet is eroding and compacting shelf and is depositing grounding subsequence (GS) on slope. d: Early stage of glacial retreat; hiatus on outer shelf has ended and deposition of next IGS has begun.

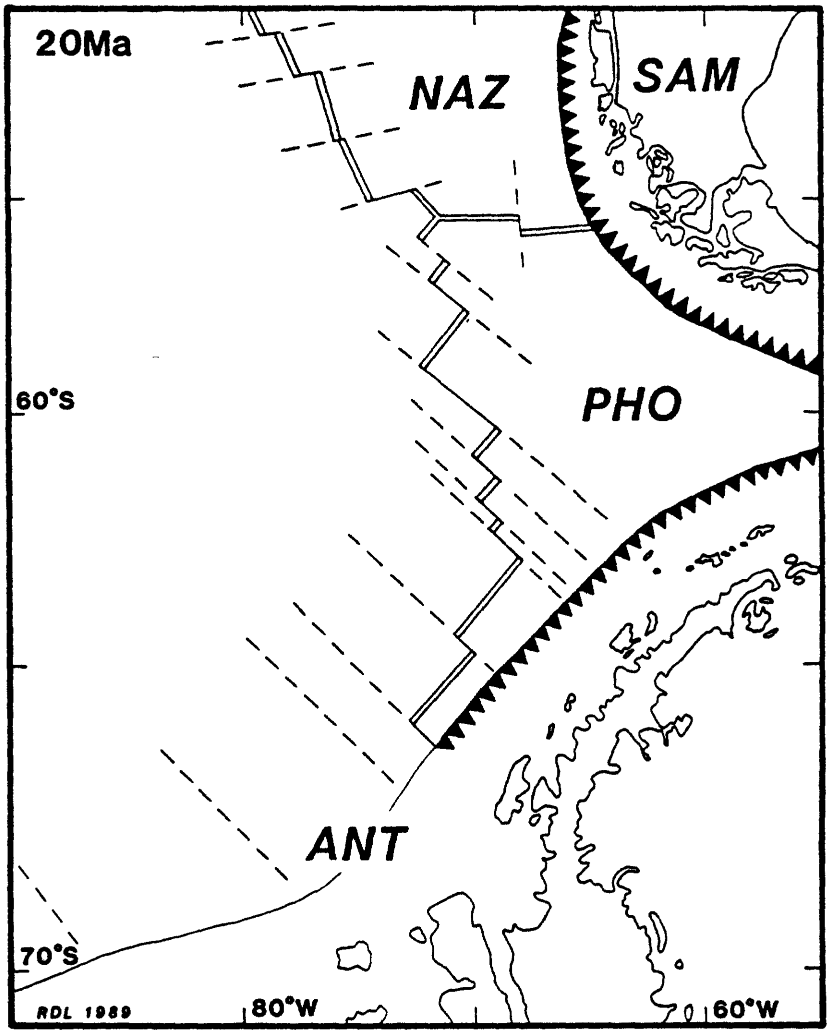


Figure 1

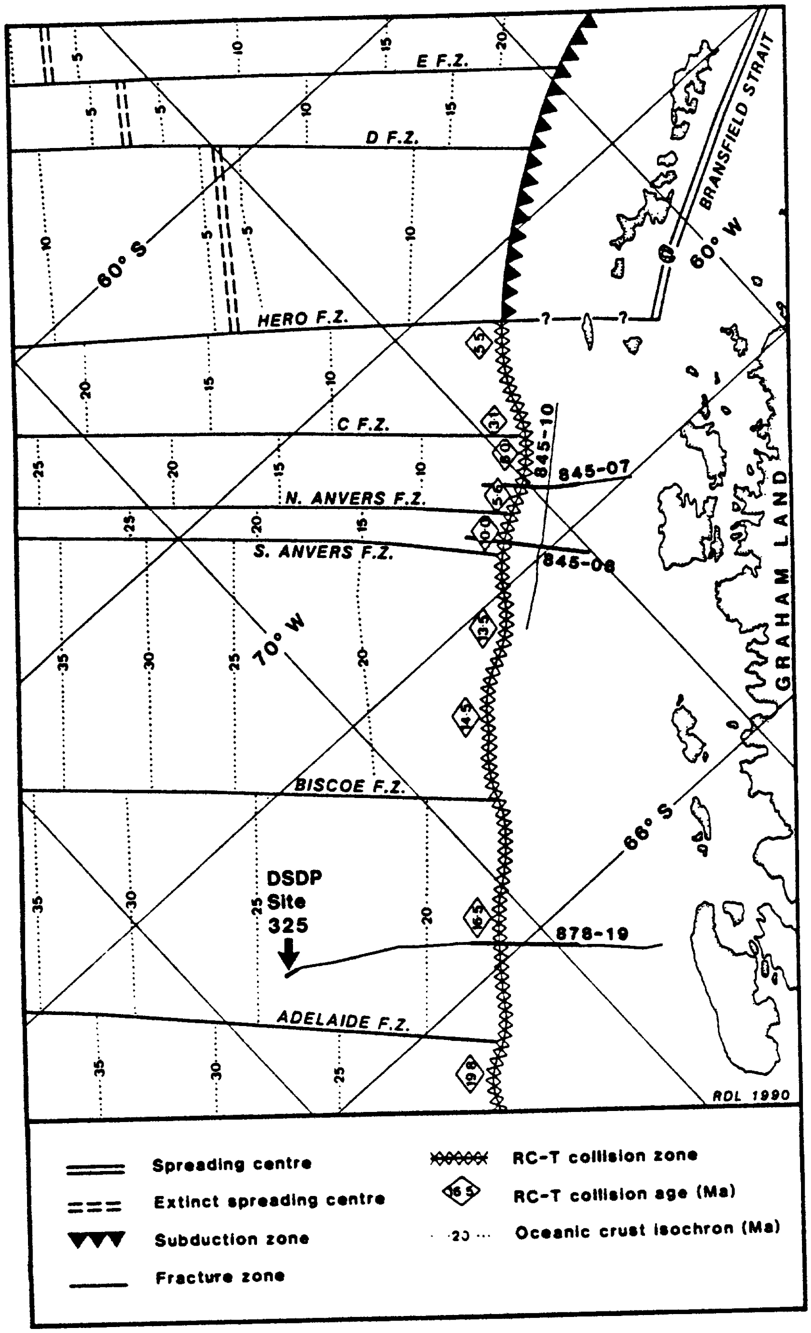

E F.Z.
D F.Z.
HERO F.Z.
C F.Z.
N. ANVERS F.Z.
S. ANVERS F.Z.
BISCOE F.Z.
ADELAIDE F.Z.
60° S
60° W
70° W
66° S
BRANSFIELD STRAIT
GRAHAM LAND
845-10
845-07
845-08
878-19
DSDP
Site
325
RDL 1990
Spreading centre
Extinct spreading centre
Subduction zone
Fracture zone
RC-T collision zone
RC-T collision age (Ma)
Oceanic crust isochron (Ma)

Figure 2

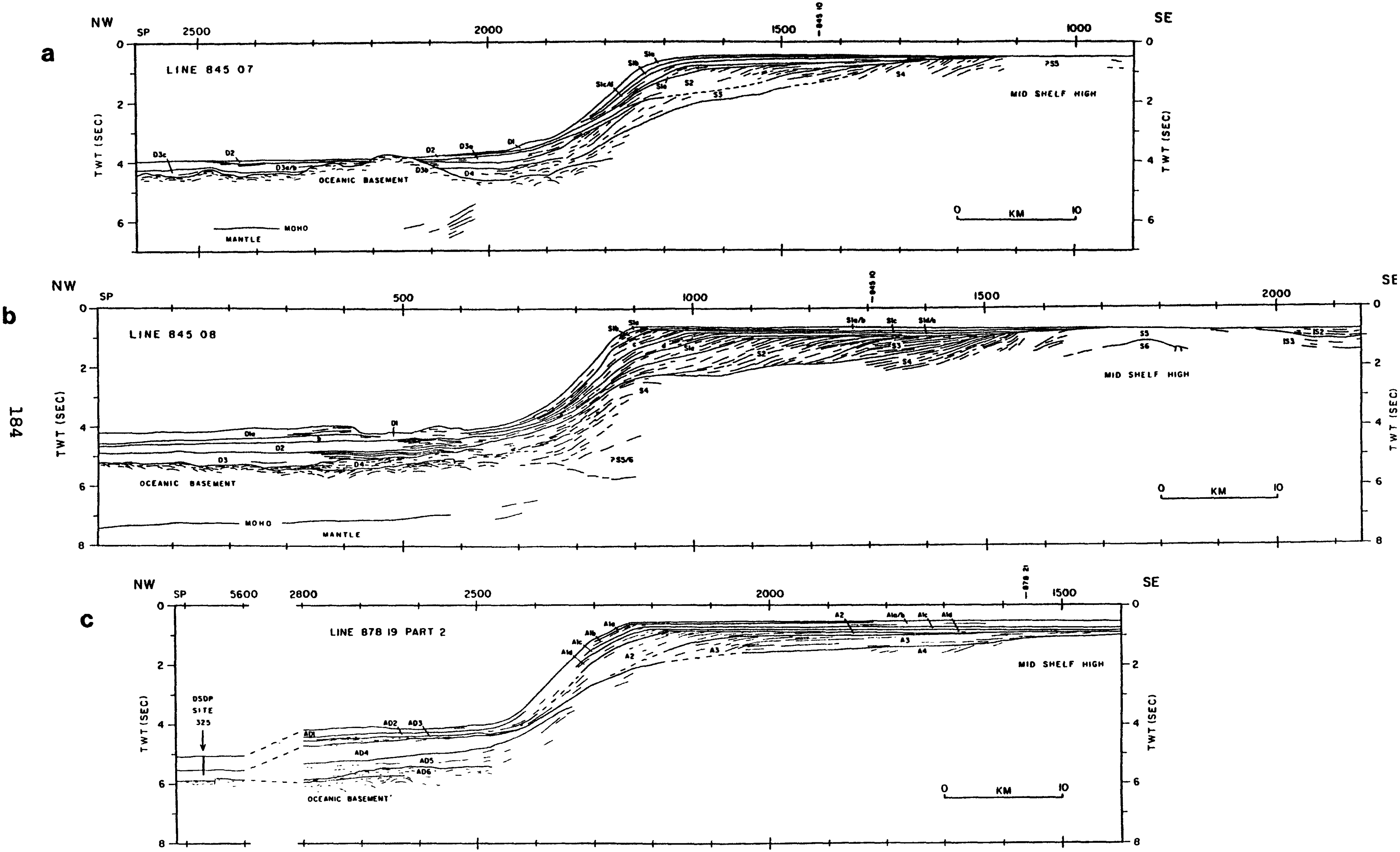
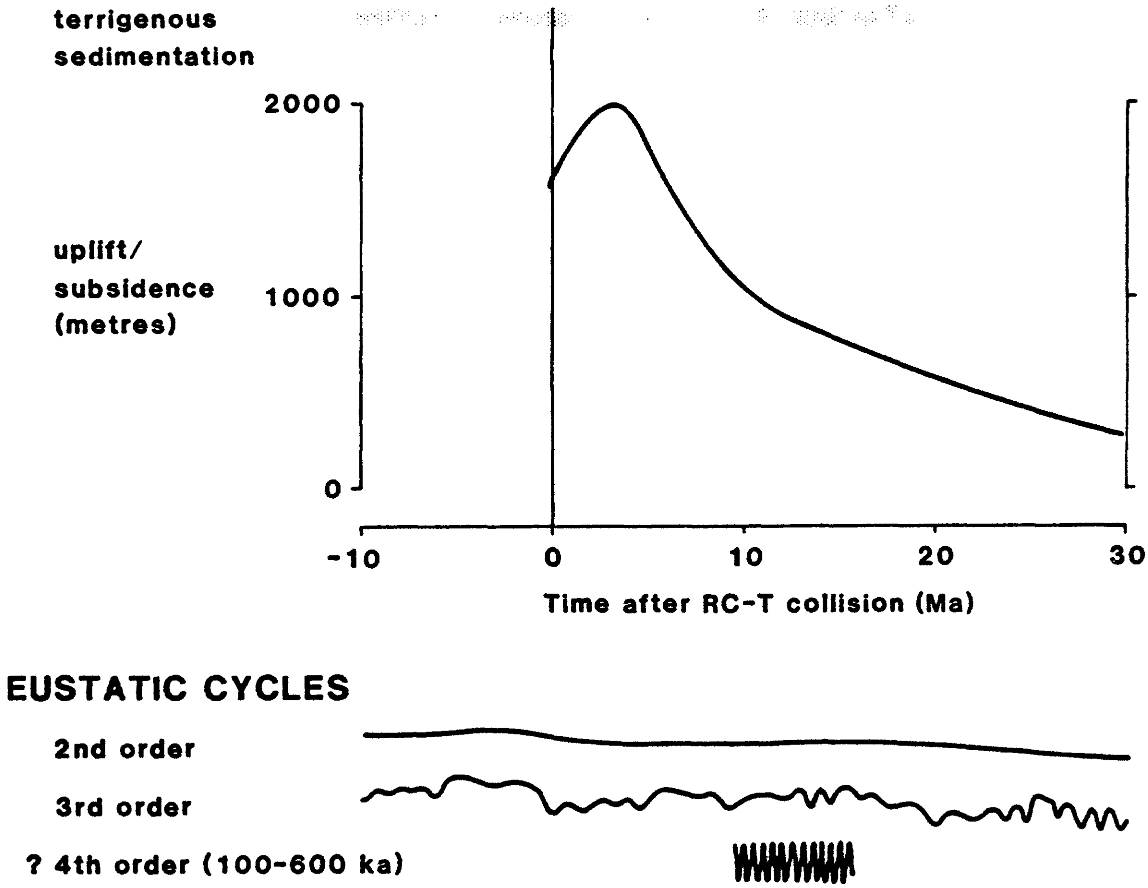

a
LINE 845 07
NW
SE
SP
2500
2000
1500
1000
TWT (SEC)
MID SHELF HIGH
OCEANIC BASEMENT
MOHO
MANTLE
KM
b
LINE 845 08
500
MID SHELF HIGH
OCEANIC BASEMENT
MOHO
MANTLE
c
LINE 878 19 PART 2
5600
2800
DSDP
SITE
325
MID SHELF HIGH
OCEANIC BASEMENT

Figure 3



terrigenous sedimentation
uplift/ subsidence (metres)
2000
1000
0
-10
0
10
20
30
Time after RC-T collision (Ma)
EUSTATIC CYCLES
2nd order
3rd order
? 4th order (100-600 ka)

Figure 4

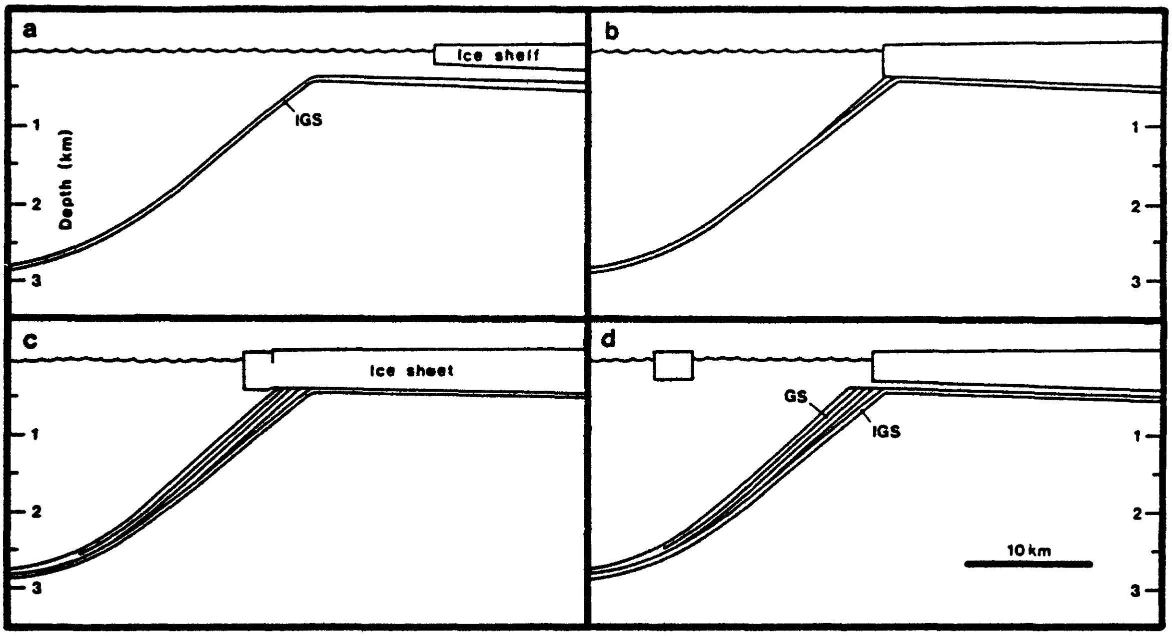

a
Ice shelf
IGS
1
2
3
Depth (km)
b
1
2
3
c
Ice sheet
1
2
3
d
GS
IGS
1
2
3
10 km

Figure 5

The sea-floor multiple problem in multichannel seismic reflection data acquired on the Antarctic continental shelf: its causes and treatment.

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Severe sea-floor multiple reverberation is an almost universal feature of multichannel seismic reflection data acquired on the Antarctic continental shelf. Predictive deconvolution and common mid point stacking, which in general adequately suppress multiple energy in data from other continental shelves, leave significant residual multiple energy in most Antarctic shelf data. The origins of this problem can be traced to the fact that ice sheets have grounded across most, perhaps all, of the Antarctic shelf during Pliocene-Pleistocene glacial maxima. Grounded ice sheets have overdeepened the shelf, deposited glacimarine sediments on the outer shelf and slope, and compacted these same sediments by glacial loading. Each of these processes contributes to the multiple problem. An approach to processing Antarctic continental shelf data adapting conventional techniques is described. This approach is effective on data acquired using a 'standard' exploration geometry (aperture:2350 metres). However, it leaves an unsatisfactory amount of residual multiple energy in data acquired using an aperture of only 750 metres, and in this case more sophisticated multiple suppression techniques are required.

Severe sea-floor multiple reverberation occurs in multichannel seismic reflection data acquired in Prydz Bay (Stagg, 1985), in the Ross Sea (Cooper, Davey and Behrendt, 1987), and on the Wilkes Land (Eittreim and Smith, 1987) and Antarctic Peninsula margins (Larter and Barker, 1989 and in press). The water depth on the continental shelf in these areas is mostly in the range 300 - 700 metres, so the sea-floor multiples have a longer period than those apparent in low-latitude continental shelf data. Long predictive deconvolution operators applied before stacking have little effect because sea-floor multiples are not truly periodic, except at very short offsets. Deconvolution after stack is also ineffective because of the phase distortion of the multiples which results from stacking at primary velocities. CMP stacking, normally the most important processing step in suppressing sea floor multiples in continental shelf data, leaves significant residual multiple energy in Antarctic Shelf Data (Fig. 4a).

Several factors which contribute to the severity of the sea-floor multiple problem on the Antarctic continental shelf can be traced to the effects of grounded ice sheets (Fig. 1). Grounded ice sheets are thought to have covered most, if not all, of the Antarctic continental shelf during Pliocene - Pleistocene glacial maxima (Barnes, 1987; Karl, Remnitz and Edwards, 1987; Barron, Larson et al, 1988; Barrett, 1989; Larter and Barker, 1989 and in press).

Erosion by grounded ice has overdeepened the continental shelf. The geophysical

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consequence is a sea-floor multiple series with reduced differential moveout with respect to primary energy. Furthermore there is a loss of energy associated with each reflection the multiple undergoes within the water column attributable to partition of energy at the interface and mode conversion. On shallower continental shelves this contributes to the attenuation of sea-floor multiples. However, Antarctic continental shelf multiples undergo fewer reverberations per unit time and so decay in amplitude more slowly.

Deposition by grounded ice has resulted in characteristic progradational sequences on the outer shelf (Larter and Barker, 1989). Acoustic interfaces that lie within these sedimentary units generally exhibit a low acoustic impedance contrast, and it seems deposition by grounded ice does not generally lead to seismically 'bright' stratigraphy. Progradational foresets on the outer shelf are also steeply dipping (Fig. 4a).

Loading by grounded ice is thought to have resulted in overcompaction of the near-surface sediment, increasing its seismic velocity. Routine velocity analyses carried out on CMP gathers, yield a near-surface velocity typically above 2000 m/s. Refracted arrivals on these same gathers confirm this. The geophysical consequence is a high sea-floor reflection coefficient of approximately 0.3 and a reduction in critical offset.

Dadisman et al. (1987) showed that a partial improvement in multiple suppression may be achieved by the application of a non-linear offset weighting function before stack. Hardy (1990(b)) has proposed a formalised approach to the treatment of long period multiples, which is summarised in Fig. 2. Multiple attenuation methods are arranged in order of cost as follows: stacking techniques, moveout-based techniques, periodicity-based techniques and adaptive modelling techniques. This strategy has the objective of establishing the most cost-effective multiple attenuation technique with a minimum of routine testing. Routine testing suggested stacking techniques may be effective. The effectiveness of moveout-based multiple suppression is dependent on the amount of residual normal moveout across the multiple after correction to primary stacking velocity. Hardy (1990(a)) has found that a residual moveout in excess of 50ms, at the far offset, is needed for moveout based techniques to be effective. This was comparable to the dominant period of the signal.

Stacking and moveout based techniques were applied to data from line AMG 845-08, which crosses the Pacific margin of the Antarctic Peninsula (Fig. 3). This line consists of 24-fold CMP data acquired using a 48 channel streamer with an aperture of 2350 metres. It was found that effective multiple suppression could be achieved by adding the following steps to the processing sequence used to produce Fig. 4a:

1. Application of a pre-stack f-k filter to CMP-gathers corrected to primary stacking velocity, to discriminate against reflections exhibiting residual moveout (multiples).

2. Application of a near-trace mute, starting just before the arrival time of the first sea-floor multiple (multiple energy on the near traces has little differential moveout and thus is relatively unaffected by the f-k filter).

The stack produced using the modified processing sequence (Fig. 4b) shows a near total removal of sea-floor multiples.

The same approach has been applied to data acquired using a 16 channel steamer with an aperture of 750 metres. In this case only partial multiple suppression was achieved. Further enhancement of these data will require application of more sophisicated and expensive techniques such as wave equation modelling and subtraction or adaptive deconvolution.

In conclusion, the severe sea-floor multiple reverberation in Antarctic continental shelf data results from erosion, deposition and loading of the shelf by grounded ice. For 'standard' broad aperture multichannel data these multiples can be effectively suppressed by addition of a pre-stack f-k filter and near-trace mute to a conventional processing sequence. However, data acquired without a large range of offsets, or without the signal-to-noise benefits of a high-fold stack, require the application of more sophisticated multiple attenuation techniques.

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Figure captions.

Figure 1. The geological and geophysical implications of grounded ice.

Figure 2. A strategy for long period multiple suppression (after Hardy, 1990(a)).

Figure 3. Locations of R.R.S. Discovery cruise 154 multichannel seismic lines. The thickened portion of seismic line AMG 845-08 indicates the position of the data shown in figures 4(a) and 4(b).

Figure 4.

(a) CMP stacked time section of a subset of multichannel seismic line AMG 845-08 after conventional processing.

(b) CMP stacked time section of a subset of multichannel seismic line AMG 845-08 after processing which includes a pre-stack f-k filter and near-trace mute.

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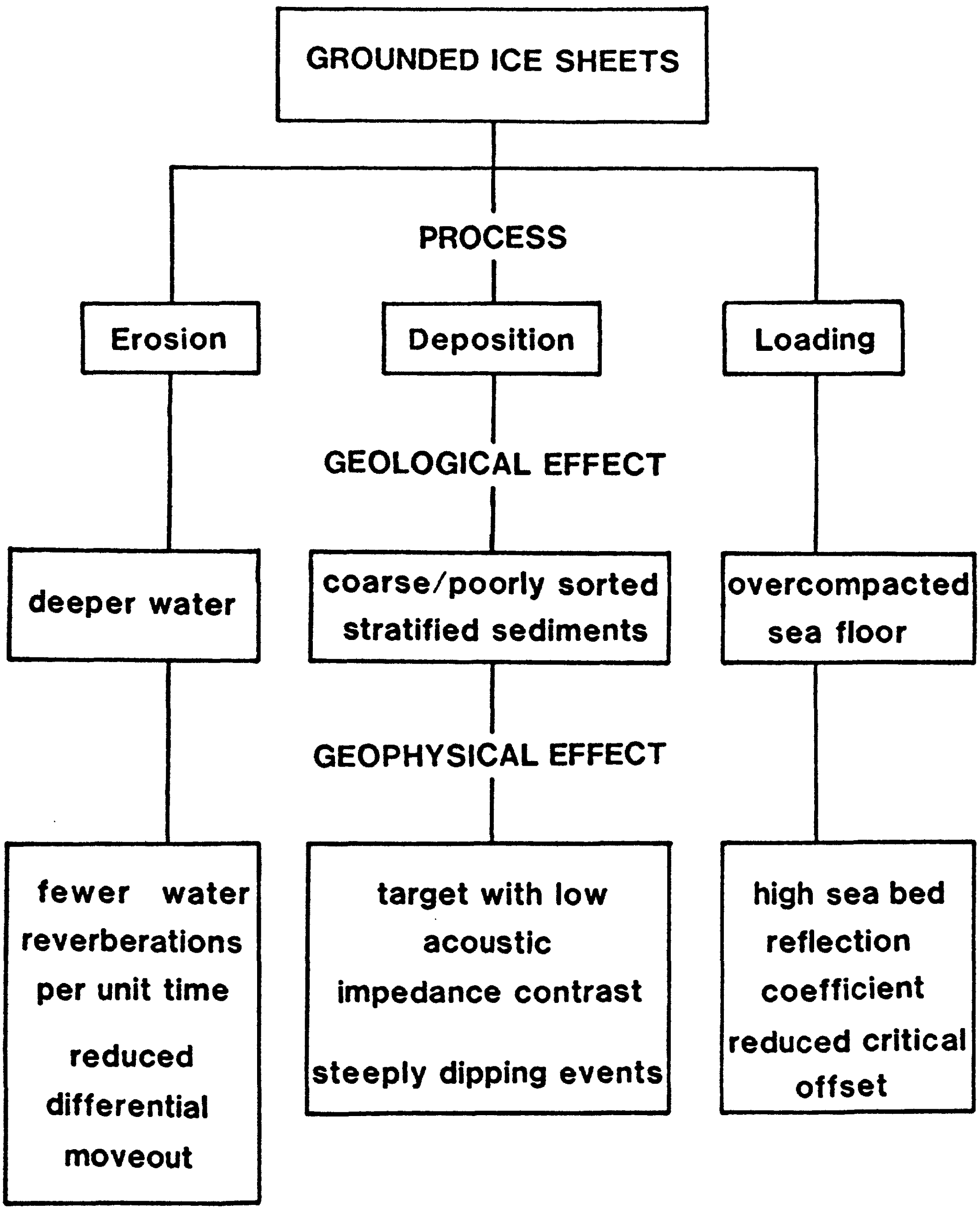
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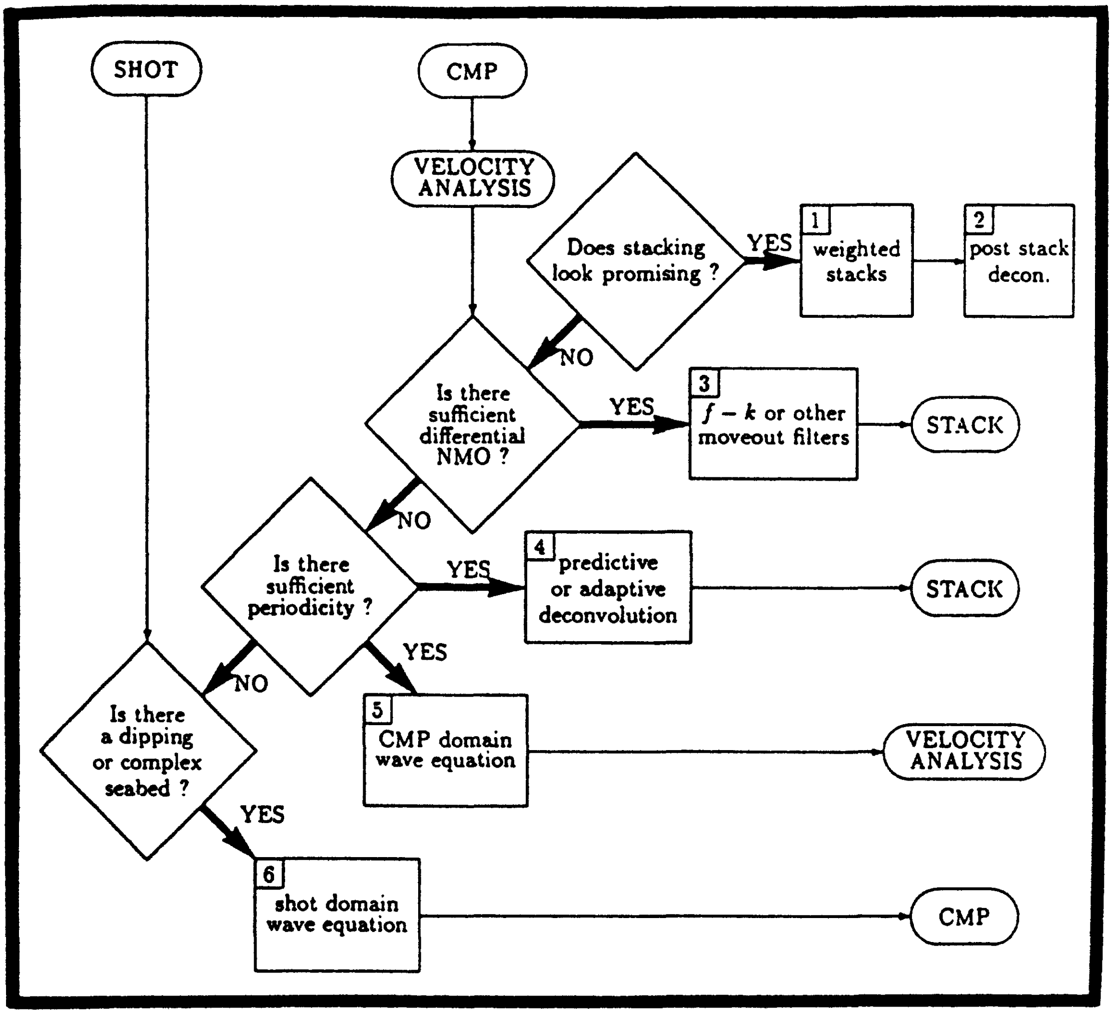
reduced differential moveout
target with low acoustic impedance contrast
steeply dipping events
high sea bed reflection coefficient
reduced critical offset

2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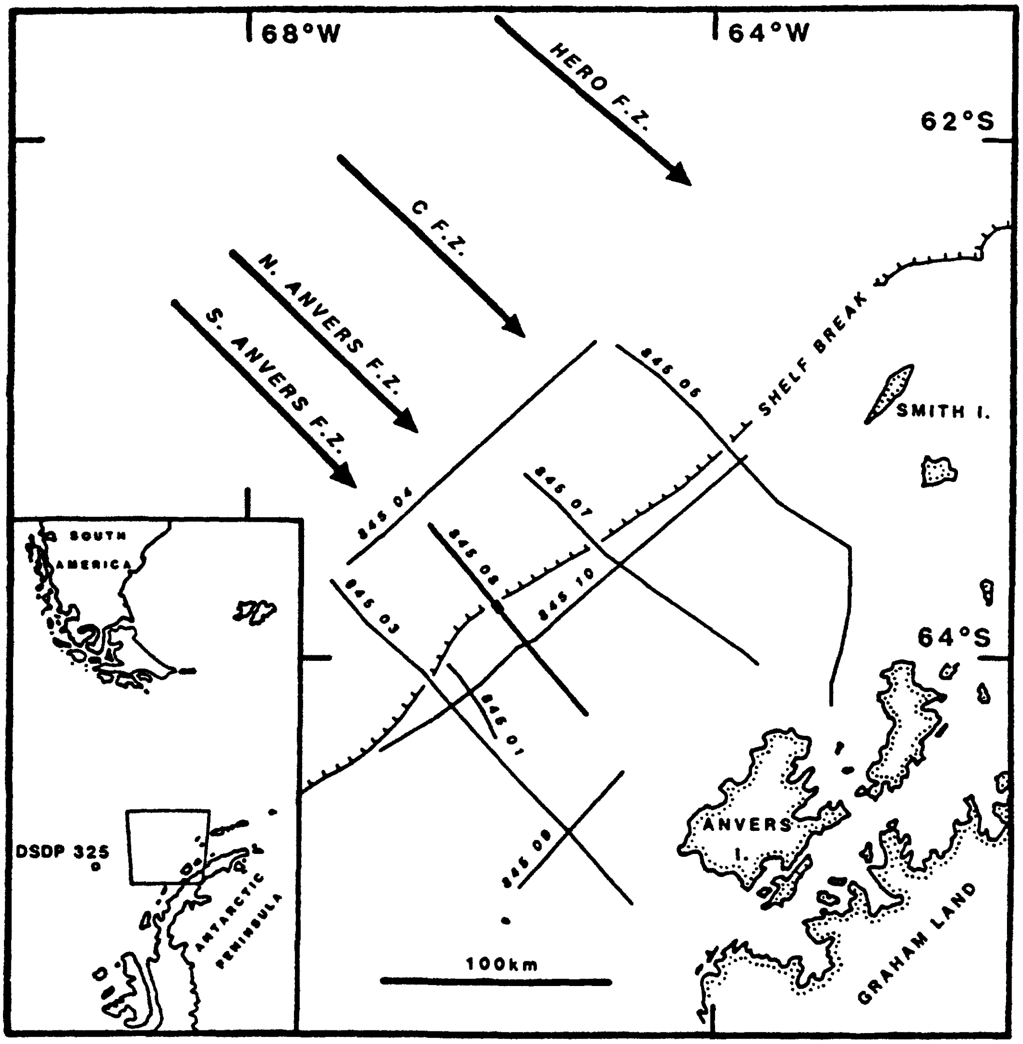
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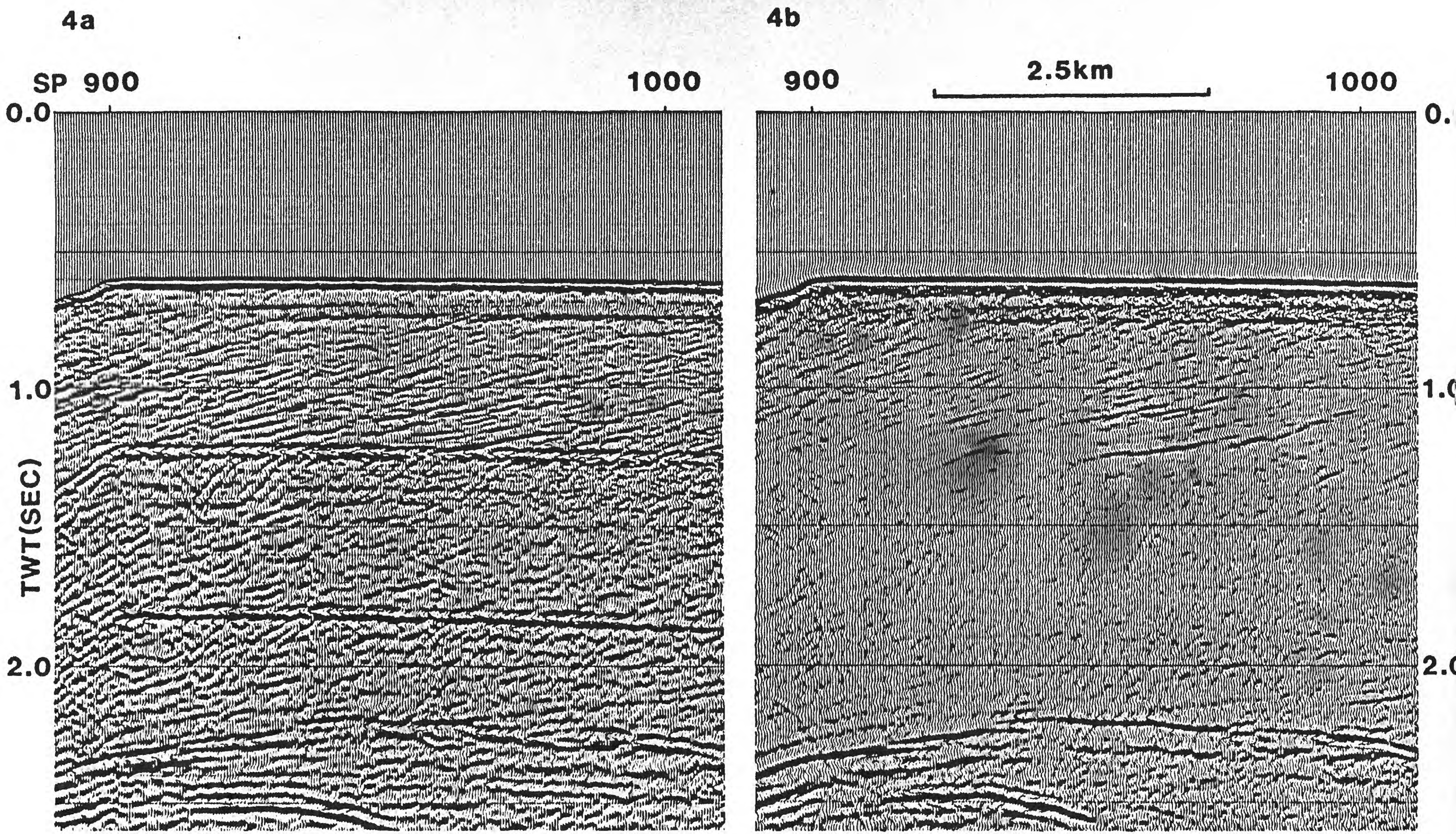
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MESOZOIC TO RECENT EVOLUTION OF THE ANTARCTIC CONTINENTAL MARGIN

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The Antarctic continental margin has evolved through time. Our first phase in the break-up involves stretching between East and West Gondwanaland. Battail *et al.*(1987) contend that Madagascar was cut from Africa by a marine barrier during the Late Permian and Early Triassic while Reeves *et al.* (1987) assert that although rifting was initiated, possibly as early as the beginning of the Karoo (late Carboniferous), that there were only slight marine transgressions, represented by minor evaporite horizons until the onset of marine conditions encroached from the north at about 200 Ma. We assume that continental stretching between East and West Gondwanaland may have begun as early as 240 Ma and produced the Late Triassic marine incursion between Madagascar and Africa, which in turn marked the beginning of the Early Mesozoic fragmentation of Gondwanaland. The sediment-filled Anza Trough in Kenya represents the failed third arm of an aulacogen and was subjected to an extensive marine transgression during the Upper Jurassic (Reeves *et al.*, 1987). This first phase of break-up produced the seaward dipping reflectors found off the Explora Coast of East Antarctica by Hinz and Krause (1982) and the Mozambique Ridge. During it, Madagascar moved away out of its tight fit position with the Somali Coast of Africa. This initial phase of stretching also resulted in North New Zealand moving away from Australia and allows for a reasonable match to the present day fit of Lord Howe Rise with North New Zealand. In previous reconstructions, if the semi-continental Lord Howe Rise was assumed to have been firmly attached to North New Zealand and was also reconstructed with Australia following the marine magnetic anomalies in the Tasman Sea, then an unexceptable overlap was produced with North New Zealand on top of the continental Campbell Plateau. It appears that the first phase of stretching involved Africa, South America, West Antarctica, and the pieces of New Zealand as West Gondwanaland, while East Gondwanaland consisted of Madagascar, India, Australia, Lord Howe Rise and East Antarctica. In Middle Jurassic, this first phase of stretching produced the widespread Ferrar and Karoo basaltic volcanism of Antarctica and Africa as well as the Jurassic silicic volcanism in southern South America.

The second phase of break-up inaugurated true seafloor spreading along the zone of weakness produced by the first phase of stretching and included the formation of the back-arc Rocas Verdes Basin in the southern Andes which may have extended towards the Ross Sea region separating East and West Antarctica. The second phase was dominated by strike-slip movements, as western Gondwanaland (Africa, South America) separated from eastern Gondwanaland (Madagascar, India, Australia, East Antarctica, Marie Byrd Land, North and South New Zealand) along a series of transform faults that ran parallel to the Davie Ridge, Mozambique escarpment, and Explora escarpment (Dronning Maud Land, East Antarctica). Some translation of the Antarctic Peninsula with respect to the southern margin of South America must have also occurred during this phase of the two-plate break-up (Lawver et al., in press). Seafloor spreading in the Somali Basin can be dated as earliest Late Jurassic, while the conjugate earliest Late Jurassic magnetic anomalies with respect to those found in the Mozambique Basin are located east of the Astrid Ridge at 12°-20° E. The earliest seafloor spreading in the present day southwestern Weddell Sea probably occurred contemporaneously with the spreading in the Somali and Mozambique Basins and resulted in the rotation and possibly the translation of a West Antarctic block that consisted of the Antarctic Peninsula, the Ellsworth and Whitmore Mountains and possibly Thurston Island. Some additional stretching of the continental crust between the Antarctic Peninsula and the Ellsworth and Whitmore Mountains may have occurred at this time as well.

With the beginning of opening of the South Atlantic at approximately M10 time [132 Ma], the simple two plate break-up of Gondwanaland developed into a three plate problem with the separation of South America from Africa. At roughly the same time, 'Greater India' began to separate from the west coast of Australia while the next phase at M4 time [125 Ma] involved the rifting of 'Lesser India' from Antarctica. Greater India included the continental material that has been thrust under South Tibet to produce the uplifted Tibetan Plateau. The rifting of Lesser India from Antarctica may have begun in the west when the Africa-Antarctica spreading center became aligned with what is now the Straits of Mannar and produced the initial rift between Sri Lanka and India. That first rift failed, then jumped to the south of Sri Lanka and succeeded in detaching Sri Lanka/India from Enderby Land, East Antarctica. Alternatively, the rift between India and Antarctica may have also begun in the east and propagated westward when the rifting of northern Greater India shifted to include Lesser India at about anomaly M5 time (128 Ma).

Thurston Island had probably coalesced with the Antarctic Peninsula by this time based on the prelimnary paleomagnetic results of Anne Grunow (Ohio State) and Dennis Kent (LDGO). The Ellsworth and Whitmore Mountains may have still moved independently of the West Antarctic Peninsula and cratonic East Antarctica simply because there is not sufficient room to fit all the pieces in the available space between Antarctica and South America. West Antarctica with the exception of Marie Byrd Land may have moved as one piece by 110 Ma. Subduction continued along the western margin of the West Antarctic Peninsula.

The stretching between Australia and Antarctica may have begun as early as 156 Ma based on oilfield data from the southern margin of Australia (Bradshaw and Yeung, in preparation), although we show the first detachment of Australia from Antarctica at 130 Ma. The deflection-of-the-vertical or first derivative of the satellite altimetry data from the GEOSAT satellite shows conclusively where Australia fit against Antarctica. Stretching began very slowly but probably accelerated after 110 Ma. Our model has all of the pre-break-up stretching between Australia and Antarctica distributed between 105 Ma and 95 Ma, although there was probably some stretching between 150 Ma and 105 Ma. Actual seafloor spreading started at 95 Ma (Cande and Mutter; 1982) and increased in speed from 4.5 mm/yr between 90 Ma and anomaly 22 (52 Ma) time to 27 mm/yr between 52 Ma to the present.

At roughly the same time (~100 Ma), the Pacific-Aluk(?) spreading center was subducted at a southward dipping subduction zone that ran north of Australia and the various pieces of New Zealand and then along the western margin of the West Antarctic Peninsula. The subduction zone was the Aluk(?)-Antarctic plate boundary and continued to operate off the Antarctic Peninsula until just 5 million years ago. After the Aluk-Pacific spreading center was subducted north of New Zealand, the Pacific-Antarctic spreading center began to propagate westward where it first opened the Bounty Trough which separated the Chatham Rise from the Campbell Plateau at about 90 Ma. This rift failed and the Pacific-Antarctic spreading center then began to rift the Campbell Plateau from Marie Byrd Land, West Antarctica at about 84 Ma. While the spreading between New Zealand and Marie Byrd Land may have extended into the Tasman Sea region, some extension occurred between Marie Byrd Land and the East Antarctic craton, which produced two very complicated triple junctions separating Australia, East Antarctica, Marie Byrd Land and the pieces of New Zealand from each other.

The Tasman Sea continued to open until 56 Ma. The plate circuit for South New Zealand/Campbell Plateau and North New Zealand/Lord Howe Rise assumes that South New Zealand acts as part of the Pacific Plate. The circuit includes seafloor spreading along the Pacific-Antarctic spreading center, an assumed rigid West and East Antarctica, seafloor spreading along the Antarctic-Australia spreading center and seafloor spreading in the Tasman Sea between Australia and the continental Lord Howe Rise. Joann Stock (1989) presented the Cenozoic motion of New Zealand at the IGC and it closely matched our calculations. Comparison of the relative positions of North and South New Zealand between 70 Ma and 40 Ma indicates that they had not really moved with respect to each other. This is remarkable considering the plate circuits that were involved. It gives us confidence that East and West Antarctica were firmly attached to one another and in their present day orientation with each other. Real motion along the Alpine Fault seems to have been initiated after 30 Ma which agrees with geological evidence for offset along the fault. The greatest motion seems to have occurred between 20 Ma and the present.

Stretching in the Ross Sea embayment probably occurred during three distinct phases. The first phase was the stretching between East and West Gondwanaland that occurred sometime between 240 Ma and 160 Ma. While the first phase may have begun in the north with the formation of the Anza Trough in Kenya, we do know that the Ferrar dolomites were intruded in the vicinity of the present-day Transantarctic Mountains at about 175 Ma. Extension in the Ross Sea Embayment would be very compatible with the intrusion of the Ferrar dolomites. We think that Marie Byrd Land and the East Antarctic craton may have then acted as a single plate until the initiation of stretching and extension between North New Zealand and the Campbell Plateau, tentively dated as ~110 Ma to 90 Ma. This Cretaceous phase may have continued until the Campbell Plateau actually rifted away from Marie Byrd Land. We assume that all extension in the Ross Sea Embayment finished by 70 Ma because the plate circuit between North and South New Zealand can easily assume a rigid Antarctica without any problems. John Behrendt of the U.S.G.S. wants to have continued extension in the Ross Sea Embayment. While there is active volcanism presently occurring in the Ross Sea region including Mt. Melbourne in North Victoria Land, Mt. Erelous on Ross Island and probable extension in the Terror Rift and Nordenskjold Basins, it can not account for a great deal of extension since that would severely affect the motion between North and South New Zealand. We feel that whatever present-day extension may be occurring in the Ross Sea Embayment, it is analogous to the East African Rift and is not analogous to the Basin and Range. Even so, it is possible that the fragmentation of Gondwanaland is continuing.

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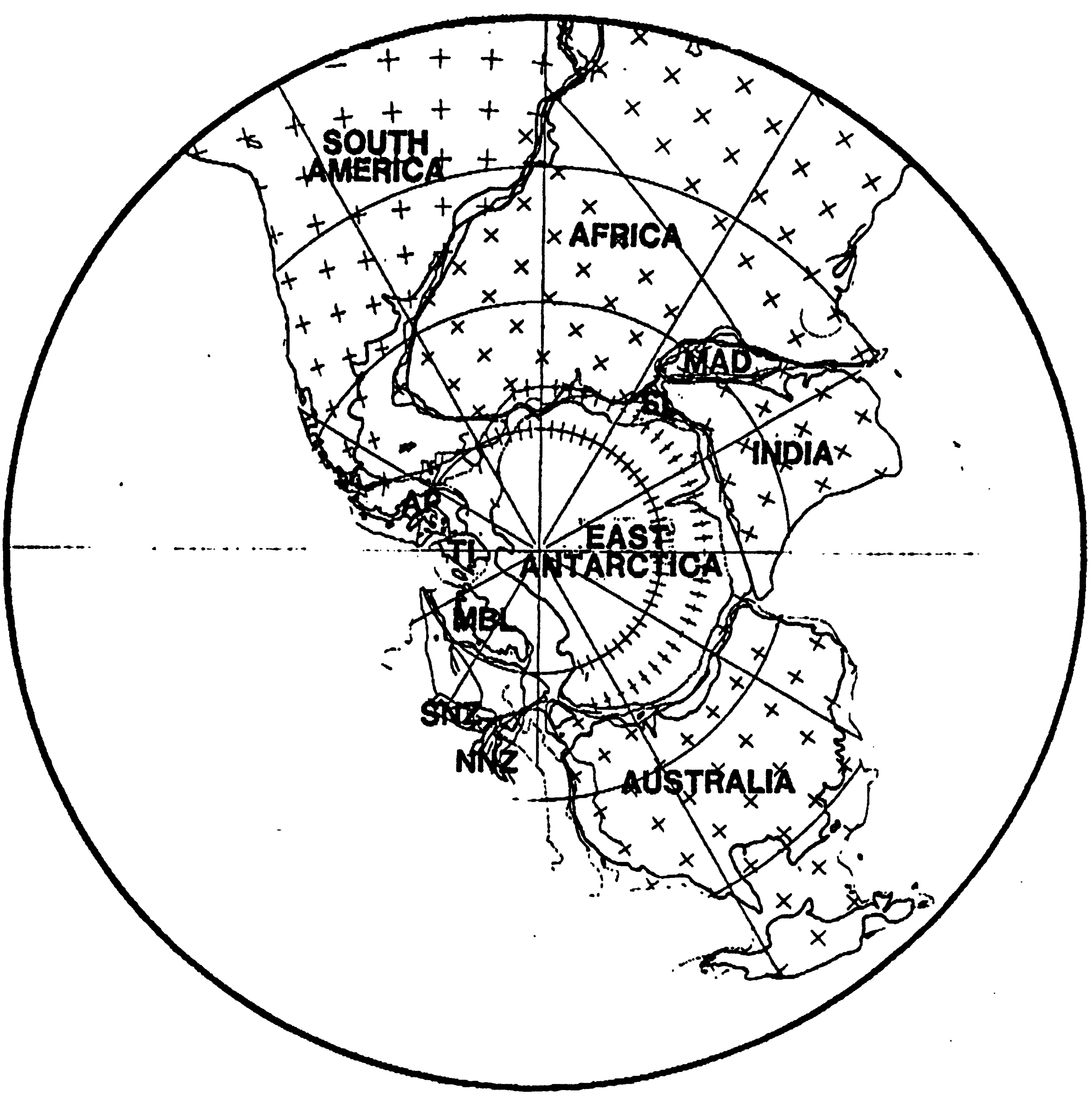

Figure 1. A tight fit reconstruction of Gondwanaland for the early Mesozoic. A polar stereographic reconstruction to 30°S is used. East Antarctica is held fixed in its present day present with the other plates rotated relative to it. Five degree grid marks are shown on the continental pieces. The 2000 m contour is used to define the continental margins. Overlap between continental pieces is allowed to make up for stretching of the continental crust during initial rifting phases. AP=Antarctic Peninsula, MAD=Madagascar, MBL=Marie Byrd Land, NNZ=North New Zealand, SL=Sri Lanka, SNZ=South New Zealand, and TI=Thurston Island.

Single channel seismic data from the Antarctic Peninsula Region: *R/V Polar Duke*, 1987-1989

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Personnel from the Institute for Geophysics of the University of Texas at Austin have led three cruises of *R/V Polar Duke* to study the structure and tectonics of the Antarctic Peninsula region. In April 1987, James A. Austin and Dale Sawyer (now at Rice University) utilized some unscheduled time on *R/V Polar Duke* to look at the Hero Fracture Zone region. They collected 850 nautical miles of single-channel seismic reflection data, 12 kHz bathymetric and magnetic data in Bransfield Strait and on the forearc of the South Shetland Islands (Figure 1). They used a HAMCO 100 cu. in. water gun and a Bolt 125 cu.in. air gun. The HAMCO gun gave excellent results in shallow (up to 1.5 km) water depths with relatively thin sediment cover while the Bolt air gun proved more suitable for the forearc region (water depths in excess of 4.5 km with up to 2.0 sec of sediment in the South Shetland trench).

Heiner Villinger of the Alfred Wegener Institute, Bremerhaven, participated in *R/V Polar Duke* cruise PD VI-88. On that cruise we collected 2480 nautical miles of digitally recorded seismic data in the North Bransfield Basin region and around the Hero Fracture Zone (Figure 2). We had planned to work in the Powell and King George Basins but both of those areas were ice covered during May, 1988. We used the HAMCO 100 cu. in. water gun for all of this cruise and it worked without fail. We were able to overcome the problems with the digital recording system and the data has been converted to Seg-y format and filtered. Orthogonal crossings of the North Bransfield Basin show southeastward tilted crustal blocks. The seismic crossings also show an abundance of same direction normal faults reminiscent of stretched continental crust. On this cruise we crossed the extinct Drake-Antarctic plate boundary and determined that spreading ceased abruptly at about 4.5 Ma. When spreading ceased presumably subduction at the South Shetland Trench either ceased or slowed substantially. It is difficult to invoke back-arc spreading in the Bransfield Straits during the past 1.3 Ma if subduction stopped or slowed at 4.5 Ma and there is no evidence of arc related volcanism during the last 20 Ma. In addition to the North Bransfield Basin work, we finished the investigation of the Hero Fracture Zone since we had to leave Bransfield Straits because of the increased ice coverage. We could find no evidence that subduction of the Hero Fracture Zone ridge disrupts the overlying plate margin.

R/V Polar Duke cruise PD IV-89 had originally been scheduled for mid-March to early May 1989 to take heat flow measurements in Powell Basin and in the King George Basin of the central Bransfield Straits (Figure 3). The *Bahia Paraiso* disaster caused our shiptime to be rescheduled to mid-April to mid-May. Ice coverage of Powell Basin precluded our working there so we took 54 heat flow measurements in the King George Basin. The heat flow values ranged from about 40 mW m^{-2} to 421 mW m^{-2}. We made three attempts to duplicate the high value but obtained lower values of 101, 104 and 142 mW m^{-2} within the accuracy of the ship's navigation and the ice conditions. Ice coverage of King George Basin was >98% when we took the heat flow measurements. The heat flow values can only be explained by hydrothermal circulation. A high value of 251 mW m^{-2} was found along the base of the South Shetland Island scarp. The closest analogy to Bransfield Straits is the Guaymas Basin of the Gulf of California. There heat flow values of up to 9 W m^{-2} are found, substantially higher than what was found in the King George Basin. After being chased from the King George Basin by the increasing ice coverage we attempted to piston core in the Central Bransfield Basin and found a pervasive ash layer presumably from nearby Deception Island. It was decided that heat flow measurements would be substantially effected by the rapid sedimentation. Consequently we left Bransfield Straits and spent the next three days collecting 500 km of high quality digitally recorded seismic data over the Shackleton Fracture Zone ridge. We used the 360 cubic inch Bolt airgun for the seismic work. We were able to distinguish up to 1.3 sec of penetration in the thick nearly flat-lying sediments on the northeast side of the Shackleton Fracture Zone ridge. We found evidence that the Scotia Plate may be underthrusting the Antarctic Plate along the southern half of the Shackleton Fracture Zone.

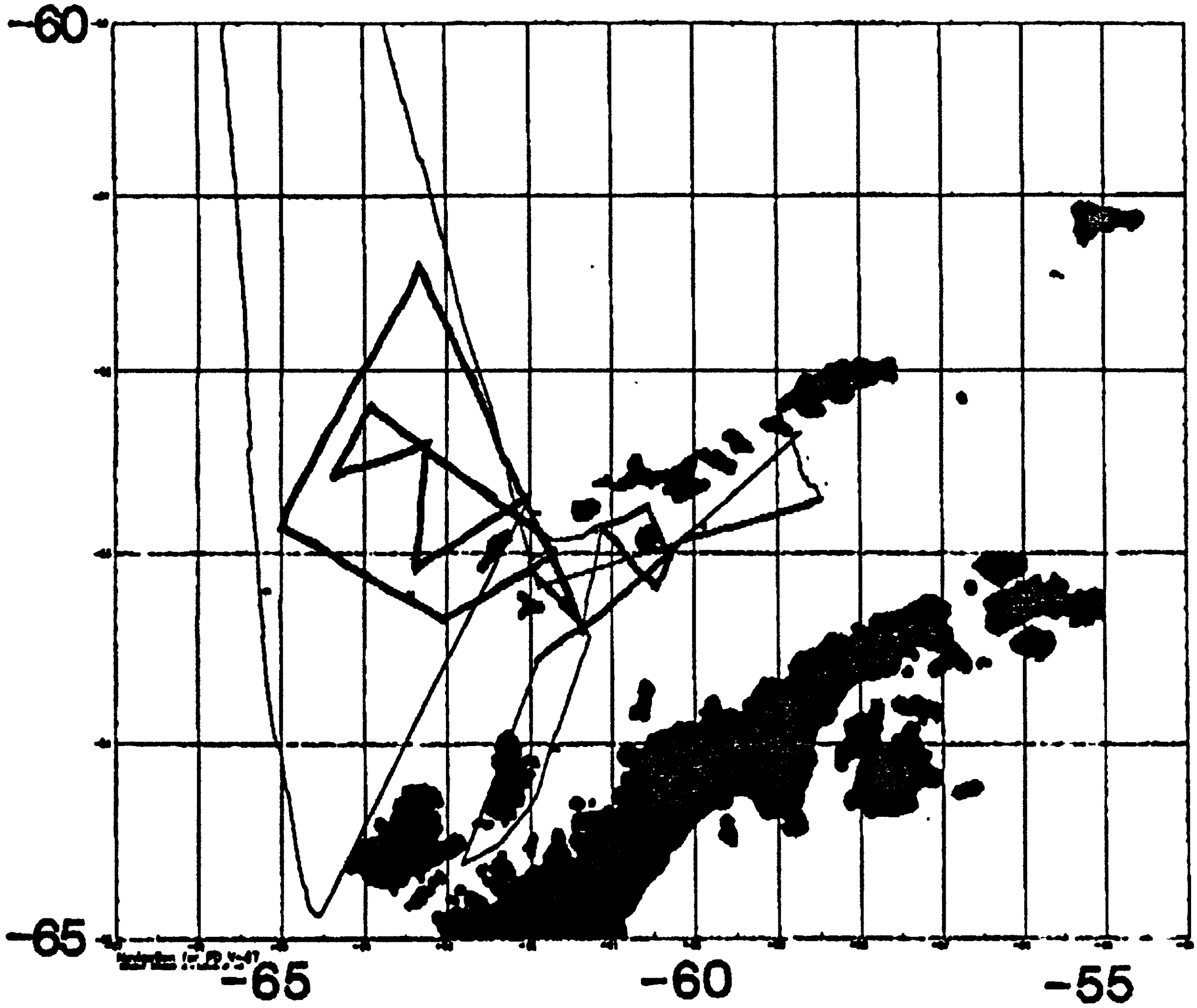

Figure 1. Cruise track for *R/V Polar Duke* cruise PD IV-87. The 850 nautical miles of single channel seismic data are shown as a heavy line.

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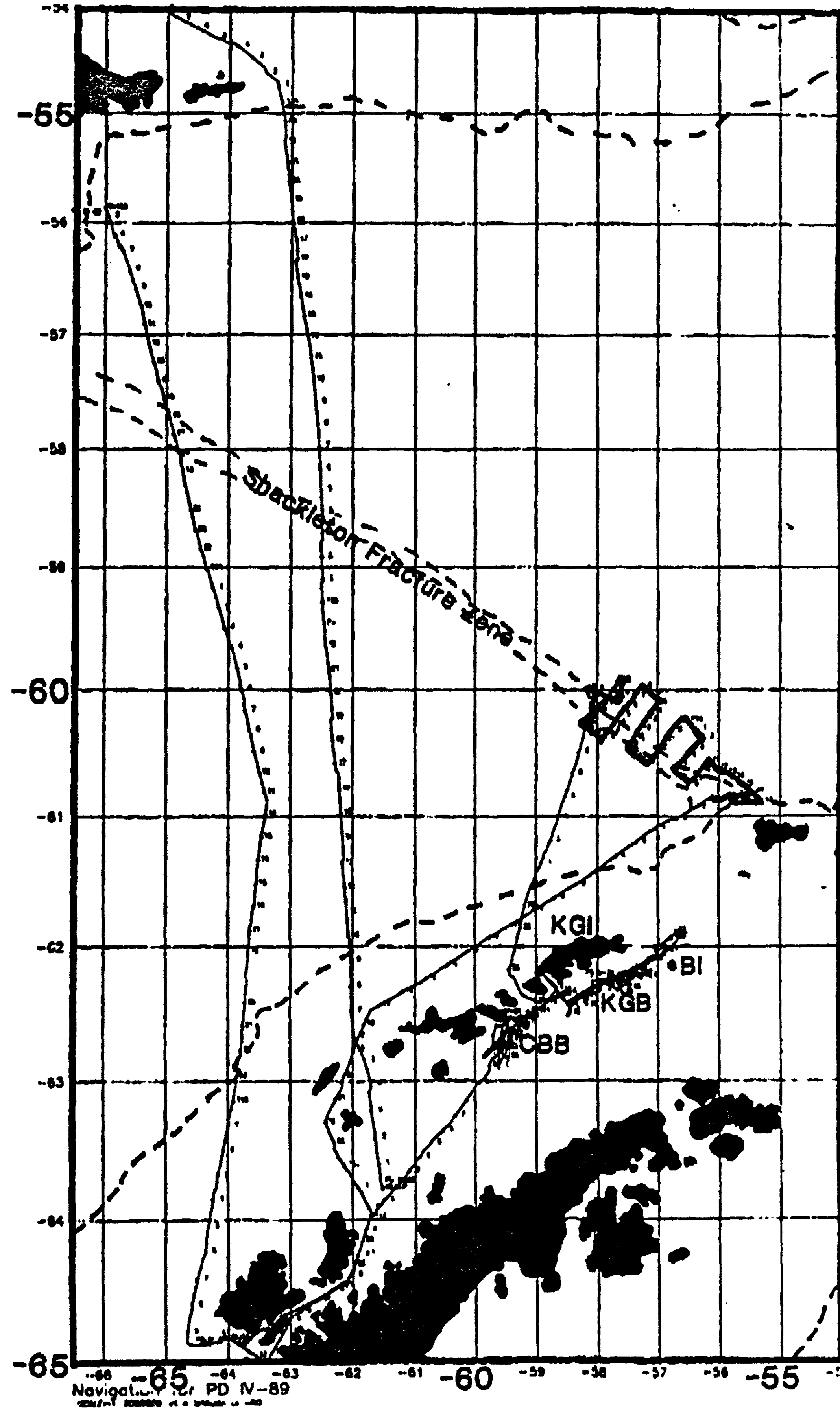

Figure 2. Cruise track for *R/V Polar Duke* cruise PD VI-88. 2480 nautical miles of single channel seismic data were collected on this cruise. Seismic data was collected during all of this cruise except for the two tracks across Drake's Passage, the run into Palmer Station on Anvers Island and the northwest bound track that terminates at 60.6°S, 61.6°W.

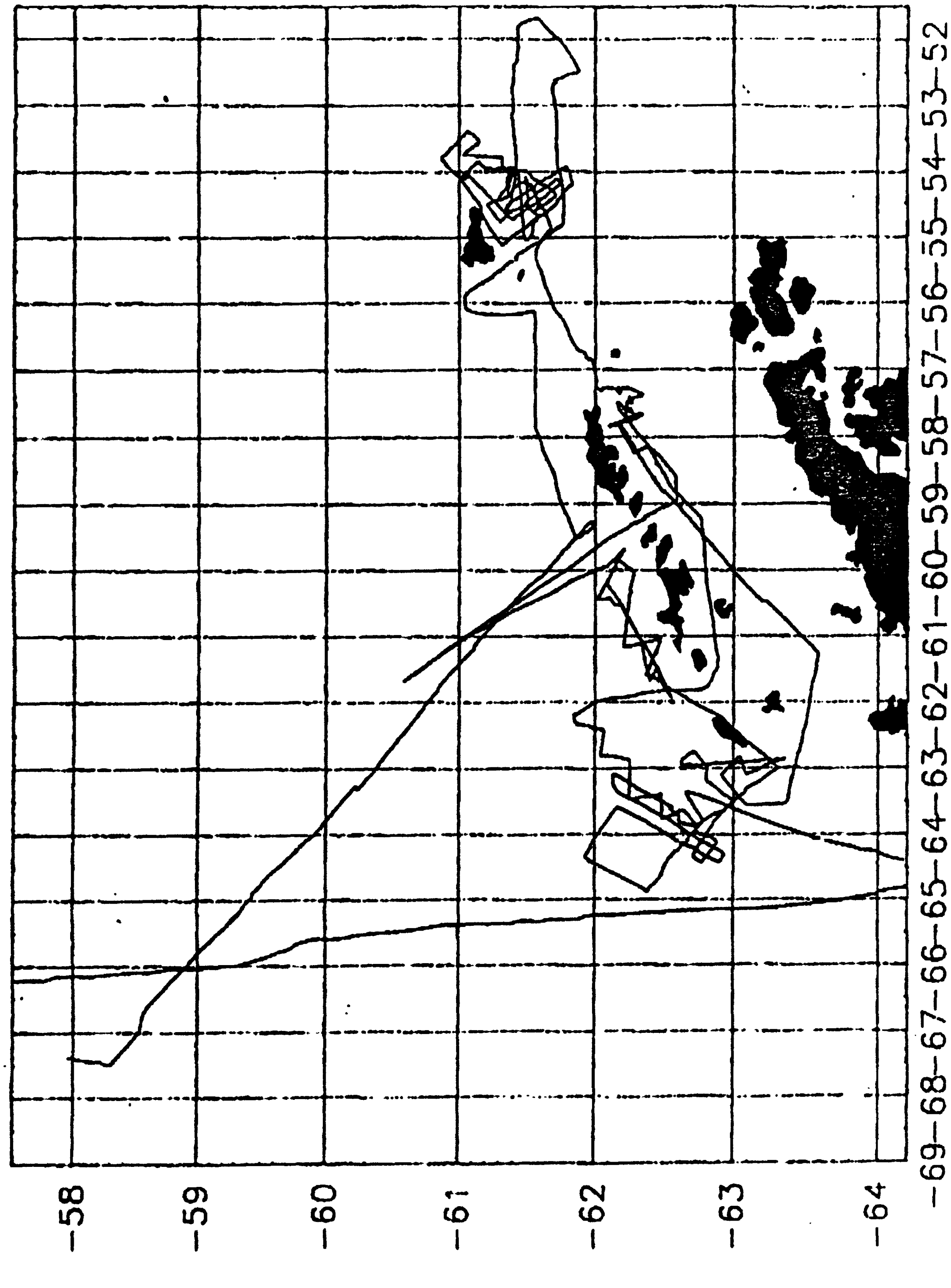

Figure 3. Cruise track for *R/V Polar Duke*cruise PD IV-89. The 500 kilometers of single channel seismic data are shown as a heavy line at the southeast end of the Shackleton Fracture Zone where it intersects the tip of the Antarctic Peninsula.

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OUTLINE OF STRUCTURE AND EVOLUTION OF THE COOPERATION SEA SEDIMENTARY BASIN

In 1985-1988 the Soviet Antarctic Expedition conducted marine geophysical research in the Prydz Bay and adjacent slope of the Cooperation Sea. It included 7700 km of MCS (24-fold) profiling accompanied by gravity and magnetic observations and sonobuoy measurements at 19 sites. Equipment consisted of a 2300 m streamer with a 100 m group interval and a 460 c. in/1700 psi airgun.

The survey was accomplished by cargo ships primarily engaged in logistic operations, which precluded acquisition of high quality seismic data. Nevertheless, it appeared possible to recognize the principal structural features of the Cooperation Sea sedimentary basin (CSSB) and outline its paleotectonic environment.

ACOUSTIC BASEMENT

Acoustic basement of the CSSB was identified to the 9-10 km depth. Its major structural feature on the Prydz Bay shelf is a broad graben which represents a seaward continuation of the Lambert-Amery Glaciers continental rift zone (fig. 2). On the south-east the graben is bounded by a shallow basement almost exposed in the sea bottom along the Princess Elisabeth Land Coast. The basement here is broken by numerous low-amplitude faults which cause extensive diffractions and often preclude recognition of its surface. To the north-west of the graben there is a prominent basement high whose surface descends to the north-east from the depths 1-3 km on the inner shelf to 5-7 km on the outer shelf. This is caused by a series of step-like listric faults trending in north-west direction (fig. 3). The top of the basement high is characterized by distinct reflections and gently undulated topography.

The graben is best delineated on the inner shelf where submergence of the basement surface is most pronounced. A seaward continuation of the graben axis is defined largely by position of a linear gravity low and associated disruption of sublatitudinal magnetic anomaly (fig. 2) according to sonobuoy and magnetic data, the depths of the graben floor nowhere exceeds 10 km.

In the western Prydz Bay there is a wedge-shaped, fault-bounded basement depression more than 6 km deep. The latter is apparently related to the northward extension of a major deep fault along the west boundary of the Lambert -Amery Glaciers rift zone.

On the slope and continental rise the basement is recognized only occasionally. Here it most likely has a more complex structure and strongly dissected topography.

SEDIMENTARY COVER

The CSSB cover varies considerably in thickness and internal structure. Three seismic units are recognized from the available Soviet data.

The lover unit is characterized by high seismic velocities (in excess of 4.0 km/s). It occurs predominantly in the main graben where its thickness reaches 2.5-3.0 km in the axial zone; towards basement elevations this unit wedges out. Its top provides high-amplitude reflections and merges with the surface of the central basement high; apparently they represent a single erosional unconformity.

The middle unit occurs extensively throughout the entire CSSB area, with the exception of the highest parts of basement rises. In the central graben this unit shows steeper bedding at the south-eastern flank than along the opposite one and reaches 2 km in thickness in the axial zone on the inner shelf and up to 5 km on the outer shelf. Within the unit there are several flat, gently dipping reflectors cut by the top boundary. In the western Prydz Bay depression the middle unit appears to constitute the bulk of the sedimentary section up to 5 km in thickness. Its internal structure differs from that in the main graben in chaotic distribution of discontinuous reflections with unstable dynamic parameters.

The upper unit on the Prydz Bay inner shelf represents an essentially undeformed relatively thin cover (0.5-1.5 km) with seismic velocities in the range between 2.0 and 3.0 km/s. The low-frequency MCS data do not allow to separate this unit on the basis of its internal features. However, high-resolution seismic evidence confirmed by drilling results indicate the presence in the upper unit of two distinct sub-units which may correspond to independent seismostratigraphic sequences (Cooper et al.,1990).

On the outer shelf and continental slope the younger subunit of the upper unit forms a persistent sediment wedge with sigmoidal internal structure. The observed thickness of that body is 1.0-1.5 km; its basement is not recorded, which precludes reliable correlation with the upper rise. The latter is characterized by the presence of up to six subhorisontal reflectors of regional extent whose correlation with unconformities recognized by JARE (Mizukoshi et al.,1986) is well established.

Highly specific reflection features have been recorded in the subbottom section in the extreme north-west of the Cooperation Sea (fig.2). They indicate the presence of dune-like forms with amplitudes about 0.04 s and up to 3 km across associated with a regional unconformity at 0.7s (fig.3) sub-bottom depth which correlates with the "B" boundary in JARE seismic sections (Mizukoshi et al.,1986). Locally the dune-like forms are recorded at a shallower level as well (0.4- 0.5 s subbottom depth). In places there are also indications of buried deep-sea channels whose areal distribution is usually reflected in location of recent bathymetric canyons. The channel sequences are in many respects similar to those described in the north-eastern Weddell Sea (Kuvaas, Kristoffersen, 1989).

BASIN EVOLUTION

The basement underlying the shelf and slope of the CSSB is believed to be continues with the Antarctic platform shield complexes. The latter include the predominantly ancient crystalline rocks and supracrustal metamorphic assemblages related to development of Precambrian mobile belts. Similar complexes essentially reworked by break-up processes and mixed with rift-related volcanics may constitute the locally recorded basement fragments beneath continental rise.

The earliest stage of basin evolution is recorded in the lower unit of sedimentary cover which occurs only in the main graben on the Prydz Bay shelf. The thickness of this unit and its mean velocity and density values calculated from refraction and gravity data match closely with respective parameters measured on the Permian Amery Group rocks in the Beaver Lake area (2.5-3.0 km; 4.5-5.0 km/s; 2.45-2.47 g/cm3). Correlation of the lower unit with non-marine clastic sediments of possible Mesozoic and/or late Paleozoic age is also supported by the ODP data (Hambrey et al., 1989). Therefore there is sufficient evidence to suggest that pre-breakup crustal extension, graben formation and related deposition of lower cover sequences in the CSSB began as early as at the Paleozoic/Mesozoic time boundary.

The middle unit of the CSSB cover is believed to represent a syn-breakup sequence whose formation was to a large extent controlled by rifting and subsidence of the developing continental margin. This is evidenced by an apparent seaward increase in the units thickness (fig.2), as well as by a structural connection between the western Prydz Bay depression (where the bulk of the sedimentary section is composed of the middle unit) and the crustal fault zone (fig.4) which controls distribution of c.130 my old alkaline ultramafics farther south (Grikurov et al.,1980). Available MCS evidence suggests that on the shelf the middle unit consists mostly of shallow water coarse clastic deposits accumulated in breakup-related grabens. The latter indicate renewal of extensional processes which involved both the preceding (pre-breakup) troughs (the main Prydz Bay graben) and adjacent crystalline basement terrains (the western Prydz Bay depression). The upper boundary of the middle unit is underformed; together with the basement top it forms a single subhorisontal erosional surface related to cessation of continental rifting and associated tectonic stabilization by the end of Early Cretaceous of the Prydz Bay shelf.

The next sedimentary cycle responsible for the formation of the third unit of the cover began in early Cenozoic, most likely during the Eocene, which defines an extremely prolonged period of planation spanning almost 50 my. Two sabunits recognized in the upper unit are correlated with the pre-glacial and glacial-marine facies; the age of the former is not precisely known, while the oldest glacial beds drilled on the outer Prydz Bay shelf belong to middle (?) Eocene (Hambrey et al.,1989).

These beds which form the base of prograding sedimentary wedge cannot be traced in MCS data beyond the shelf break. However the internal structure observed in the subbottom part of the glacial sequence indicate a considerable predominance of progradational features over aggradational. By comparison with the Ross Sea shelf where active subsidence throughout much of the Cenozoic time led to accumulation of thick AP

-sequences (Hinz and Block, 1983) it may indicate a less intensive crustal extension in the Prydz Bay combined with a much greater bottom exaration during the glacial maxima.

Some conclusions about the nature of the upper part of the deep-water sedimentary cover may be achieved by assuming that the dune-like features recorded at two subbottom levels on continental rise (fig. 2) are similar to present-day bottom forms observed on the Brazil continental rise and attributed to intensive contour currents (Damuth, 1975). Such paleocurrents could have developed in the Cooperation Sea area as a result of global redistribution of deep water dynamics in connection with final stages of Gondwana separation. Two major events in that process were related to Antarctic-Australia breakup about 40-50 m. y. ago, when a quasicircumpolar paleocurrent was formed and to the opening in approximately mid Tertiary time of the Drake Passage which led to establishment of the circumpolar hydrodinamic regime and extensive growth of Antarctic ice sheet (fig. 5). It is conceivable that during each of these events the principal trend of the circumpolar current was influenced by the Kerguelen block which could cause a local cyclonic clock-wise circulation. The south-east to north-west direction of such circulations is confirmed by analysis of geometry of the dunelike forms at both levels (fig. 2,3,5).

If the above assumptions are valid, they may help to recognise in subbottom section the surfaces relatrd to major changes in South polar paleoenvironments and to correlate these surfaces over vast distances on the basis of regional seismic unconformities.

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FIGURE CAPTIONS

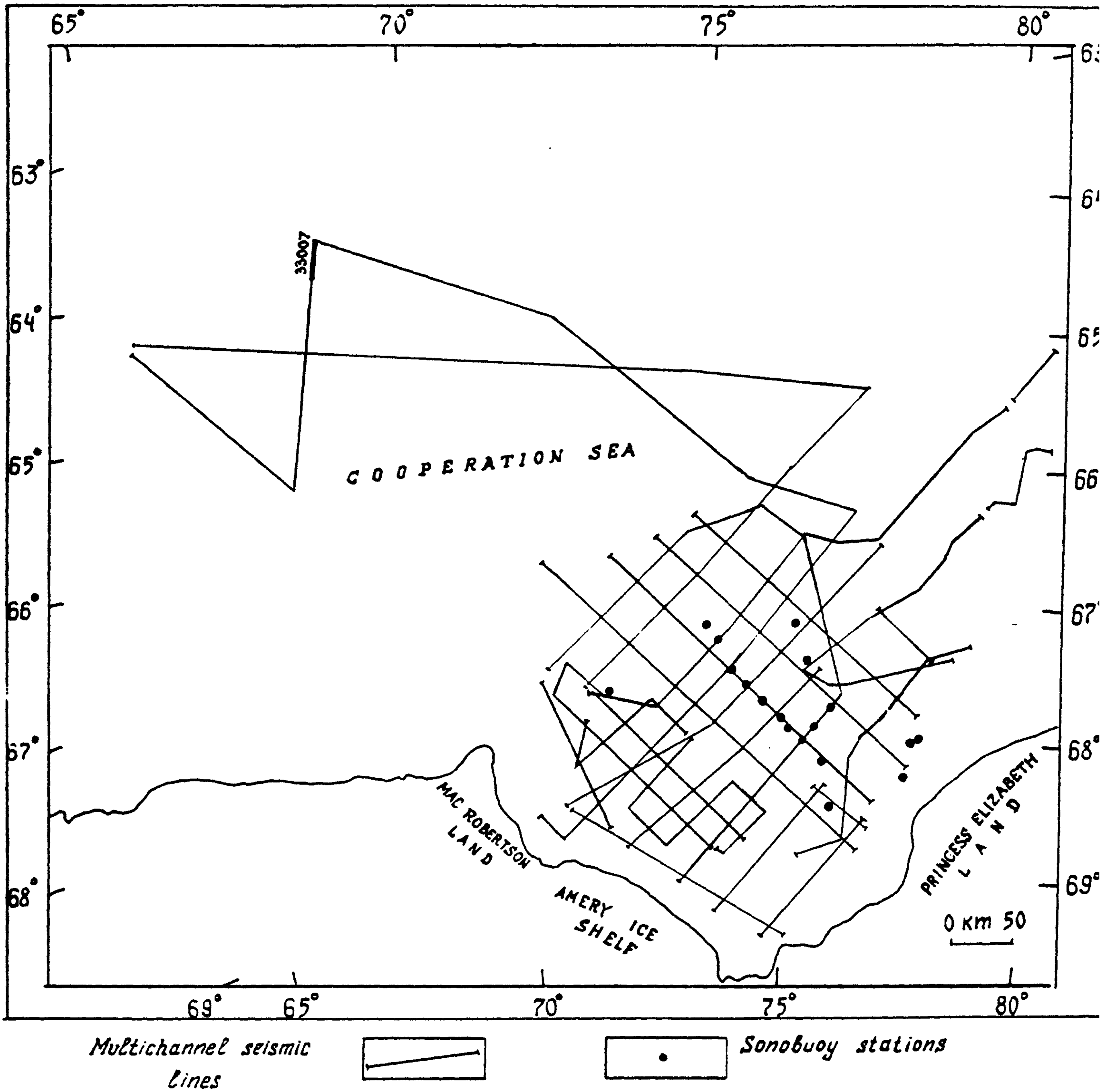
Fig. 1 Map showing locations of the USSR multichannel seismic reflection lines and sonobuoys in the Cooperation Sea.

Fig. 2 Structural map for the Cooperation Sea Sedimentary Basin: 1 - isopachs (km) of total sedimentary cover (a - definite, b - inferred); 2 - summary isopachs (km) for middle and upper seismic units (a - definite, b - inferred); 3 - isopachs (km) of the upper unit; 4 - present shelf edge; 5 - paleoshelf edge; 6 - axial line of relative gravity low associated with main graben; 7 - axial line of magnetic anomaly; 8 - buried dune-like features at the 0.7-0.8 s subbottom depth; 9 - buried dune-like features at the 0.4-0.5 s subbottom depth; 10 - buried channels on the continental rise; 11 - bathymetric channels on the continental rise; 12 - trend of paleocurrents.

Fig. 3 Seismic section showing dune-like features at the upper part of the deep-water sedimentary cover. Profile location is shown in fig. 1.

Fig. 4 Principal tectonic features of the Cooperation Sea Sedimentary Basin: 1 - Precambrian basement of the Antarctic Platform; 2 - post-breakup Cenozoic cover underlain in basin downwarps by syn-breakup Mesozoic sequences; presumable basin stratigraphy is shown on the cross -section; 3 - faults: a - major escarpments bounding the basin, b - intrabasin fault benches, c - unspecified, d - inferred position of crustal fault; 4 - isobaths, m; 5 - line of the section; 6 - seismic boundaries (a - definite, b - inferred); 7 - basement highs; 8 - magmatic bodies.

Fig. 5 Inferred position of contour paleocurrents in the southern Indian Ocean in relation to the Kerguelen block. Gondwana reconstructions from (Norton, 1982). Paleocurrent after (Losev et al. 1980), with supplements.



65°
70°
75°
80°
63°
64°
65°
66°
67°
68°
33007
COOPERATION SEA
MAC ROBERTSON LAND
AMERY ICE SHELF
PRINCESS ELIZABETH LAND
0 KM 50
69°
65°
70°
75°
80°
Multichannel seismic lines
Sonobuoy stations

Fig 1

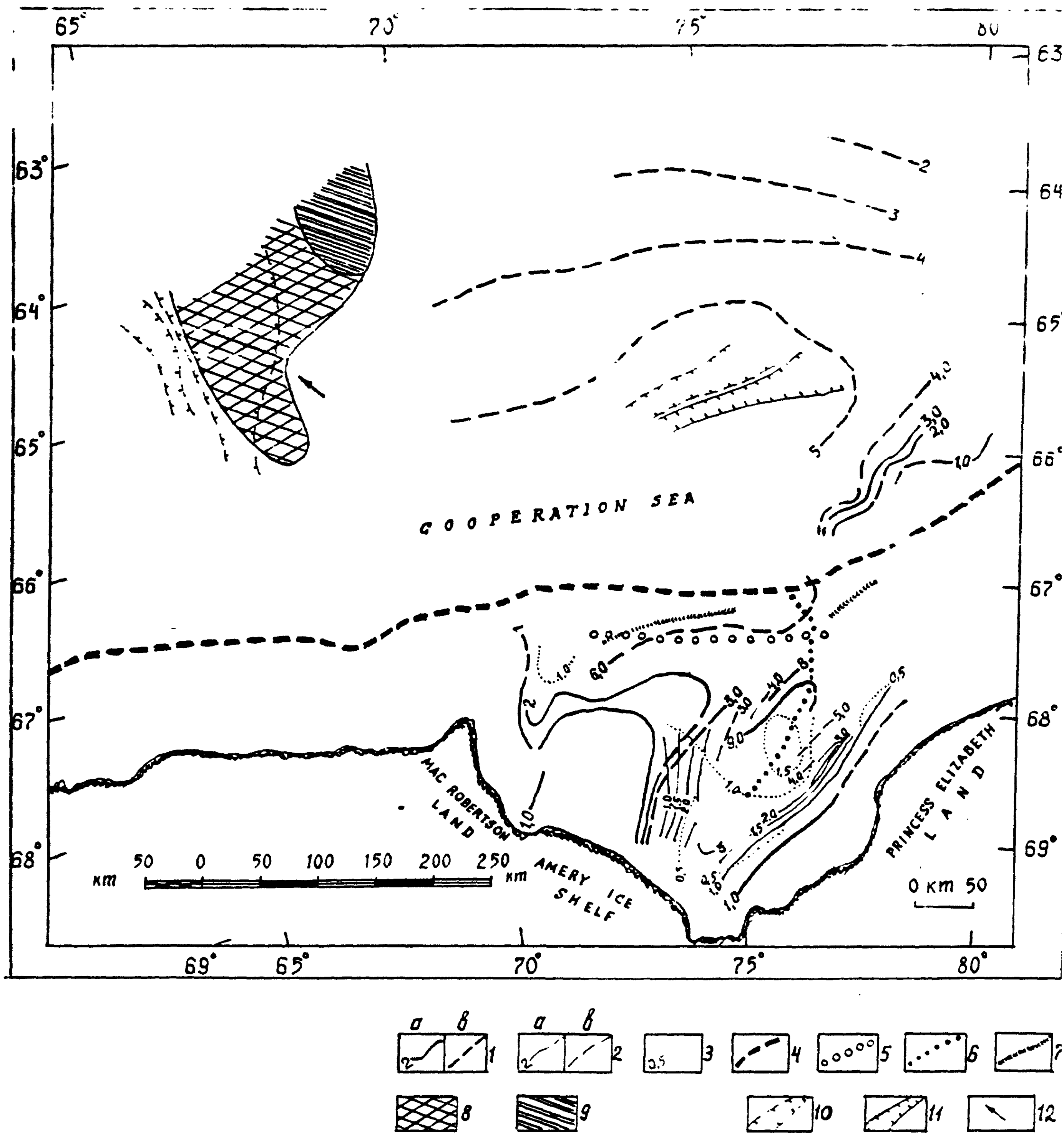


Fig. 2

MADE FROM BEST AVAILABLE COPY

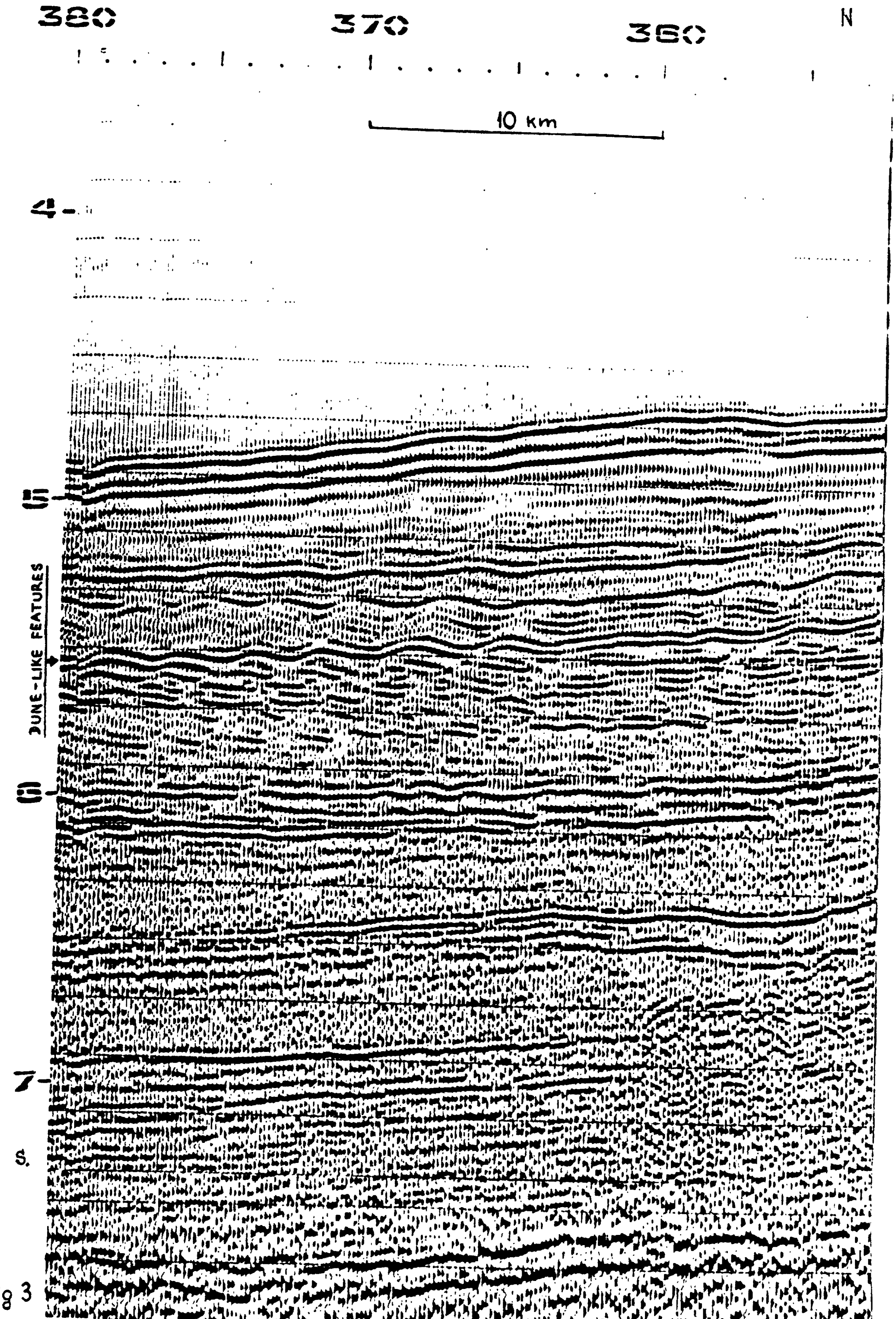
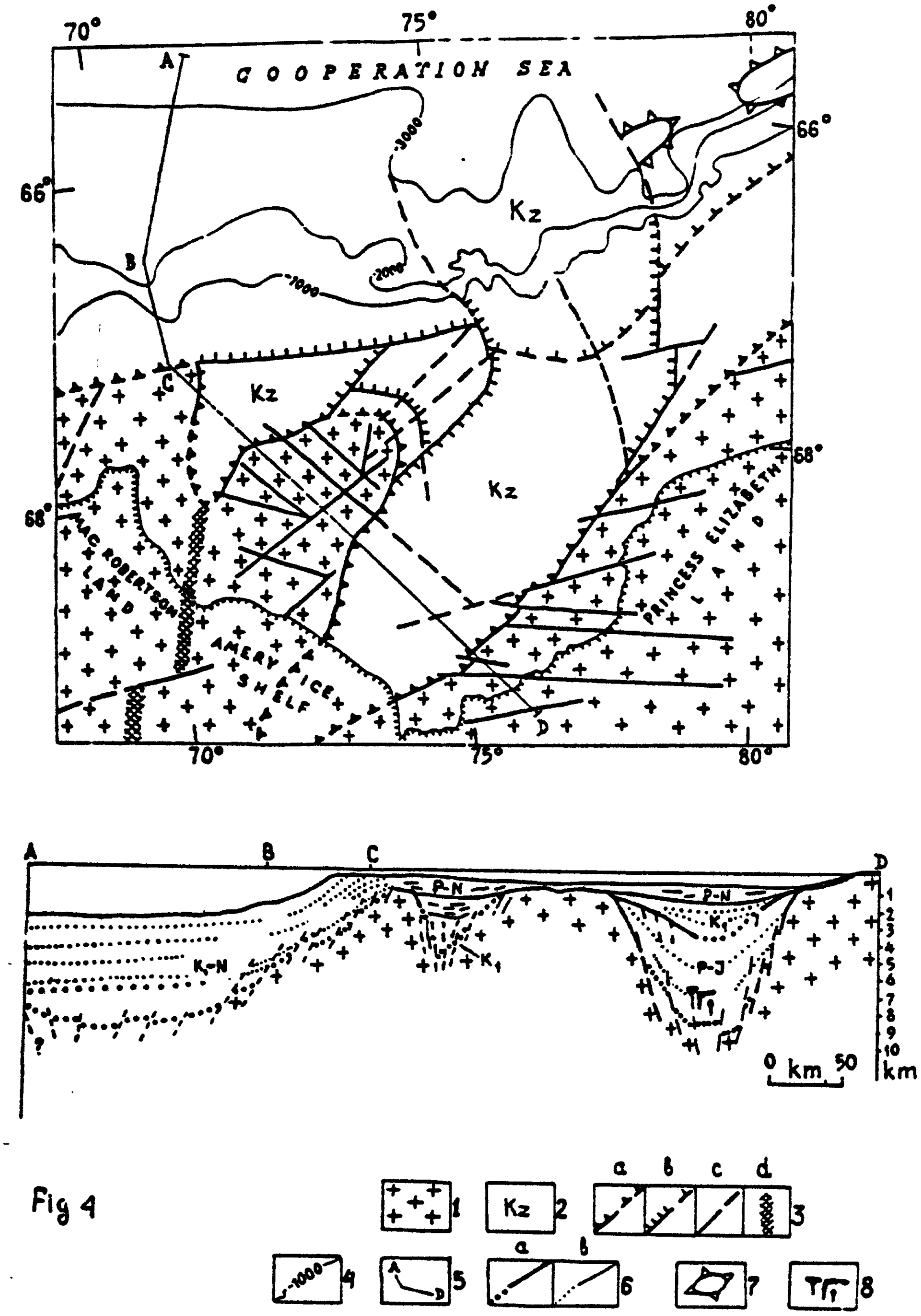


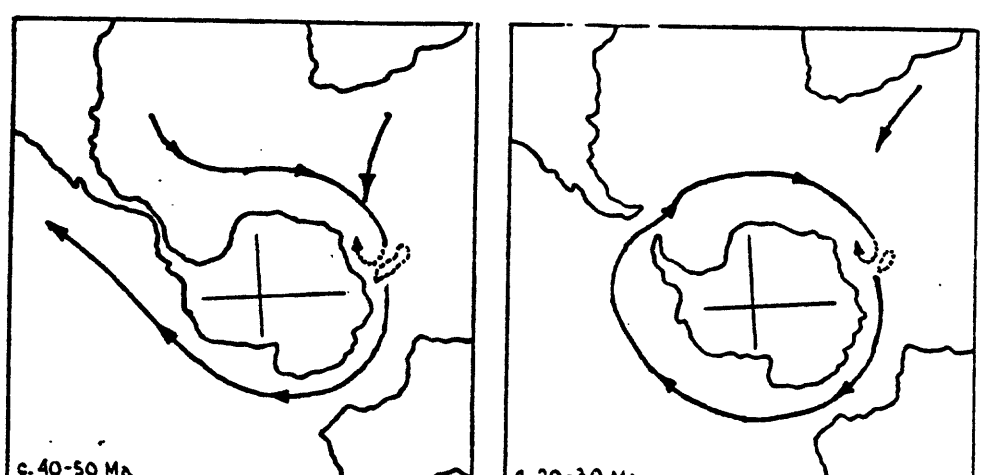
Fig 3

33007



70°
75°
80°
COOPERATION SEA
66°
68°
Kz
-3000
-2000
-1000
A
B
C
D
MAC ROBERTSON LAND
AMERY ICE SHELF
PRINCESS ELIZABETH LAND
P-N
K-N
K_1
P-J
T_1
0 km 50
km
a
b
c
d
1
2
3
4
5
6
7
8

Fig 4



c. 40-50 Ma
c. 20-30 Ma

Fig 5

ANTARCTIC DATA MANAGEMENT - LESSONS FROM THE ARCTIC

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During the past few years, the earth, space, and environmental science research communities have begun to address issues regarding the coordination, archiving, management, and exchange of data and information. Two key reasons for addressing these difficult questions were: (1) the realization by many in the different scientific communities that, with the advent of new land- and sea-based technologies and new Earth observing sensors, such as the National Aeronautics and Space Administration's (NASA) planned Earth Observing System (Eos) mission, the scientific world is on the brink of an exponentially increasing, data explosion (Fig. 1); and (2) the need for easy means to identify, locate, and access existing data, considering the rapidly increasing cost to conduct research and the rapid expansion of the size of the international research community. The statement that "you can't tell the players without a scorecard" is equally true in the data management community.

In 1984, the Congress of the U.S. passed the Arctic Research and Policy Act (ARPA). The ARPA requires U.S. Federal agencies to develop a systematic multiyear research plan, including an Arctic data management component. In 1988, an international Arctic data working group, was formed as a result of the activities of the Interagency Arctic Research Policy Committee (IARPC), a committee composed of representatives of the U. S. Federal agencies conducting research in the Arctic. The missions of the working group were: (1) to guide the development of an Arctic data directory, an inventory of existing Arctic data; and (2) to develop innovative tools for the electronic distribution of Arctic information. The development of this Arctic Environmental Data Directory (AEDD), is an attempt designed to enhance Arctic data management and coordination. The AEDD concept is one that could be used by the Antarctic research community as a model for the development of Antarctic data management procedures.

The international Arctic data working group, formally named the Arctic Environmental Data Directory Working Group (AEDDWG), has been successful in its attempts to systematically identify and organize information about its data holdings, compiling information on more than 300 Arctic data sets in its first year-and-one-half of existence. AEDD is operated by the U.S. Geological Survey (USGS) and has been included as part of a larger Earth Science Data Directory (ESDD), maintained and operated by USGS at its headquarters in Reston, Virginia. ESDD/AEDD is an on-line system, accessible from anywhere in the world, housed on a USGS mainframe computer. ESDD/AEDD is also distributed on compact disk (CD ROM) by the OnLine Computer Library Center, Worthington, Ohio. ESDD/AEDD consists of a compilation of information about specific earth science, environmental, and natural resources data sets. Data bases referenced and described in ESDD/AEDD are both automated and non-automated, and are held by a number of entities,including the academic community, government agencies, and the private sector. As designed, ESDD/AEDD accommodates earth science, environmental, and natural resources data referring to any systematic body of knowledge, automated or not, relating to the Earth, its geology, its fauna and flora, its atmosphere, and the relationship between these components. Descriptions of more than 2,000 unique data sets are included in the ESDD.

The more than 300 data sets that are described in AEDD are uniquely Arctic or are broader in areal coverage with a specific Arctic component. AEDD and ESDD were designed to assist users in two principle ways: (1) by providing descriptions of existing data sets, and (2) by identifying the contact for each data set. Data sets referenced in AEDD include: complex computerized indices, digital data systems, paper records and files, aerial photography, satellite imagery, maps, and even petrographic thin sections.

A typical AEDD entry includes information about the following catagories:

1. data set name
2. acronym
3. responsible organization
4. contact
5. address
6. telephone number
7. telex
8. telefax
9. coordinate system
10. time span of data
11. data set status
12. access method
13. number of records
14. bytes per record
15. computer type
16. computer location
17. data base management system
18. format for data set
19. data set description
20. keywords
21. geographic coverage
22. coverage description
23. data category
24. documentation
25. comments
26. data set type
27. producing agency
28. contributors review (date)
29. northwestern latitude
30. northwestern longitude
31. southeastern latitude
32. southeastern longitude

Figures 2, 3, and 4 are examples of typical entries. Figure 2 is an AEDD entry describing a digital data base recording Alaska radiocarbon data, while Figures 3 and 4 are descriptions of two remotely-sensed Antarctic data sets held by the USGS, prepared in the style of typical AEDD entries. Figure 3 is a description of a collection of more than 300, 30-m resolution, Landsat Thematic Mapper images of coastal areas, exposed bedrock areas, and ice shelves, glaciers, and ice streams. Many of these Landsat images were acquired in cooperation with other Scientific Committee on Antarctic Research (SCAR) investigators. Figure 4 is a description of a series of maps and tabular listings summarizing the availability of more than 7,000 Sojuzkarta photographic images of Antarctica.

By electronically linking AEDD with other data directories, an "interoperable directory" has been created. AEDD's contents, as well as the contents of many other on-line data directories, are fully retrievable through the data directories of NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and USGS.

In addition to fostering AEDD activities, the working group has been active in developing a prototype Arctic electronic data journal. Named the Arctic Data Interactive (ADI) project, this project is an attempt to develop and distribute an Arctic electronic research journal using multimedia and compact disk (CD ROM) technologies. Preliminary plans call for a systematic release of new issues of ADI, each containing the latest version of AEDD and a variety of other new Arctic data and information, at an interval that has yet to be determined. A compact disc (CD ROM) can hold more than 600 megabytes of digital information, a volume substantially in excess of more than 10,000 printed pages. Support from the USGS and the U.S. Global Change Program will made it possible to complete the ADI prototype.

A key motivation for developing the Arctic digital journal was the recognition that an increasing number of researchers were gaining access to, and using desktop computer workstations to analyze polar data and information. Improvements in, and standardization of compact disc (CD ROM) technology provided a new mechanism to substantially increase, by more than an order-of-magnitude, the volume of data that could be analyzed and manipulated at desktop computer workstations at any time. The Arctic community, being relatively small, organized, and highly computer literate seemed to be an excellent community in which to test the concept of systematic compilation and release of Arctic-related data on compact disk (CD ROM). Similarly, the Antarctic research community is another group that could effectively make use of AEDD/ADI concept.

Hence, an ADI prototype, which can put extremely large quantities of Arctic data in the hands of a researcher in a mode where it can be used on a standardized and inexpensive workstation, is being developed for use on Apple-Macintosh II and IBM PC-compatible computers. ADI uses a graphical and intuitive hypermedia interface, a software system that permits full-text retrieval of bibliographic data and data set descriptions, image display, and text and graphic integration. In addition to AEDD, the ADI prototype compact disc will contain an Arctic permafrost bibliography, sample full-text articles with illustrations, and selected data sets, including tabular data, text with figures, and imagery. Data sets and articles that will be included on the ADI prototype compact disk were selected by an editorial board representing the data working group. Figure 5 is the listing of the contents of the ADI pilot system, the first phase in the development of the ADI prototype. The ADI prototype will be completed in Fall, 1990 and distributed throughout the polar research community.

The AEDD/ADI concept is an effective way for a research community to inventory the results of past programs, keep track of present research, and provide selected results and data for peer groups. The concept is working in the Arctic and is being evaluated for data management and exchange by the U.S. Global Change community. Canada, Norway, USSR, and Australia have already sent data descriptions to AEDD or have expressed interest in entering data descriptions. The data directory developments, the CD ROM innovations, and the benefits of the lessons learned from the Arctic data effort are available to the Antarctic community for their data management activities.

FIGURE CAPTIONS

Figure 1 - Cartoon depicting the exponential increase in availability of scientific data before the end of the twentieth century.

Figure 2 - Example of an Arctic Environmental Data Directory entry describing the Alaska radiocarbon data base.

Figure 3 - Sample Arctic Environmental Data Directory-style description of the Antarctic SCAR Landsat image data set.

Figure 4 - Sample Arctic Environmental Data Directory-style description of USGS data base of Sojuzkarta photographic images of Antarctica.

Figure 5 - Listing of the contents of the Arctic Data Interactive pilot system.

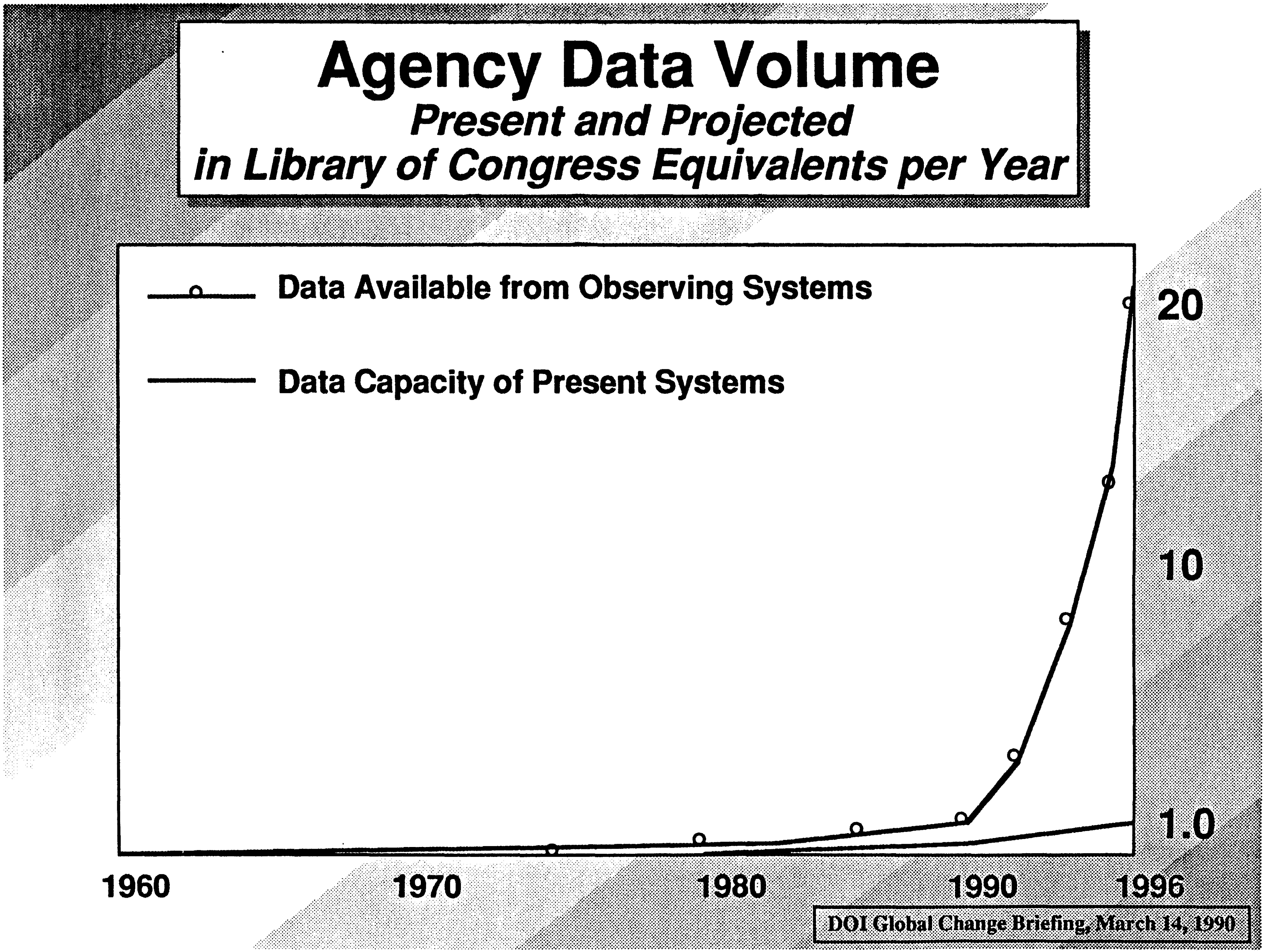

Agency Data Volume
Present and Projected
in Library of Congress Equivalents per Year
Data Available from Observing Systems
Data Capacity of Present Systems
20
10
1.0
1960
1970
1980
1990
1996
DOI Global Change Briefing, March 14, 1990

FIGURE 1

1. data set name:	Alaska Radiocarbon Data Base
2. acronym:	RCFILE, RCBIB
3. responsible organization:	U.S. Geological Survey
4. contact:	John Galloway
5. address:	Branch of Alaskan Geology, 345 Middlefield Road, Mail Stop 917, Menlo Park, California 94024
6. telephone number:	(415) 329-5688
7. telex:	n/a
8. telefax:	n/a
9. coordinate system:	latitude/longitude
10. time span of data:	1951 - present
11. data set status:	operational
12. access method:	interactive
13. number of records:	RCFILE contains 2,820 records (918,528 bytes. RCBIB contains over 450 references (107,520 bytes).
14. bytes per record:	n/a
15. computer type:	IBM XT
16. computer location	Menlo Park, California
17. data base mgt. system:	Nutshell, MS-Word
18. format for data set:	digitized data sets, bibliographies
19. data set description:	This data set contains published radiocarbon dates which consist of a laboratory and a reference number. The data set is subdivided into RCFILE - which contains the radiocarbon dates and author citation; and RCBIB - which is a complete bibliography of all published dates. The RCFILE can be sorted by date, author, citation, latitude and longitude, geographic region, and quadrangle.
20. keywords:	AEDD, Alaska, Arctic, Radiocarbon age determinations, USGS
21. geographic coverage:	US state - Alaska
22. coverage description:	Alaska
23. data category:	terrestrial, marine
24. documentation:	Galloway, J.P., 1987; USGS Open-File Reports OF-87-517-A and OF-87-517-B (IBM disk).
25. comments:	RCFILE can be converted to ASCII, DBase II, DIF. RCBIB can be converted to ASCII.
26. data set type:	automated
27. producing agency:	U.S. Geological Survey
28. contributors review:	0589
29. northwestern latitude:	72 degrees N.
30. northwestern longitude:	179 degrees W.
31. southeastern latitude:	50 degrees N.
32. southeastern longitude:	140 degrees W.
31	

Figure 2 - Example of an Arctic Environmental Data Directory entry describing the Alaska radiocarbon data base.

1.	data set name:	SCAR Landsat 4 & 5 Image Database
2.	acronym:	SCAR TM/MSS
3.	responsible organization:	U.S. Geological Survey
4.	contact:	Jane G. Ferrigno or Bruce F. Molnia
5.	address:	927 National Center, Reston, Virginia USA 22092
6.	telephone number:	(703) 648-6360 or 648-4120
7.	telex:	160443 USGS
8.	telefax:	(703) 648-4227
9.	coordinate system:	latitude/longitude; UTM
10.	time span of data:	1984 - present
11.	data set status:	operational
12.	access method:	manual
13.	number of records:	n/a
14.	bytes per record:	n/a
15.	computer type:	n/a
16.	computer location	n/a
17.	data base mgt. system:	n/a
18.	format for data set:	photographic images, negatives, microfiche
19.	data set description:	more than 300 selected Landsat 4 & 5 TM and MSS black and white, and color composite photographic prints and negatives of the coastal regions and ice shelves of Antarctica obtained under EOSAT copyright. Data acquisition, which started in 1984, is ongoing.
20.	keywords:	Antarctica, Landsat, glaciers, imagery
21.	geographic coverage:	Antarctica
22.	coverage description:	ice shelves and coastal regions of Antarctica
23.	data category:	terrestrial
24.	documentation:	n/a
25.	comments:	microfiche have been made that include the 219 SCAR acquisitions obtained from 1984 through early 1988.
26.	data set type:	non-automated
27.	producing agency:	U.S. Geological Survey
28.	contributors review:	052190
29.	northern latitude:	64 degrees S.
30.	longitude:	all
31.	southern latitude:	82 degrees S.

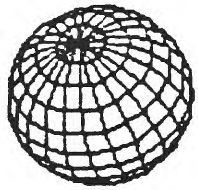
Figure 3 - Sample Arctic Environmental Data Directory-style description of the Antarctic SCAR Landsat image data set.

1. data set name:	Sojuzkarta Antarctic Image Database
2. acronym:	SAID
3. responsible organization:	U.S. Geological Survey
4. contact:	Jane G. Ferrigno or Bruce F. Molnia
5. address:	927 National Center, Reston, Virginia USA 22092
6. telephone number:	(703) 648-6360 or 648-4120
7. telex:	160443 USGS
8. telefax:	(703) 648-4227
9. coordinate system:	latitude/longitude
10. time span of data:	1976 - 1988
11. data set status:	operational
12. access method:	manual
13. number of records:	n/a
14. bytes per record:	n/a
15. computer type:	n/a
16. computer location	n/a
17. data base mgt. system:	n/a
18. format for data set:	maps, tabular listings, floppy disk
19. data set description:	more than 6,000 photographic images of Antarctica have been obtained by the Sojuzkarta photographic systems. USGS has compiled descriptions and mapped locations of these photographs in this data base. Information includes quality and percent cloud cover.
20. keywords:	Antarctica, Sojuzkarta, photography, imagery
21. geographic coverage:	Antarctica
22. coverage description:	ice shelves, ice sheets, mountains, and coastal regions of Antarctica
23. data category:	terrestrial
24. documentation:	A USGS Open-File Report is being released.
25. comments:	Images are not available through USGS.
26. data set type:	non-automated
27. producing agency:	U.S. Geological Survey
28. contributors review:	052190
29. northern latitude:	64 degrees S.
30. longitude:	all
31. southern latitude:	84.5 degrees S.

Figure 4 - Sample Arctic Environmental Data Directory-style description of USGS data base of Sojuzkarta photographic images of Antarctica.

Pilot V 1.0 Sept 89

ARCTIC DATA INTERACTIVE



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To Overview...

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FIGURE FIVE

Japanese Expedition Data around the Antarctic Peninsula

Seizo Nakao (Japan National Oil Corporation,
Technology Research Center)

Japanese Expedition on marine geoscience off Antarctica began in 1980. It has been sponsored by the Ministry of International Trade and Industry, and conducted by the Japan National Oil Corporation (JNOC). In the Expeditions, multi-channel seismic survey combined with gravity and geomagnetism measurements, refractive seismic survey with a sono-buoy, bottom sampling (coring, grabing and/or dredging), and heat-flow measurement have been generally carried out. Acoustic source for the seismic survey had been an air-gun system before 1984, when JNOC introduced a water-gun system instead. Almost all cored sediment materials up to ca. 8m long have been analysed for microfossils (foraminifers, radiolarians and diatoms) and natural remanent magnetization.

JNOC named each research cruise as TH-80, TH-81 etc. In these names, "TH" are very initials of the Technology Research Center, JNOC and R/V Hakurei-maru which is owned by the Metal Mining Agency of Japan and chartered for the survey, and the two-digit number after the hyphen means the corresponding calender year in the beginning of each cruise.

Bellingshausen Basin, sea area off South Orkney Isl., and Bransfield Basin are the fields where the Japanese Expedition acquisited scientific data around the Antarctic Peninsula. Outline of the data in each area are as follows.

1. Bellingshausen Basin (TH-80 Cruise)

The area is bounded by the meridians of 65deg.W and 105deg.W, and the parallels of 62deg.S and 70deg.S. Three-fold seismic reflection data with total length of 3280 km, and 5 seismic refraction data were obtained during this cruise. Almost all the seismic survey lines are in the deep sea area of 3000-5000m deep. Only the southernmost part of the Line 9 and almost of the Line 10, 220 km in total, are traceable on the continental shelf. On the Line 9, between SP250 and 1250, large-scale submarine erosion and afterward deposition of sedimentary body with slump structure.

Eight core samples of bottom sediments obtained with a piston corer (8m long barrel) are all from the continental rise or abyssal plain. Some of them hit sand layers delived from a nearby submarine canyon to be prevented further penetration. As to the dredge samples, no ancient and in-situ sediments, e.g. semi-consolidated mud as groundmass of conglomerate, were collected.

2. Sea area off South Orkney Isl. (TH-87 Cruise)

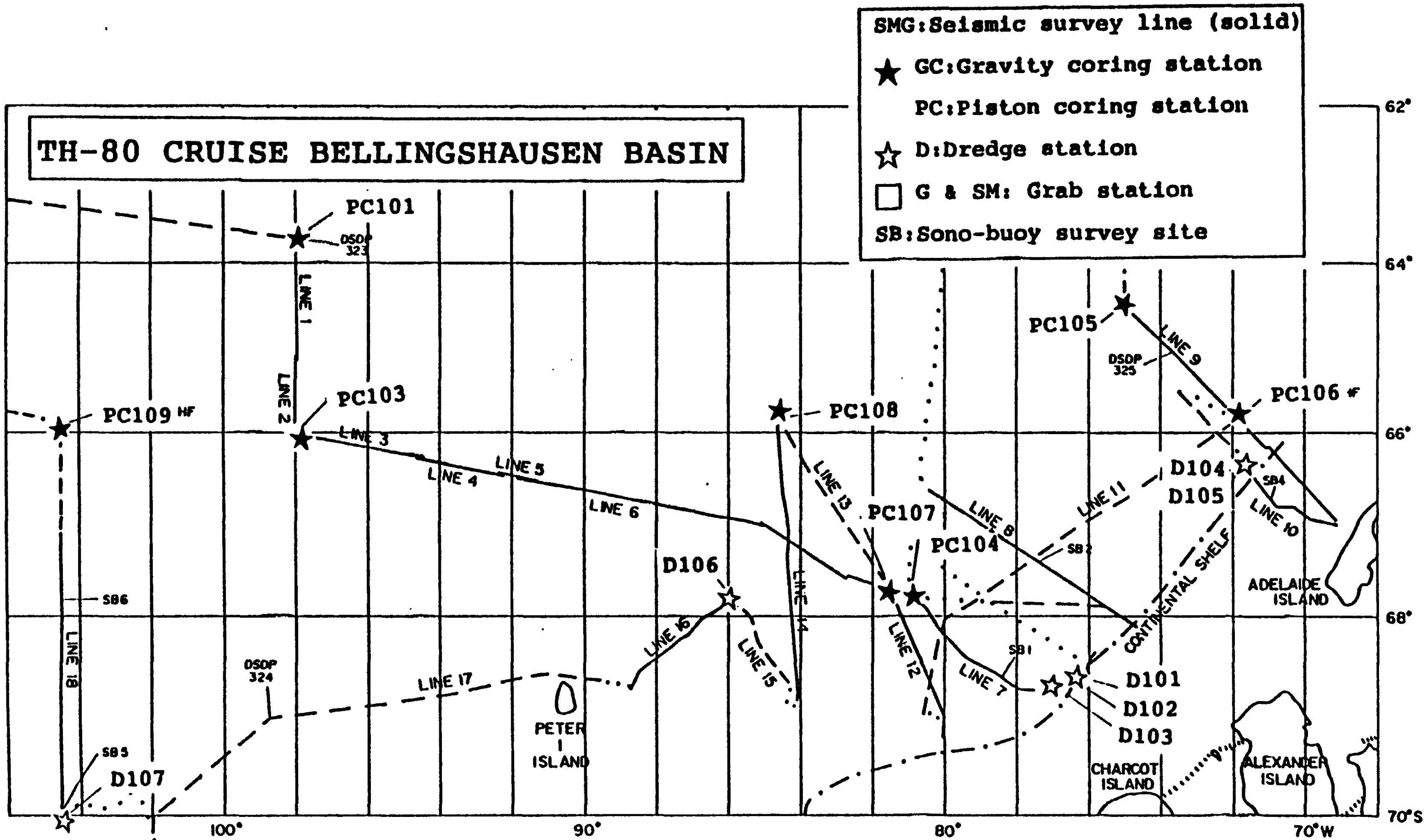
The area is bounded by the meridians of 40deg.W and 54deg.W, and the parallels of 60deg.S and 63deg.S. Six-fold seismic reflection data with total length of 2265 km, and 8 seismic refraction data were obtained during this cruise. About one third of the reflection seismic survey lines (802 km) is traceable on the island shelf around the South Orkney Islands. The rests are in adjacent slope areas, the Powell Basin and a trouth area between the Elephant Island and the South Orkney Islands. On the line 4SMG (SP500-3800), steady sedimentation of younger sedimentsis revealed in the marginal part of South Orkney Islands shelf.

Nine core samples of bottom sediments with a gravity corer (up to 7m-long barrel) were obtained. Diatomaceous ooze of the core GC808, which is one of the two cores from the island shelf, gave out so violent odor of hydrogen sulfide that they had to leave the sample on the working deck for several hours. Geologic age of siliceous (diatomaceous?) mudstones, which was dredged at the site D801 located on the eastern slope of the South Orkney Islands, were identified as lower Miocene based on a diatom fossil zone, Thalassiosira fraga Zone.

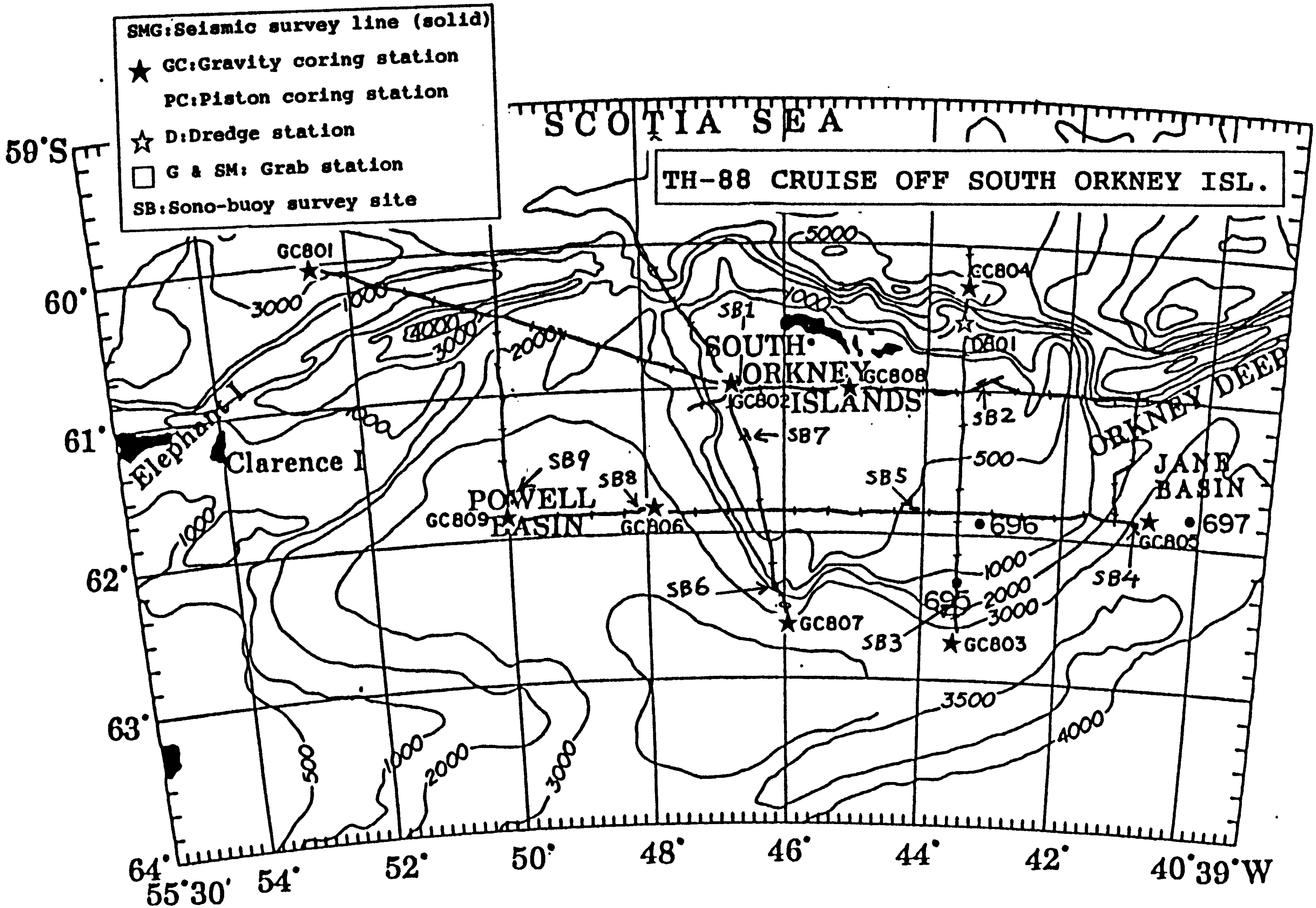
3. Bransfield Basin (TH-88 Cruise)

The area is bounded by the meridians of 52deg.W and 66deg.W, and the parallels of 60deg.S and 65deg.S. Six-fold seismic reflection data with total length of 2200 km, and 9 seismic refraction data were obtained during this cruise. About 18% of the reflection seismic survey lines (399 km) is traceable in the shelf area around the South Shetland Islands. The rests are in adjacent slope areas, and the South Shetland Trench and northward abyssal plain. Around the edge of the shelf, west of the South Shetland Islands (Line 15SMG, SP2200-2700), fan-shaped profile ofthick sedimentary strata are observed. On the line ,11SMG (SP520-740), large-scale submarine canyon is observed in spite of rather steady sedimentation of nearby older sediments.

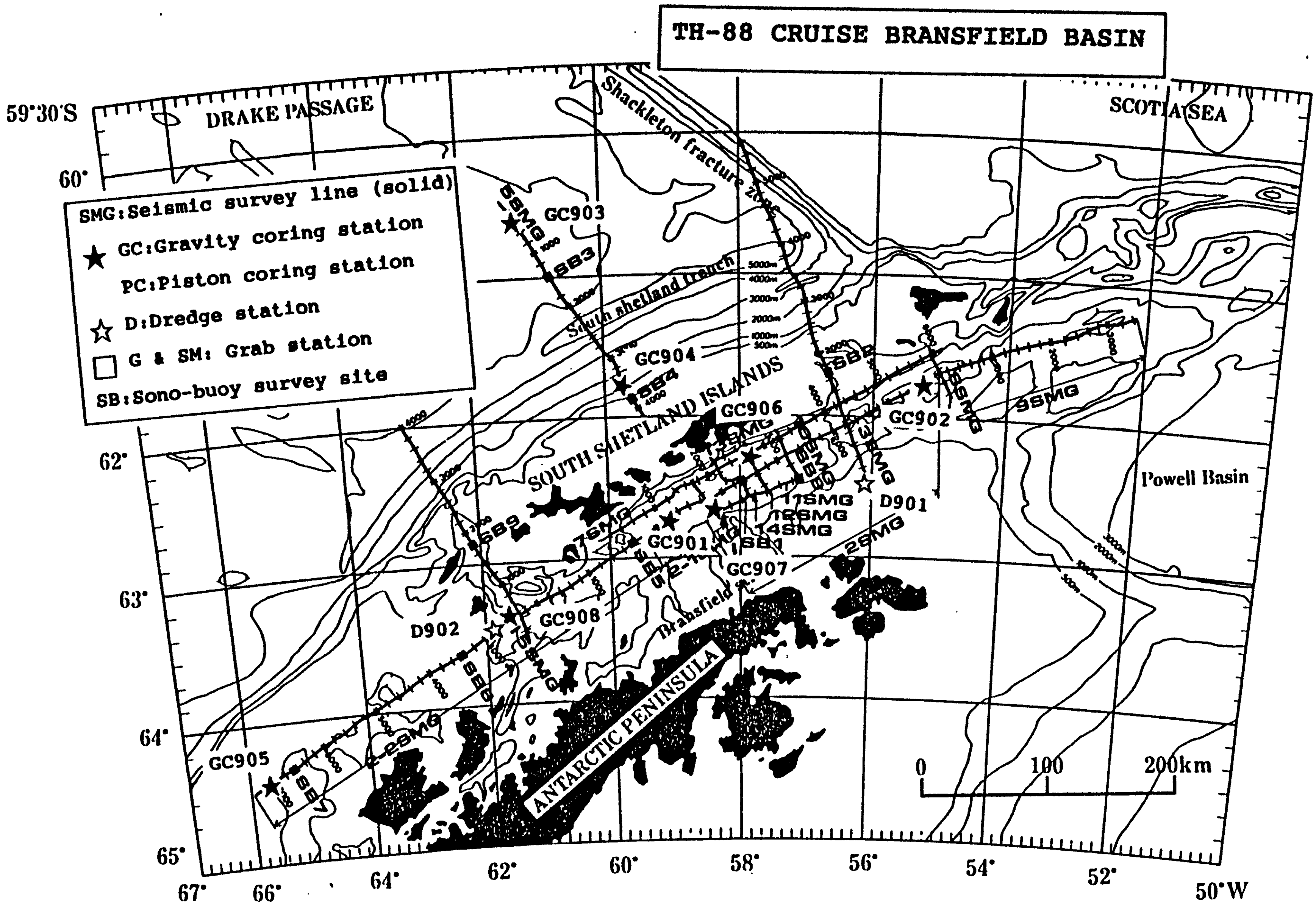
Eight core samples of bottom sediments with a gravity corer (up to 7m-long barrel) were obtained. Six cores of them are from Blansfield Basin area between the South Shetland Islands and the Antarctic Peninsula. the rest two are from abyssal plain north of the South Shetland Trench and the upper slope north of the South Shetland Islands. As to the dredge samples, volcanic breccia, tuff and slate of the sample D902 seem to be delived from exposed bedrock.



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN BELLINGSHAUSEN BASIN (TH-80)



LOCATIONS OF ACOUSTIC AND SAMPLE DATA OFF SOUTH ORKNEY (TH-87)



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN BRANSFIELD BASIN (TH-88)

Japanese Expedition Data in the Prydz Bay and Its Vicinity

Seizo Nakao (Japan National Oil Corporation,
Technology Research Center)

Nature and general specifications of Japanese Expedition on marine geoscience off Antarctica were described in the abstract for Presentation 3.1.9.

Japanese Expedition team visited so-called Prydz Bay area twice. The first one was in 1984 when they introduced a water-gun system as acoustic source for the seismic survey, instead of a air-gun system, and the second was last year (1989-1990).Data obtained during thewe cruises are outlined below.

1. Enderby Basin (TH-84 Cruise)

The area is bounded by the meridians of 68deg.E and 81deg.E, and the parallels of 62deg.S and 68deg.S. Six-fold seismic reflection data with total length of 2350 km, and 10 seismic refraction data were obtained during this cruise. Well developed Amery Ice Shelf and pack ice prevented the vessel from the continental shelf area, i.e. the Amery Basin and Prydz Bay in early 1985. Therfore, small parts of the lines 9SMG and 10SMG, 120 km in total, are traceable in the shelf area. On the line 9SMG (SP1000-2500), a series of sedimentary strata prograding seaward are observed around the shelf edge.

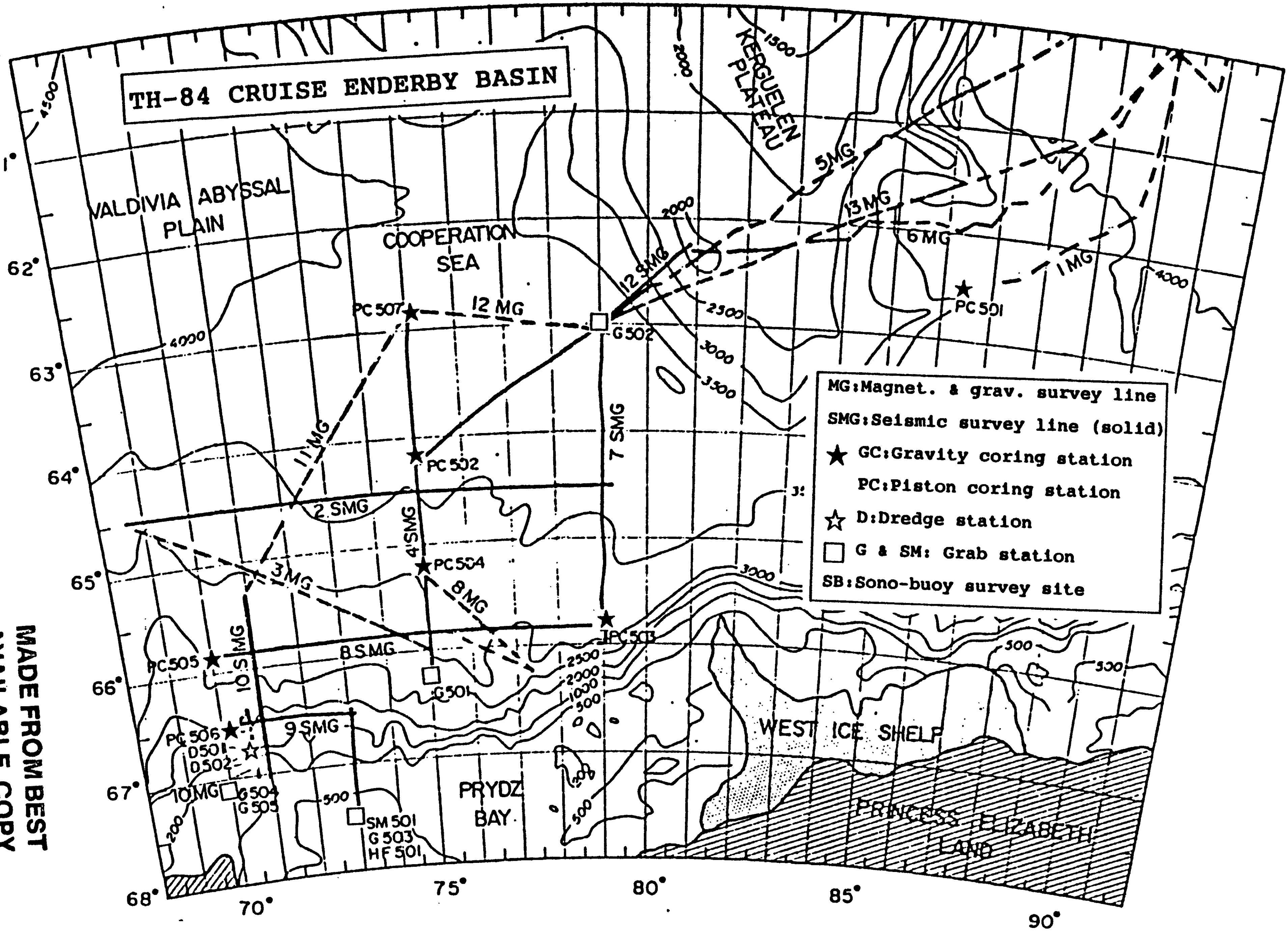
Sediment samples at 13 stations (7sts with a piston corer, 5sts with a gravity corer and 1st with a grab sampler) and dredge samples at two stations were obtained. Dredged samples from the upper part of continental slope are judged not to be autochthonous.

1. Enderby Basin (TH-89 Cruise)

The area is bounded by the meridians of 71deg.E and 81deg.E, and the parallels of 61deg.S and 69.2deg.S. Six-fold seismic reflection data with total length of 1836 km, and 10 seismic refraction data were obtained during this cruise. About 40 mile regression of the AmeryIce Shelf compared to GEBCO Chart (5.18 published in 1981) led the vessel down to the parallel of ca. 69deg.10min.S. Thus about 47% of the seismic survey line (865 km) is traceable on the continental shelf to clarify geological structure of the central partof the Amery Basin. At this opportunity, though I can show only unprocessed single-channel profiles, basement high bounding western end of the Basin is clearly shown. In the Princess Elizabeth Trough between the Kerguelen Plateau and the shelf, large-scale deep-sea channel was observed in the southern part of the lines, 3SMG and 5 SMG.

In addition to refraction seismic survey with a sono-buoy, JNOC tried to obtain refraction data with serial ocean bottom seismometer (OBS), in the shelf area and the Princess Elizabeth Trough.

Gravity core samples at 6 stations (3sts on the continental shelf, 2sts in the Princess Elizabeth Trough and 1st on the southern slope of Kerguelen Plateau) and three dredge samples all from the shelf area. One of them contains definitely autochthonous sediment (stiff mud) as groudmass of boulders D103).



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN ENDERBY BASIN (TH-84)

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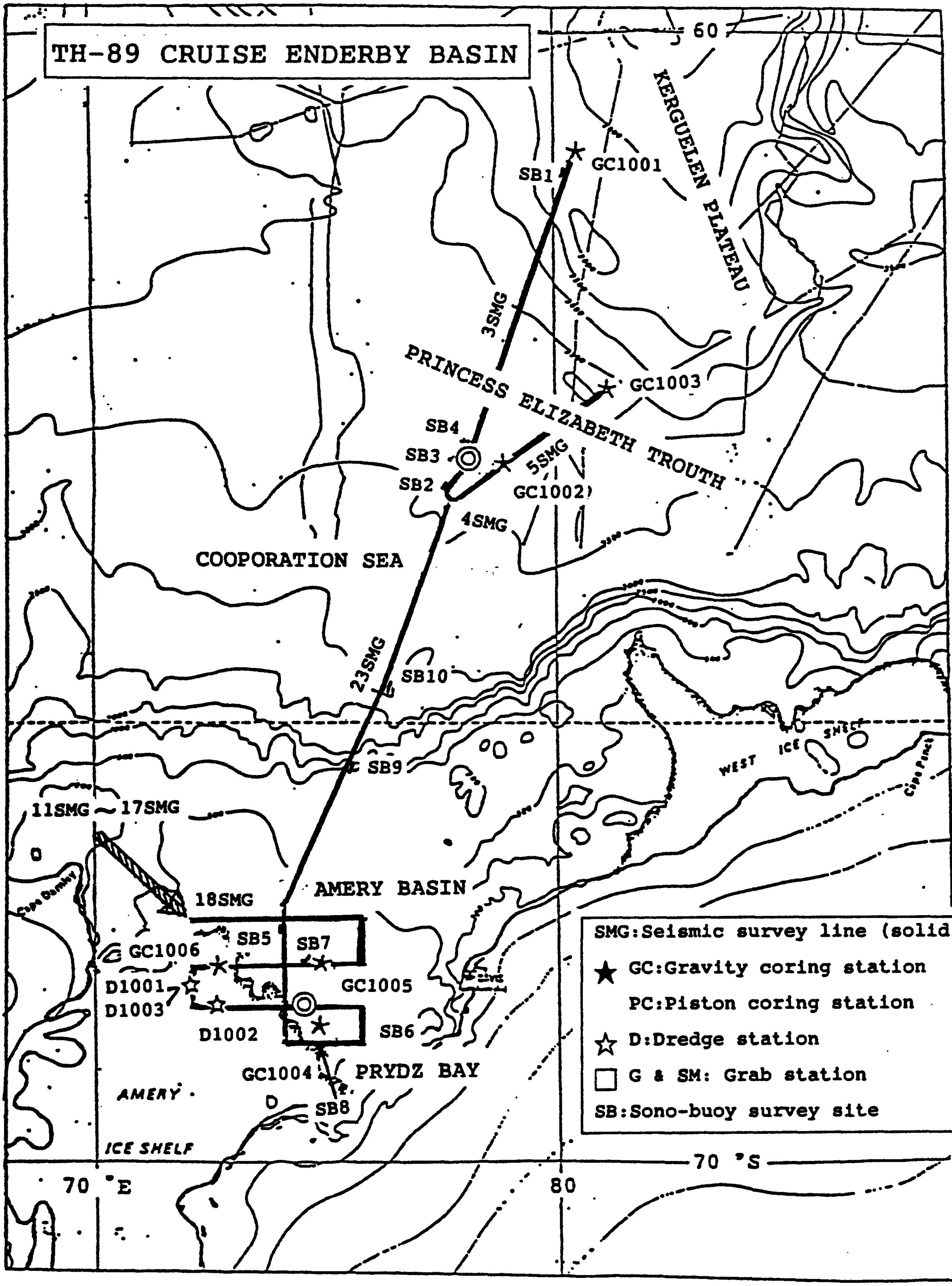

LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN ENDERBY BASIN (TH-89)

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TECTONIC CONTROLS ON SEA LEVEL CHANGE

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Sea level can be defined as the relative elevations of the Earth's land surface and the Earth's sea surface. It is important to distinguish, however, between the concepts of relative sea level and eustatic sea level. While relative sea level is the elevation of the sea surface relative to a particular point on the Earth's surface, eustatic sea level reflects the relationship of ocean water volume to ocean basin volume, and must be measured relative to some special frame of reference. Glacial variations are the most significant cause of water volume changes, but ocean basin volume is controlled primarily by plate tectonics. Figure 1 illustrates some of the various mechanisms which control sea level.

The greatest amplitude component of the tectonic control of sea level is the average age of ocean floor, which controls the average ocean depth, and reflects global mid-ocean ridge spreading rate history as well as age of subducting lithosphere (Pitman, 1978; Heller and Angevine, 1985). When new ocean lithosphere is generated at a mid-ocean ridge, it begins to cool from magmatic temperatures by conductive heat flow to the surface. Consequently, the thermal evolution is that of a cooling half-space, and any point in the lithosphere cools as a function of the square-root of time. Global average mid-ocean ridge spreading rates were slower in the Cenozoic than in the Cretaceous (Davis & Solomon, 1981), causing the ocean floor to age further before eventual subduction. This led to deeper oceans on average, and lower sea levels.

Referring to figure 2, isostasy demands that the masses in any vertical column through the lithosphere to the depth of compensation (base of deepest lithosphere) be equal. Consequently, the mass in a column at 1 and at 2 must be equal. The depth of the water thus depends on the density of the lithosphere, which in turn depends on the temperature, which cools with the square-root of time. Sea level is controlled by the average depth of all oceans. As a first approximation, a change in average ocean depth will cause an equal change in sea level. This is true to the extent that the ocean basins have vertical walls, which they do not. More accurate estimates must include the effect of coastal hypsometry, which determines the fractional rate of increase in ocean surface area with sea level rise (Harrison, 1988).

The above form of the solution of the heat equation is valid only so long as the lithosphere cools as a half-space, or about 70 m.y. After this time, the cooling thermal structure begins to feel the effects of mantle convection (Richter, 1984), and subsidence rate slows to an exponential function of time.

Continental breakup has a strong effect on the average age of ocean floor and thus on ocean depth and sea level. Breakup of Pangea created extensive new ridges, which reduced the average age of ocean floor by generating new ocean lithosphere. As time went on, however, the average age of Atlantic, Indian, etc. ocean floors increased, so that the global average age began to increase again (Heller and Angevine, 1985) (Fig. 3). This effect would have caused this component of sea level to have been a maximum in the Cretaceous, monotonically falling throughout the Cenozoic. However, some new ridges were created in the Cenozoic, creating the Red Sea, the Gulf of California, the Sea of Japan, and the separation of Antarctica from Australia (table 1).

Other important tectonic controls include continental stretching and orogeny, which reduce and increase ocean basin area, respectively, by varying continental area. Several of these events that occurred in the Cenozoic are summarized in table 1. For example, it is possible to calculate the effect on sea level of the collision of India with Asia and the development of the Alpine-Himalayan chain by continental crustal shortening by

$$SL = \frac{Ad^2}{V_o} = 84 \text{ m}$$

where
SL is sea level fall
A = reduction in continental area = increase in ocean area
= (length of suture) x (closure after contact) = 2500km x 2500km = 6×10^6 km^2
d = average ocean depth = 4 km
V_o = total present ocean volume = 1.2×10^9 km^3

Calculations of the effects of continental stretching such as that occurring in the Basin and Range province of North America can be performed in the same manner.

Submarine hot spot volcanism and the development of seamounts and ocean plateaus act to displace seawater by reducing the volume of ocean basins. The Cretaceous was apparently a period of unusually high volcanic activity in the Pacific, leading to edifice development and the direct displacement of seawater, as well as thermal uplift of the oceanic lithosphere causing further seawater displacement. This would have led to increased eustatic sea level (relative to present) of 60 to 100 m (Harrison, 1988; Schlanger et al., 1981; Watts et al., 1980). This anomalous activity apparently ceased in the Cenozoic, so that thermal subsidence led to a deepening of these areas of the ocean, contributing to the Cenozoic long-term reduction in eustatic sea level.

Besides directly controlling eustatic sea level, tectonics also modulates the measurement of sea level. There is considerable motivation to quantify eustatic variations through geologic history. A truly eustatic sea level curve could be directly applied to correlation of sequences in widely separated continental margins of all types. In addition, the eustatic signal could be filtered out of continental margin sequence stratigraphic data, so that the remaining stratigraphic information is a more direct measure of tectonics and sediment input. Given that sedimentation rate is recorded by sediment age and thickness data, the quantification of eustasy may eventually lead to a direct measure of thermal subsidence history of passive margins, and other tectonics of active margins. Furthermore, quantification of long-term eustatic variations is essential for the measurement of epeirogenic activity of continental interior sections.

Since the surface of the earth is tectonically active, different locations on the lithosphere uplift and subside relative to one another. Sea level change, in turn, effects epeirogeny through the effects of differential lithospheric rebound and water loading of continental margins (Clark et al., 1978; Farrell & Clark, 1976; Nakada & Lambeck, 1987). Consequently, if sea level is to be measured with respect to these portions of the lithosphere, these tectonically activated epeirogenic motions must be taken into account when attempting to establish the relationship between ocean basin volume and ocean water volume throughout the Cenozoic.

The melting of continental ice sheets causes unloading of the lithosphere beneath the ice, and loading of the ocean basins and margins elsewhere due to the addition of meltwater. The isostatic adjustment includes uplift of the glaciated regions, subsidence of adjacent peripheral bulges, and more complex low-amplitude effects at greater distances from the glacial load (low latitudes) (Peltier and Tushingham, 1989; in press). The response of the lithosphere to this water load represents sea level control on tectonics (epeirogeny). Peltier and Tushingham (1989; in press) corrected for the differential response to glacial meltwater loading at margins from all continents, and filtered out the resulting signal from tide gauge records, to obtain a coherent signal of a rate of present sea level rise of 2.4 mm/yr. In the regions immediately adjacent to Antarctica, the lithospheric response to the Cenozoic waxing and waning of glacial load may be the primary factor controlling relative sea level. Clark and Lingle (1977; 1979) calculated the sea level effect of future Antarctic glacial variations, and accounted for meltwater loading to obtain a value of .67 m global average sea level change for every meter of meltwater contributed by Antarctic ice, with variations depending on distance from Antarctica and distance from continental margins.

Elevation of the earth's land surface is always measured relative to sea level. We wish to measure sea level relative to the earth's lands surface. This arrangement is ripe for circularity which can be avoided by clever choice of reference frames. There are many reference frames available to choose from for the purpose of measuring eustasy, and two criteria must be considered. The first is the usefulness of the frame for measuring the relationship between ocean water volume and ocean basin volume. The second is the ability to measure sea level against the chosen frame. Each reference frame has associated with it a different method (or methods) of measurement. A few such reference frames include the center of the earth,the ocean floor, passive continental margins, flooded areas on continents, and cratonic continental interiors (fig. 4).

Eustasy could be measured relative to the center of the earth. This would measure the relationship between ocean water and ocean basin volumes provided the lithospheric surface maintained an invariant distance from the center of the earth. However, while this may fit the first criterion above, it cannot satisfy the second, as we have no direct way to measure ancient sea level relative to the center of the earth. On the other hand, if the assumption can be made that ice volume changes are solely responsible for some sea level events, then ^{18}O isotopic measurements on dated foraminifera (Matthews, 1984; Prentice & Matthews, 1988; Miller et al., 1987) or direct measurements of Antarctic ice cover (Webb et al., 1984) would provide useful data relative to this frame of reference. The necessary assumption is only valid on timescales short relative to the mechanisms responsible for changes in ocean basin volume such as changes in average age of ocean floor, seamount development, continental stretching or orogeny, sedimentation rates, etc. (Harrison, 1988).

Alternatively, the ocean floor could be defined as a frame of reference. Measurements relative to this frame would record the depth of ocean water. However, any point on the ocean floor is subject to epeirogenic subsidence in a fairly predictable manner as calculated above (Parsons & Sclater, 1977). However, the only practical way to measure ocean depth is by using ocean islands as "dipsticks" (Lincoln & Schlanger, in press; Quinn, in press), and the formation of an ocean island by hot spot volcanism perturbs the otherwise predictable ocean floor subsidence in a way not accurately quantifiable for timescales relevant to long-term sea level changes (Detrick & Crough, 1978; Sleep, 1987; Crough, 1984).

A third possible reference frame is individual (or collective) passive margins. As a consequence of their subsidence due to thermal reequilibration and sediment loading however, these regions do not satisfy the first criterion for long-term eustasy unless the subsidence (relative to a stable frame) can be quantified with precision at least as great as the precision with which we wish to measure eustatic changes. Passive margins do however, satisfy the second criterion extraordinarily well. Thick continuous sequences bounded by datable unconformities make this frame of reference ideal for measuring relative sea level changes (Haq et al., 1987; Vail et al., 1984; Hardenbol et al., 1981). In addition, for timescales short relative to subsidence (or other tectonic) rates, passive margin data can provide high resolution detail for eustatic changes.

A frame of reference that is used implicitly in hypsometric analyses is that of lowlying continental margins which are subject to flooding from time to time during marine transgressions (Harrison et al., 1983; Bond, 1978). Hypsometry involves the cross-sectional profiles (hypsometric curves) of the present continents and the percentages of present continental areas that were flooded at various times in the past based on paleogeographic reconstructions (Ziegler et al., 1985; 1982). From these data, relative sea level (relative to each individual landmass) is obtained.

A fifth possible frame of reference is that of cratonic continental interiors. It has been shown (Sahagian, 1987; 1988) that some continental regions have experienced large epeirogenic displacement and deformation and as such would be unsuitable reference frames from the standpoint of the first criterion. There are however, certain continental interior regions which have apparently not been so affected (Sahagian, 1989). The utility of stable continental interiors is limited by the second criterion to times of high sea level (relative to the chosen frame), since the sea must transgress the reference frame in order to leave a preservable sedimentary record, and thus is not very useful for the Cenozoic.

While each of these reference frames has advantages and disadvantages, it is clear that for the purpose of quantifying long-term eustatic changes that the most suitable frame is one against which eustasy is the only factor affecting stratigraphy, chemistry, or any other tools used for measurement. Other frames are only useful for special local measurements of relative sea level, since they would not reflect the relationship between ocean basin volume and ocean water volume. Ideally, data from all types of measurement should be applied to the problem so that different reference frames stable at different timescales can be tied together. This will allow the determination of eustasy to the highest degree of accuracy as well as resolution.

Tectonic activity is thus intimately related to eustasy, both as a controlling mechanism for sea level changes, and as a modulating factor affecting sea level measurement techniques. A more complete understanding of the relevant tectonic processes and specific Cenozoic events will lead to more useful sea level curves.

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TABLE 1

PARTIAL LIST OF CENOZOIC TECTONIC EVENTS WHICH MAY HAVE AFFECTED EUSTATIC SEA LEVEL

EVENT	TIME
INDIA SEPARATED FROM AFRICA	NEAR K-T BOUNDARY
GREENLAND SEPARATED FORM EUROPE	PALEOCENE
AUSTRALIA SEPARATED FROM ANTARCTICA	EOCENE
INDIA COLLIDED WITH ASIA	EOCENE
PACIFIC PLATE MOTION TURNED TO WEST	EOCENE
FARALLON PLATE LOST UNDER N. AMERICA	OLIGOCENE
BASIN AND RANGE SPREADING BEGAN	OLIGOCENE
SEA OF JAPAN FORMED	OLIGOCENE
RED SEA AND GULF OF ADEN OPENED	OLIGOCENE
S. AMERICA SEPARATED FROM ANTARCTICA	EARLY MIOCENE
MEDITERRANEAN DRIED UP	LATE MIOCENE
BAJA SEPARATED FROM MEXICO	EARLY PLIOCENE
PANAMA CUT OFF ATLANTIC FROM PACIFIC	PLIOCENE

CAUSES OF SEA LEVEL CHANGE

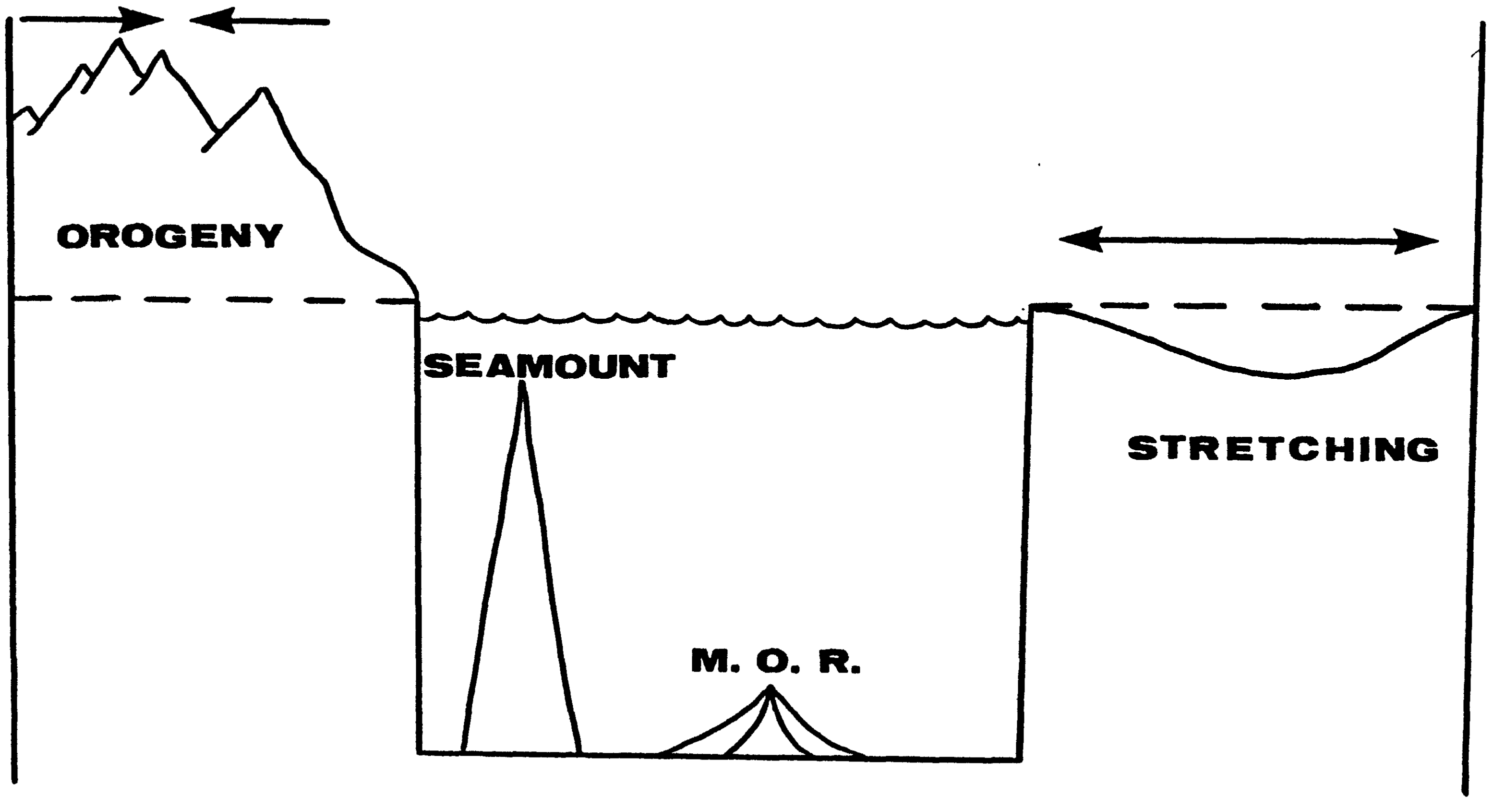

FIGURE 1

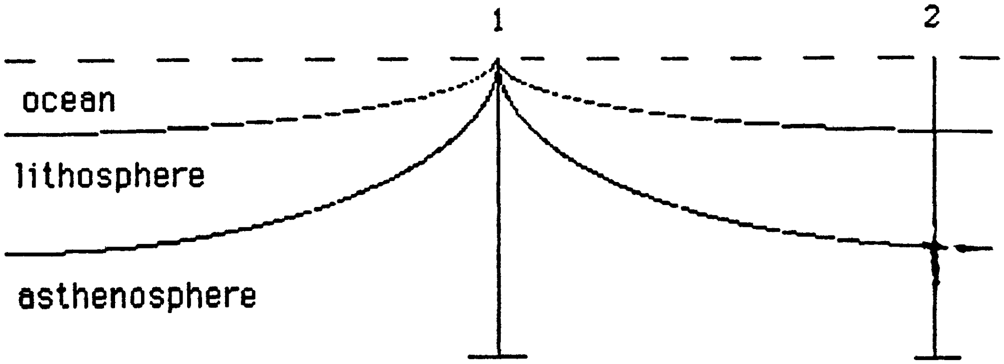

FIGURE 2

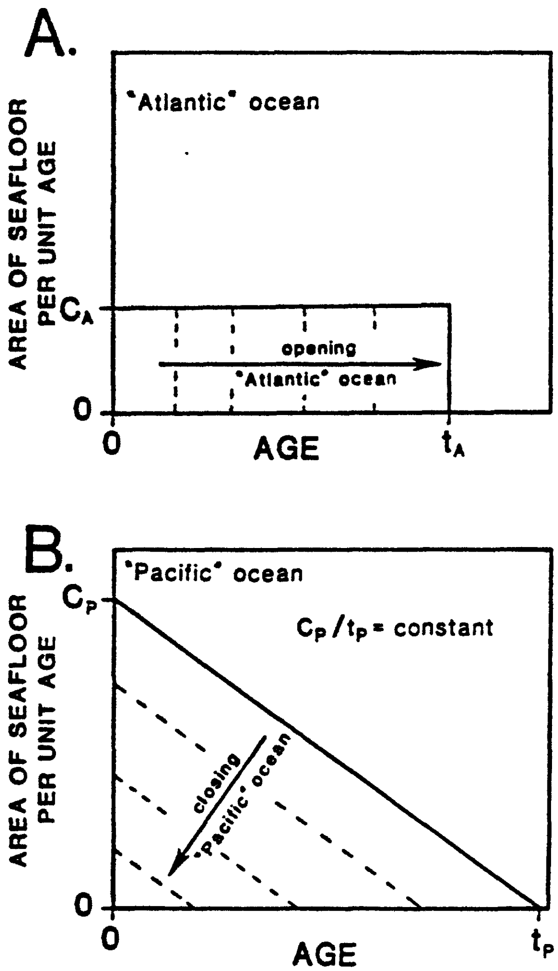

Fig. 2. Hypothetical area/age distributions for the (A) "Atlantic" and (B) "Pacific" ocean basins. The "Atlantic" ocean is assumed to spread at a constant rate C_A and has an age of t_A. As the "Atlantic" ocean continues to open t_A increases. In the "Pacific" ocean, subduction reduces the amount of older seafloor, giving a triangular area/age distribution. The "Pacific" ocean spreading rate is C_P and the age of the oldest seafloor is t_P. As the "Pacific" ocean closes both C_P and t_P decrease in such a way that the ratio of C_P/t_P remains constant.

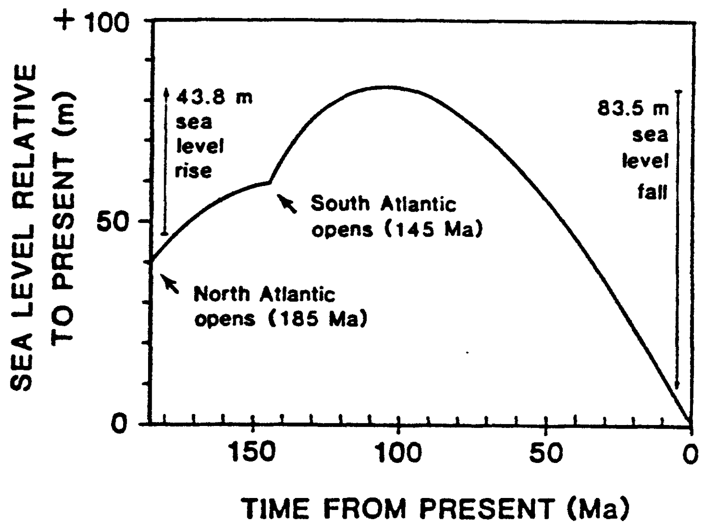

Fig. 6. Relative sea level as a function of time during a two-stage opening of the "Atlantic" ocean. The North Atlantic opens at 185 Ma with a spreading rate of 0.2 km^2/a while the opening of the South Atlantic is delayed until 145 Ma. Spreading rate for the South Atlantic is 0.26 km^2/a. Sea level reaches a peak of 83.5 m above present at 105 Ma. No corrections for continental shelf flooding have been made.

FIGURE 3

from Heller & Angevine, 1985

SEA LEVEL REFERENCE FRAMES

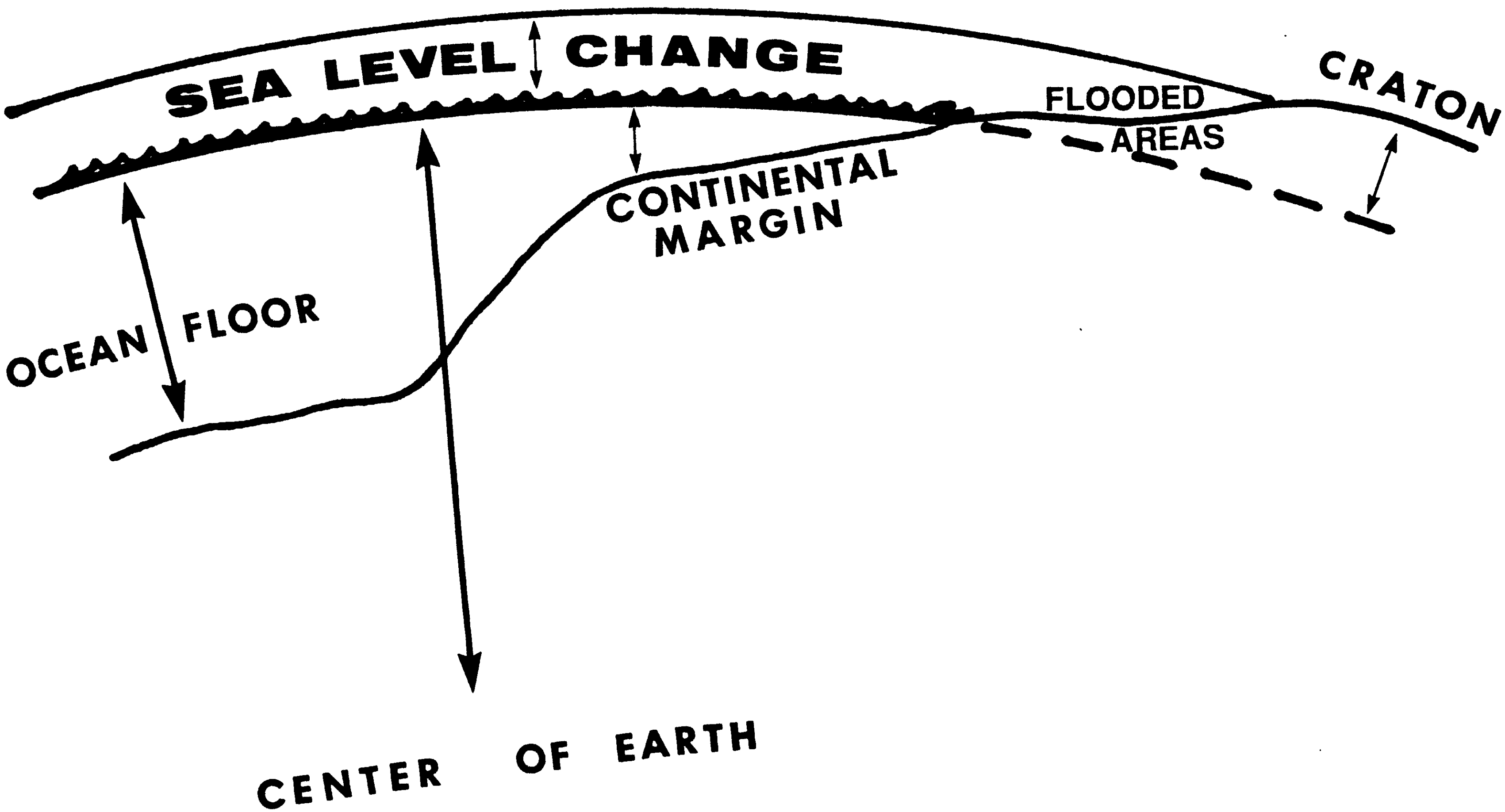

FIGURE 4

GEOTECHNICAL PROPERTIES OF GLACIGENIC SEDIMENTS, BASED ON RESULTS FROM ODP LEG 119 IN PRYDZ BAY

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Prior to ODP Leg 119 in Prydz Bay, reports on geotechnical properties of glacigenic sediments from the Antarctic continental shelf were sparse, and mainly limited to material recovered by piston, -vibro -or gravity coring. DSDP Leg 28 and the CIROS drilling cored sediments at greater depths, but only relatively limited shipboard/drillsite measurements were carried out on this material.

Five sites were drilled across the continental shelf and upper slope during Leg 119 (Fig.1) (Barron, Larssen et al., 1989). The cored sequence consisted of sediments ranging from pre-glacial terrestrial sandstones (possibly of early Cretaceous age) to Holocene diamictons and diatomaceous sediments. The main part of the recovered material however, consisted of glacigenic sediments. Particularly three sites were important from a glacigenic point of view; at sites 739 and 742, 486 and 316 m respectively of hard diamictites were penetrated, while at Site 743, 98 m of softer diamictons were drilled. The former two sites are situated at the outer shelf and have clearly been affected by grounded glacier ice, while Site 743 is situated on the continental slope, beyond the reach of grounded glaciers. The recovery was poor in these sediments (generally < 50%), and this limits the continuity of shipboard measurements as well as the chronostratigraphic control.

Standard ODP measurements of water content, bulk density, porosity, P-wave velocity and undrained shear strength, with the addition of fall cone and pocket penetrometers for shear strength measurements, were carried out shipboard. In addition to this, 24 whole-round core samples were obtained for a shore based program consisting of oedometer consolidation tests, simple shear and triaxial tests for undrained shear strength, permeability measurements, grain size analyses and Atterberg limits (Solheim et al. in press a,b). Grain size analysis was also carried out on approximately every other one of the shipboard samples analysed for index properties. Because of the unsorted character of the diamict sediments, both the shipboard index properties and the grain size distributions show a great scatter. Much larger samples than the ones usually used within ODP are needed for representative measurements.

Based on seismic sections and drilling results, the sediments included in the Prydz Bay study are likely to be representative also for other parts of the Antarctic continental shelf. Therefore geotechnical and acoustic properties similar to those found in the Prydz Bay diamictites may be expected on a regional scale.

Normally consolidated diamictons are found throughout the cored sequence at Site 743 on the slope, but only as a thin top cover, usually < 30 m, on the shelf. The physical properties of these sediments show typical down-hole trends of increased overburden. At Site 743, the water content (% of wet weight) drops from values around 20% at the top to 12-13% at 70 mbsf (meters below sea floor). Porosity drops from 36-38% at the top to 27% at 70 mbsf. Wet bulk density increases down-hole from 2.2 g/cm^3 to 2.35 g/cm^3, P-wave velocity from 1700 m/s to 2000 m/s and undrained shear strength from values around 10-30 kPa to values around 200-300 kPa.

At the shelf sites, physical properties of the diamictites show them to be highly compacted immediately beneath the top cover of normally consolidated or weakly overconsolidated diamicton, and with no further down-hole trends apparent which could be ascribed to the effects of increased overburden. Hence, the sediments clearly bear evidence of a past consolidation history. Typical values are (approximately):

	Minimum	Maximum	Average
Water content (% wet wt.)	< 10%	32%	15%
Porosity	15%	55%	30%
Wet bulk density	1.8 g/cm^3	2.5 g/cm^3	2.26 g/cm^3
P-wave velocity	1800 m/s	2500 m/s	2200 m/s

Note that the difference between these values and those for the normally consolidated diamictons found at Site 743 is relatively small. A great down-hole variation is superimposed on the average values, and within the range of variation the values for normally -and overconsolidated sediments overlap. Grain size analyses have shown all the cored sediments to have a relatively high proportion of sand relative to clay and silt. The generally low values for water content and porosity and high values for bulk density and velocity are combined effects of a relatively high sand content and overconsolidation. Frequent down-hole variations are, on the other hand, mainly effects of variations in the grain size distribution, with incresed mud content causing lowered velocity and bulk density and higher water content and porosity.

This variation is most evident at Sites 739 and 742, where it causes frequent down-hole velocity shifts, both increases and reversals, giving rise to seismic reflections. Because of the reversals, seismic refraction measurements may give erroneous results. The variations in lithology most likely reflect oscillations of the ice sheet grounding line, i.e. distance to the sediment source. However, care should be taken in interpreting seismic reflectors as glacier sliding planes.

Based on a series of oedometer tests, run to loads as high as 24,000 kPa, the diamictites of Sites 739 and 742 are shown to be highly overconsolidated (Solheim et al., in press). Preconsolidation stresses up to 10,000 kPa are measured, and this is interpreted to be caused by former loading by sediments that subsequently were removed in periods of extensive glacial erosion. Distinct stepwise increases in Pc′ therefore contain important glacial history signals, but do not necessarily imply any distinct changes in other physical properties. Very rough estimates based on the measured preconsolidation stresses indicate a total erosion in excess of 1 km on the Prydz Bay shelf.

Undrained shear strength was generally too high to be measured by the shipboard devices (> 900 kPa). Four triaxial tests and one simple shear test show shear strengths up top 2500 kPa. Because of development of negative pore pressures during the tests, the stress-strain curves do not show clear maximum values, and exact values for undrained shear strength are difficult to estimate.

Permeabilities were estimated from the consolidation tests and measured in oedometer and triaxial cell. The values are low and classify as being of low permeability to practically impermeable. As permeability decreases considerably more rapidly than porosity with increasing degree of consolidation, the low permeabilities may be a function of the overconsolidated state of the samples. Despite the low permeabilities, estimates indicate that full compaction of the sediments may be achieved well within the time frames under consideration when discussing the glacial history of Antarctica.

Geotechnical properties like the ones found for the sediments in Prydz Bay are typical for glacigenic sediments also in other shelf areas that have been heavily affected by the action of grounded glaciers, e.g. the Barents Sea (Solheim et al., 1988, Solheim, in press) and the North Sea (e.g. Løken, 1976, Eide & Andersen, 1984). A main difference between the Antarctic and Arctic regions in terms of glacial history is the total time for Cenozoic glaciations, which differs by one order of magnitude between the two regions. Still, sediment thicknesses of the same scale as in Prydz Bay may have been eroded from the Barents Sea during the Quaternary (Riis & Eidvin, 1990).

Another aspect with the Prydz Bay sediments is that the bulk of the recovered sediments are interpreted as being deposited in a relatively ice proximal environment. Most likely the major part of the glacier distal sediments have been removed by erosion. Therefore, as the physical properties variations to a large degree are functions of lithology superimposed on consolidation effects, the Prydz Bay material mostly represents the lower end of the range for water content and porosity values and the higher for velocity and bulk density in glacigenic sediments.

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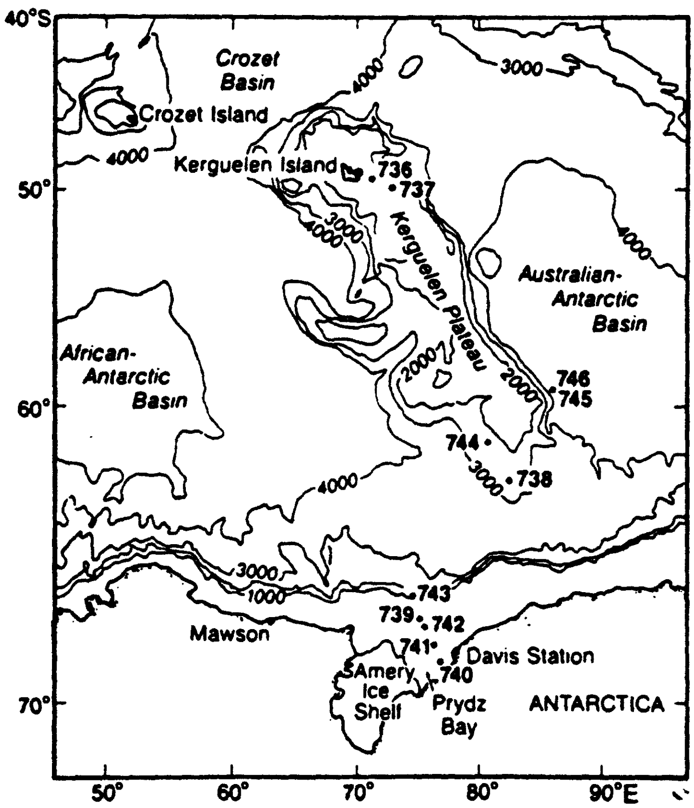
FIGURE CAPTIONS

Fig.1. Sites drilled during Ocean Drilling Program Leg 119.



40°S
50°
60°
70°
50°
60°
70°
80°
90°E
Crozet Basin
Crozet Island
4000
3000
Kerguelen Island
736
737
Kerguelen Plateau
Australian-Antarctic Basin
African-Antarctic Basin
2000
746
745
744
738
743
1000
739
742
741
740
Mawson
Davis Station
Amery Ice Shelf
Prydz Bay
ANTARCTICA

Fig.1

SHALLOW GEOLOGICAL AND GEOPHYSICAL DATA FROM THE SOUTHEASTERN WEDDELL SEA.

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Shallow geological and geophysical programs have been carried out during three Norwegian Antarctic Research Expeditions (NARE), in 1976/77, 1978/79 and 1984/85. In all three cruises, the principal study area has been the southeastern Weddell Sea, from the Riiser Larsen ice shelf southwestwards to the Filchner ice shelf. Main emphasis has been on the Crary Trough (Fig.1), running from the Filchner Ice Shelf northwards to the shelf edge. The main objectives of the programs have been:

- Investigations of the types, thickness and distribution of unlithified sediments covering the bedrock, and also to map suitable areas for future bedrock sampling by means of shallow rock-core drills or related equipment.
- To study the glacial history of the Weddell Sea shelf, with main emphasize on establishing the maximum extent and timing for withdrawal of the last ice sheet that covered the Weddell Sea shelf.
- To investigate sediment facies distribution, lithology and depositional rates outside ice shelves.
- Mapping and characterization of bedforms related to iceberg scouring.

The following data base has been acquired:

- 3000 km of analogue, single channel seismic data , using 1-5 kJ sparkers as source and band pass filtering of 80 - 500 Hz. The quality of the sparker data is variable, but particularly from NARE 1984/85 good quality data exist. In general the penetration is 0.5 - 1.0 s, giving a good coverage of the unconsolidated sediments and the uppermost bedrock (Fig.2).
- Approximately 5000 km of 3.5 kHz PDR data (O.R.E. Mod.140). These data show poor penetration and provide only sparse information on the thickness and type of the uppermost sediments.
- 200 km side scan sonar data, using Klein Mod. 400 with 100 kHz transducers, mainly concentrated in a local area outside Riiser Larsenisen. Good records on various types of iceberg scouring were obtained.
- 40 shallow cores, mainly taken with gravity corers (3 m and 6 m) and a 3.5 m vibrocorer. Core lengths are between 0.1 m and 3.5 m.
- 14 grab samples
- 16 dredge hauls
- Sea floor photographs from approximately 20 of the coring stations.

The sparker data indicate crystalline basement rocks to be exposed in the easternmost part of the Crary Trough (Elverhøi & Maisey, 1983). Along the deeper parts of the trough the basement rocks are overlain by an onlapping sequence of stratified sedimentary rocks, dipping seawards. A major, regional angular unconformity forms the boundary to the overlying acoustically more transparent sediments. The latter forms a thin flat-lying sequence in the inner and central parts of the Crary Trough, and based on sediment cores and the acoustic character, these sediments are interpreted to be of glacigenic origin. The cover of glacigenic sediments is generally less than 50 ms (two-way time) in the inner parts of the shelf and locally almost absent. Internal reflectors are sparse and can rarely be followed over long distances. The thickness increases northwards, and a > 200 ms sediment complex forms a sill in the outer part of the trough. This complex consists of two units of different acoustic character, one resting unconformably on the other. The upper unit is also clearly eroded, as internal reflectors can be followed to outcrop on the flanks of the complex. Hence, this sediment complex most likely represents several glaciations, and the upper unit, which forms the main part of the topographic sill, is an erosional remnant of a formerly more extensive layer.

Towards the shelf edge the thickness of assumed glacial sediments increases beyond the sparker penetration and deeper seismic data are needed to map the sediment wedge. However, based on the results of ODP Leg 119 drillings in Prydz Bay (Barron, Larsen et al., 1989), the division between glacial sediments and pre-glacial sedimentary rocks is not straightforeward in the outer continental shelf, based on seismic records alone. Therefore, great uncertainties exist in determining the total thickness of glacial sediments until "ground truth" is obtained through drilling.

The sediment cores from the shelf generally show a thin (< 2 m) layer of soft, glacial marine sediments covering a firmer and more pebbly sediments (Elverhøi & Roaldset, 1983). The latter sediments are clearly overconsolidated, but with undrained shear strengths often found in an "intermadiate range", less than 100 kPa. This a situation equivalent to that found in other glaciated shelf areas, e.g. the Barents Sea (Elverhøi et al., in press; Solheim et al., in press), and may result from poor drainage of water in a deformation zone under a grounded ice sheet (Boulton & Jones, 1979). Extrapolation from Holocene dates indicate a Late Weichselian (Late Wisconsin) age for the base of the soft sediments, indicating an extended ice sheet being grounded to the shelf edge in Late Weichselian time. Two radiocarbon dated shells in firm material from the southeastern flank of the Crary Trough sill complex give infinite ages, while one dating near the shelf edge west of the Crary Trough gives 31 kY only 15 cm below sea floor. The latter date further favours the existence of a grounded Late Weichselian ice sheet out to the shelf edge (Elverhøi, 1981).

The side scan sonar survey off the Riiser Larsen Ice Shelf show that most sea floor morphological features in the scale of 10-100 m are related to the action of grounded icebergs (Lien et al., 1989).

Iceberg plough marks of a similar appearance as those from Arctic regions prevail, despite the abundance of large, tabular icebergs in the Antarctic. On sloping sea flor, gravity driven sediment movement may be induced by the grounded icebergs. This may cause a hummocky appearance of the sea floor. Grounded icebergs close to the ice shelf may be pushed directly by the advancing ice front, which is a mechanism unique to the ice shelf environment.

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FIGURE CAPTIONS

Fig.1. Shallow seismic (sparker) lines in the Crary Trough region. There are also lines in two local areas eastwards along the coast, at approximately 16-17° W and 1-2° W.

Fig.2. Sparker profiles from the Crary Trough; A. Line 14-85, B. Line 17-85, for location, see Fig.1.

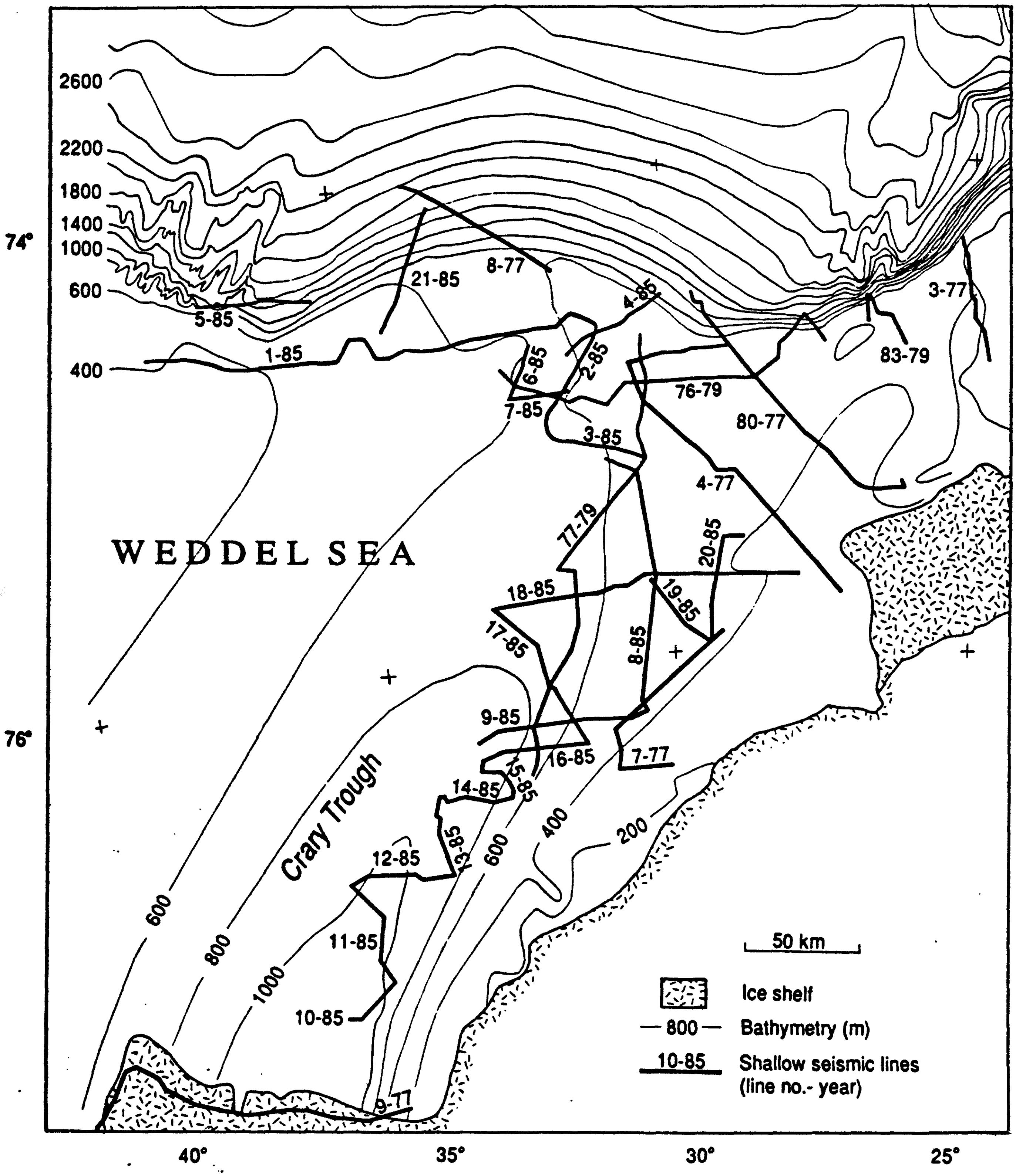
2600
2200
1800
1400
1000
600
400
74°
76°
40°
35°
30°
25°
WEDDEL SEA
Crary Trough
5-85
1-85
21-85
8-77
4-85
6-85
2-85
7-85
3-85
76-79
80-77
4-77
3-77
83-79
77-79
20-85
18-85
19-85
17-85
8-85
9-85
16-85
15-85
14-85
7-77
13-85
12-85
11-85
10-85
9-77
600
800
1000
600
400
200
50 km
Ice shelf
800
Bathymetry (m)
10-85
Shallow seismic lines
(line no.- year)

Fig.1.

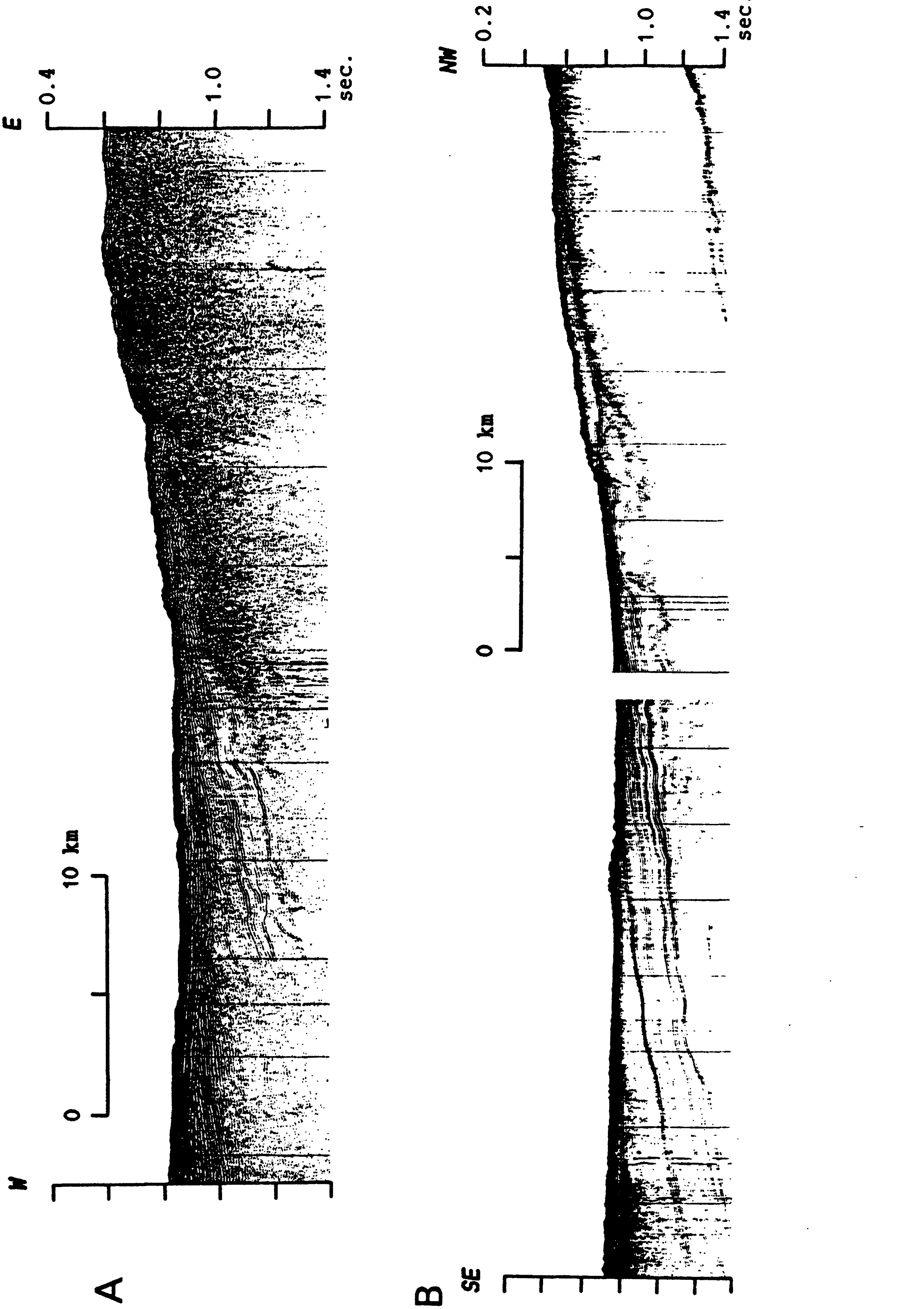

Fig.2.

Australia's Offshore Antarctic Program: Current Data Availability and Future Intentions

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PAST PROGRAM - PRYDZ BAY

Between January and March, 1982, the Australian Bureau of Mineral Resources (BMR) acquired approximately 5000 km of 3- and 6-fold reflection seismic data along a series of traverses across Prydz Bay and the adjacent continental margin (Figs 1, 2; Table 1) aboard the Antarctic resupply vessel *Nella Dan*. Abnormally good ice conditions in that season allowed many lines to be shot to within 20 km of the coast in Prydz Bay. However, grounded icebergs west of Prydz Bay restricted the survey in that area to the outer shelf and continental slope, with the exception of a single line that traversed the entire shelf, east of Mawson Station.

Since the *Nella Dan* was a less-then-ideal seismic platform, data quality varied widely, dependent particularly on the weather. In optimum conditions, penetration of >2.5 s TWT could be achieved on the continental slope and rise, where water-bottom multiples were too deep to be a problem. Principal data problems included severe water-bottom multiples, which could not be removed by processing due to the short streamer length, tow noise, and clipping of the water-bottom reflection. This latter problem has made it impossible to systematically remove the 'bubble pulse' from the airgun signature, and this bubble pulse is characteristic of all the shallow water sections. Despite these problems, the overall data quality is moderate, permitting the resolution of quite fine-scale structuring and stratigraphy, particularly on the continental rise. The combination of limited depth of penetration and shallow-water multiples means that the Prydz Bay data set is best-suited to the study of Cainozoic structure and stratigraphy.

Interpretation of the Prydz Bay data has been in two phases. The initial interpretation by Stagg (1985) had no geological 'ground truth' available, and was based on analysis of seismic stratigraphy and structure from unprocessed seismic data in combination with sketchy geological information from adjacent areas and pre-breakup reconstructions against the east coast of India. The second phase of interpretation was instigated by the drilling of five stratigraphic holes in Prydz Bay during ODP Leg 119 (Barron, Larsen, *et al.*, 1989). This new information has allowed a major revision to the previous interpretation (Cooper *et al.*, in press), and prompted the completion of seismic processing for the BMR data. Studies of the combined seismic/drill data set are continuing.

All data have been processed to stack stage, as outlined in Table 2. Field and stacked data tapes and film and paper copy seismic sections are available on a line-by-line basis, with standard BMR purchase costs and discounts applying. Alternatively, BMR will consider any proposed data exchange arrangement with sister organisations overseas that hold data off East Antarctica that is of interest to Australia.

FUTURE AUSTRALIAN PROGRAM

The Australian marine geoscience program in Antarctica has effectively been dormant since the Prydz Bay cruise in 1982. Since then, several attempts have been made to get a long-term program back into the water, with the dual aims of solving some of the geoscience problems of the Antarctic margin and of providing information of value to the Antarctic Minerals Convention. These attempts, which were based on using the BMR's research vessel *Rig Seismic* and which required funding outside our normal sources, have not been successful. With the decision of the Australian Government to oppose the Antarctic Minerals Convention and the intention to push for the setting up of an International Antarctic Heritage Park, it is obvious that an Australian program for work off Antarctica must have substantially different aims to programs which have been proposed previously. BMR Marine Division is now actively looking at the possibility of using *Rig Seismic* in Antarctica as part of the vessel's normal annual program (as opposed to an 'add-on' program). The revised program, which could commence in 1992, has the following aims (Stagg & Davies, 1989):

1) to define the sedimentologic and geochemical evolution of the margin; and

2) to decipher the record of past environmental change such as carbon dioxide flux, onset and periodicity of Antarctic glaciations, and Southern Ocean circulation patterns.

The Program is intended to have three elements:

1) Environmental Baseline Studies
   - definition and distribution of seabed bathymetry and substrate types on the continental shelf, with a view to recognising the principal breeding and feeding grounds for Antarctic marine faunas;
   - definition of geochemical baseline levels and processes involving metals and nutrients in both sediments and water column as an aid to estimating the advance of pollution and to define future management policy.

2) Geoscience Studies in Unique Wilderness Laboratory
   - the effects of ice rafting on shelf sedimentation and morphology;
   - the mechanisms, rates, and timing of glaciations and their relation to sea level;
   - the processes and rates of formation of certain sedimentary minerals, *eg* carbonate and organic carbon production and preservation under conditions of low temperatures;
   - studies of conjugate margins (*eg* East Antarctica and southern Australia; East Antarctica and the east coast of India). Recent models of passive margin formation propose that conjugate margins are inherently asymmetric; rational analysis of this major geological problem therefore requires the simultaneous study of passive margin <u>pairs</u>. As the structures that control passive margin formation lie at depths of a few kilometres to Moho, it follows that solutions to understanding their formation will require deep penetration seismic data.

3) Studies of Global Climatic Change
   - The Southern Ocean, and particularly the seas surrounding the Antarctic margin are key elements in the present global climate system. A detailed record of the forcing functions of climatic change occurs in the Antarctic sedimentary record. Data collected will define when and how climate fluctuations occur, and an estimate of the variability of oceanic CO_2 and heat flux over time and their effects on oceanic and atmospheric circulation. These studies, together with studies of the mechanisms and timing of major glaciations will define the natural variability of climate and sea level change. In particular, such studies will provide a

better basis for predicting the next glacially-induced sea level fall, against which predicted greenhouse effects must be judged.

The tools that it is anticipated would be used in this program include multichannel seismic (MCS) with large (1600 or 3200 in^3) airgun array, high-resolution MCS with water-gun array (400 in^3), piston-gravity- and vibro-coring, and water-column sampling.

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Table 1: BMR Prydz Bay Seismic Data - Recording Parameters

Vessel: Nella Dan	
Ship Speed: 5.5 or 6.7 knots	Shot Interval: 25 or 50 m
Source: 1 x 8.194 litre airgun	Source Depth: 6 m
Group Length: 50 m	Nominal Cable Depth: 8 m
No. of Traces: 6	Leading Trace: 1
CDP Spacing: 25 m	Coverage: 3- or 6-fold
Near Offset: 175 m	Maximum Offset: 425 m
Sample Rate: 2 ms	Record Length: 6000 ms
Data Recording Format: BMR SEG-Y	

Table 2: BMR Prydz Bay Seismic Data - Processing Sequence

1. Geometry definition
2. Reformat to Cogniseis DISCO internal format.
3. Resample to 4 ms.
4. Static correction for start of data.
5. Spherical divergence correction.
6. Velocity analysis.
7. Normal moveout correction.
8. 3- or 6-fold stack.
9. Bandpas filter from 20-80 Hz
10. AGC with 200 ms gate (for display only).
11. Output of stack data to SEG-Y tape.

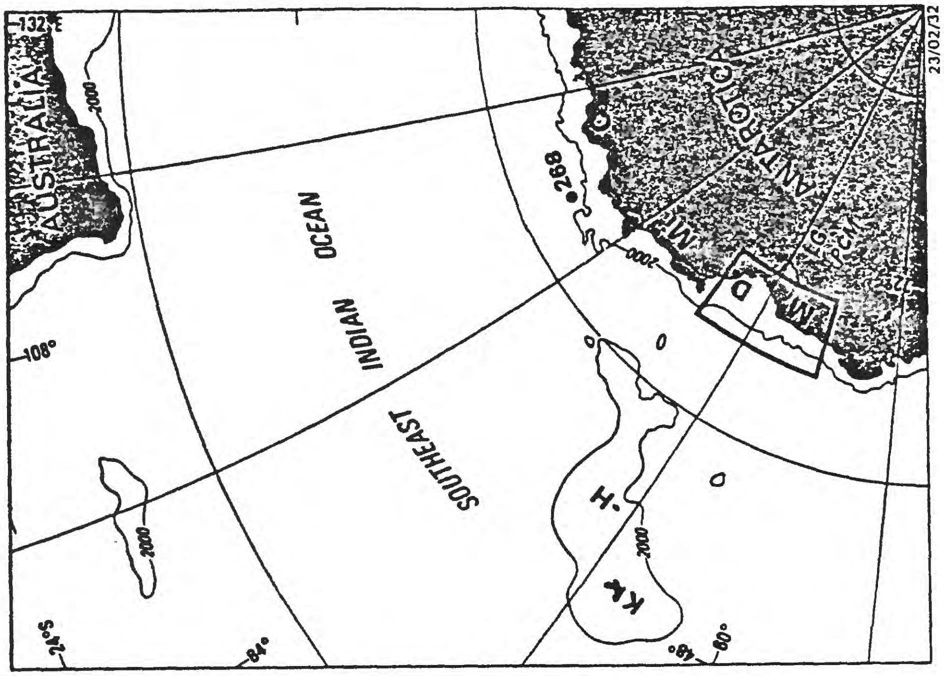

Figure 1: Map showing location of survey area in East Antarctica. Abbreviations: K - Kerguelen Is; H - Heard Is; M - Mawson Station; D - Davis Station; Mi - Mirny Station; C - Casey Station; LG - Lambert Graben; PCM - Prince Charles Mountains.

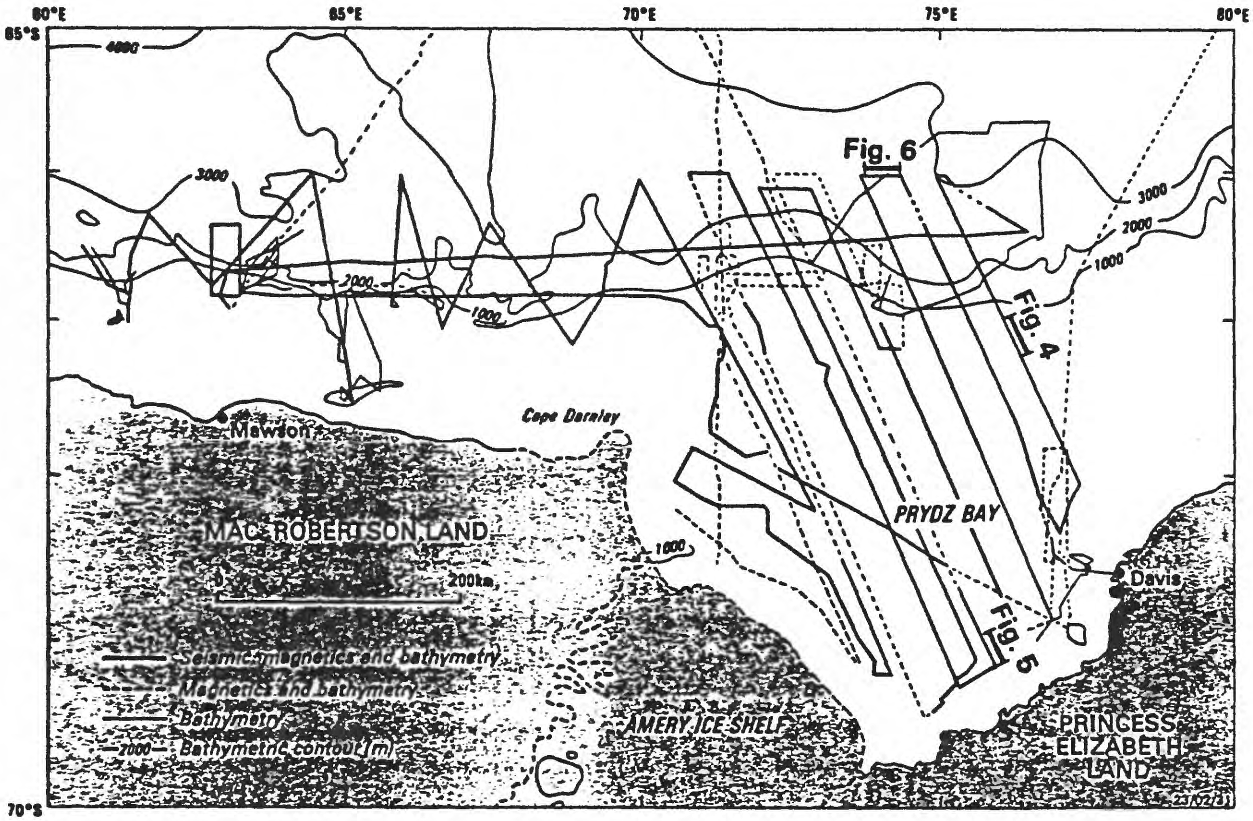

Figure 2: Tracks of the M.V. *Nella Dan* during the 1982 BMR survey. Locations of seismic sections illustrated by Stagg (1985) are shown.

Cenozoic Sequences from the Continental Rise North of Prydz Bay

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The 1982 BMR seismic survey of the Prydz Bay region was concentrated on the continental shelf (Fig. 1), although most lines extended onto the continental rise. Subsequent interpretations also concentrated on the geology of the rocks underlying the continental shelf, culminating in the drilling of a transect of five holes across the shelf by the Ocean Drilling Program (ODP; holes 739-743) in early 1988. Four of these holes penetrated Cenozoic to ?Mesozoic sequences on the shelf (Barron, Larsen, *et al.*, 1989), while the fifth hole (Site 743) penetrated 98 m of ?Quaternary intebedded sand, silt, and gravels, largely of glacial origin, at a water depth of 989 m on the upper continental slope. In this abstract, we present a brief interpretation of the Cenozoic sedimentary sequences underlying the continental rise, north of Prydz Bay.

The seabed morphology of the continental slope and rise from 65-80°E shows three distinct sectors. From 70-74°E, a prominent northward bulge can be mapped in the bathymetry; the surface of this feature appears to be smooth and little-affected by present-day canyon development. From 65-70°E and 74-80°E, the slope and rise are dominated by two valley/canyon systems that drain to the NNW and NNE, respectively. Cooper *et al.* (in prep.) have interpreted the continental slope 'bulge' as being the surface expression of a slope fan deposit at the outlet of a wide glacial erosion channel that extends north-south across the continental shelf to the Amery Ice Shelf; in this abstract, we will refer to this feature as the Prydz Bay Fan (PBF).

SEISMIC DATA

Unprocessed seismic data imaging Cenozoic sediments beneath the slope and rise were described briefly by Stagg (1985), who identified two seismic sequences - PD 2 and PD 1. PD 2 was described as 'not strictly a seismic sequence' as it appeared to consist of a number of poorly-defined sequences containing moderate amplitude reflectors of generally low continuity; the sequence was interpreted to consist of marine sands and shales of Cretaceous and Cenozoic age. Sequence PD 1 was deduced to be Pliocene and younger turbidites and hemipelagic sheets. The improved quality of the processed seismic data now available, and the age and lithology information from ODP driling, permits some refinement of this interpretation.

Even with the availability of ODP data, dating of the seismic sequences beneath the slope and rise is problematic, principally because of the difficulty in tracing seismic reflectors through the shallow seabed multiples at the edge of the shelf. However, it appears that the majority of the seismically-visible section on the slope and rise is of Cenozoic (Late Paleogene and younger) age.

The slope/rise sequences have been deposited in two apparently quite different settings that overlap in space and time. Beneath the PBF, the Cenozoic section has the form of a fairly simple fan, showing little internal channel/canyon development. In this area, a prominent and highly continuous reflector lying 0.5-1 s TWT below seabed can be traced from the continental rise on to the outer continental shelf (Fig. 3). This reflector, which is a mild erosional unconformity and may correspond to reflector 'A' of Mizukoshi *et al.* (1988) can be tentatively traced landwards to the vicinity of Site 739, indicating an age in the range of Early Oligocene to Late Miocene. We speculate that the unconformity may reflect the final separation of Australia and Antarctica in the mid-Oligocene (*ca* 32 Ma) and the initiation of the Circum Antarctic Current. The post-mid-Oligocene section thins onto the continental rise, and it seems that sediments have partly bypassed the PBF since that time.

In the valley/canyon zones east and west of the PBF, seismic character becomes highly variable and reflector continuity is generally poor. While the ?Oligocene unconformity is somewhat difficult to trace in this area, it does apear to pre-date the onset of canyon development - ie canyon development probably began in the Late Oligocene or Early Miocene. Sedimentation within the canyons is restricted, except in abandoned channels, and the bulk of post-mid-Oligocene sediments have been deposited as thick levees and overbank deposits adjacent to the canyons (Fig. 4). These levee deposits have produced the NNW- and NNE-trending ridges that are now evident in the bathymetry. The seismic character of the levees is highly-distinctive, with bands of thin, continuous reflectors being interbedded with zones that are seismically quite transparent or which contain chaotic reflections. Extensive syn-sedimentary faulting soling out above the ?Oligocene unconformity is indicative of rapid deposition of fine-grained sediments and of a major change in the sediment properties at that level. We speculate that the seismic character may be due to the interbedding of glacial and interglacial sediments, with the transparent/chaotic zones perhaps corresponding to poorly-sorted glacial debris (including boulders) deposited during glacial maxima. If this is correct, then the levee deposits may prove to be suitable sites for the recovery of samples detailing the Miocene and younger glacial history of this part of the Antarctic margin. Such deep-water samples should have the advantage of not having been subjected to over-compaction by grounded ice sheets, as has occurred on the shelf.

DEPOSITIONAL HISTORY - SLOPE AND RISE

The Cooper *et al.* (in press, fig. 15) conceptual model of depositional environments associated with a grounded and moving ice sheet, predicted that in going from just below the shelf edge out to deep water, the sediments deposited changed from basal glacial debris (with a large coarse component), through gravity-flow deposits with intermingled dropstones from melting icebergs, to mainly biogenic debris with occasional dropstones. We believe that this depositional model describes the formation of the PBF, particularly pre-mid-Oligocene, and the formation of the slope below the mid-Oligocene unconformity in the canyon zones.

Wright & Anderson (1982), in a study of sediments from the continental margin in the Weddell Sea, suugested two models for the formation of slope canyon deposits on over-deepened Polar margins, where eustatic lowstands (which are commonly assumed to be responsible for canyon initiation and sediment supply on low-latitude margins) have had little effect. The alternative models were - 1) shelf-edge contour currents causing winnowing of poorly-sorted shelf edge silt, sand, and gravel, and their transport into the heads of canyons, and 2) glacial outwash streams. Since canyon development off Prydz Bay is interpreted to post-date the mid-Oligocene unconformity which is presumed to correlate with onset of the Circum Antarctic Current, we believe that the first of the Wright & Anderson models is the more likely in this area. We also note that the marked change in sequence stratigraphy at the ?Oligocene level may be accounted for by the change in sedimentation from mainly glacial debris eroded off the shelf and deposited from the ice-base, to a combination of glacial debris and sand/silt winnowed from the shelf and upper slope by contour currents.

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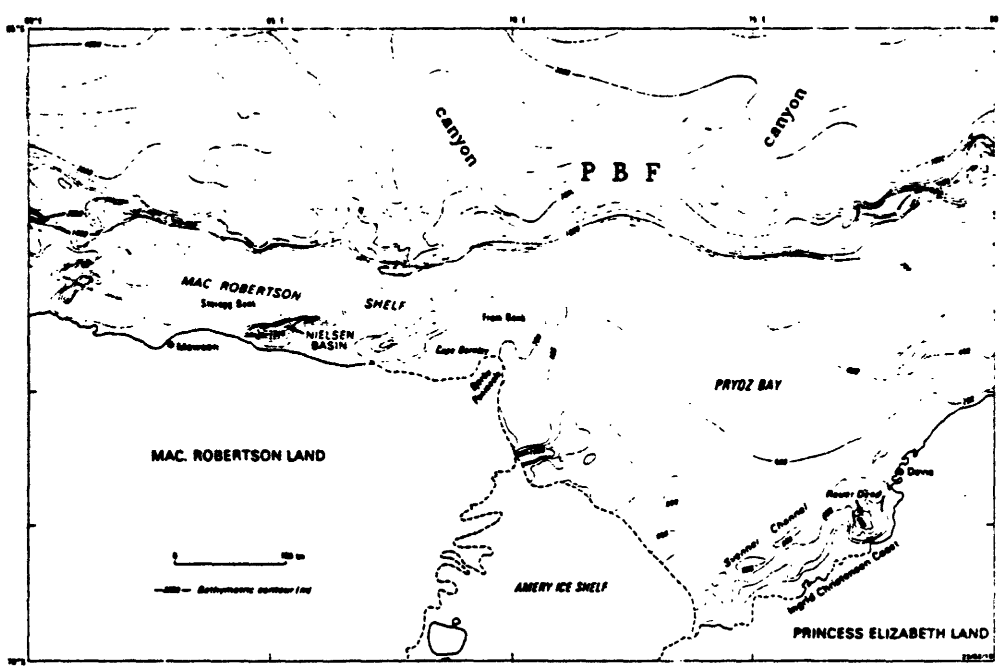


Figure 1: Bathymetry of the Prydz Bay region; contours in metres. Prydz Bay Fan (PBF) and adjacent canyons are shown.

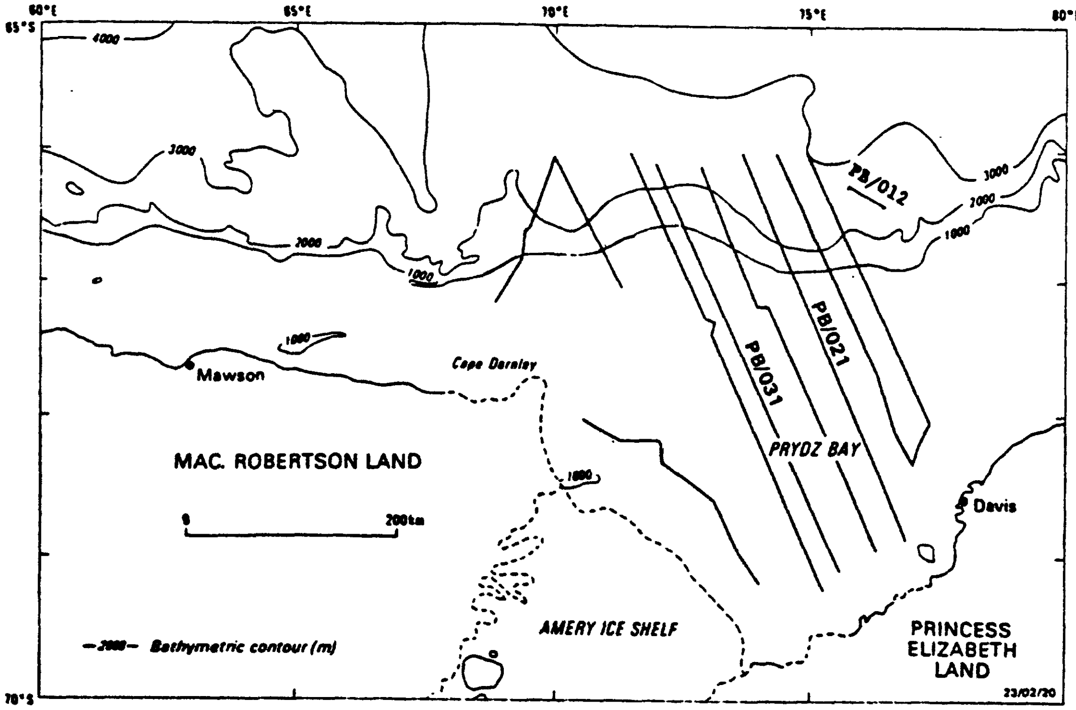


Figure 2: Location of seismic profiles shown in Figures 3 and 4.

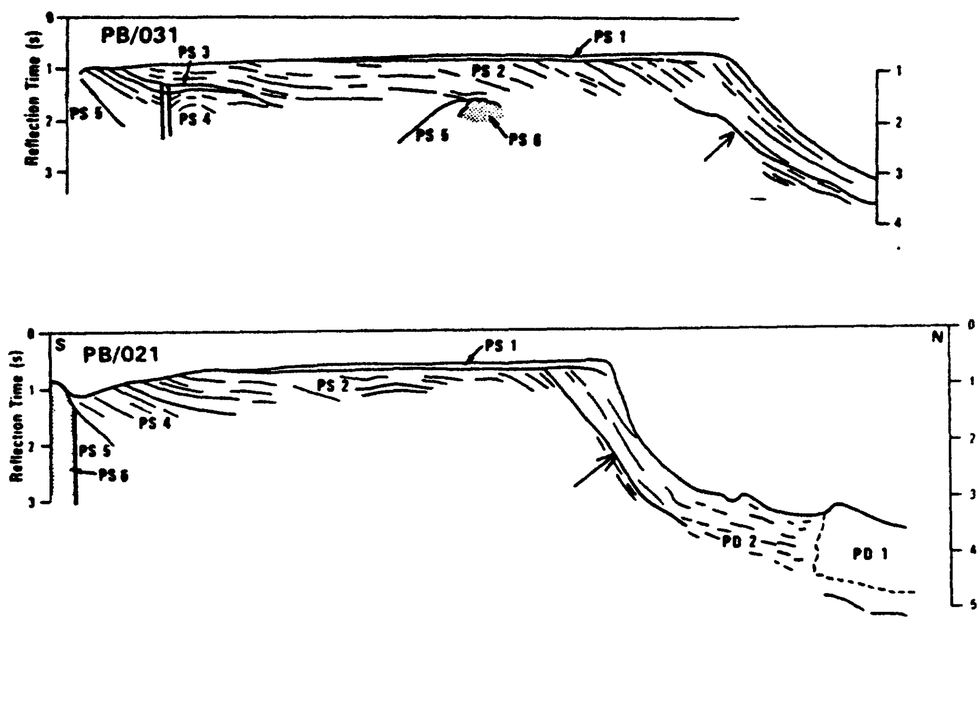


Figure 3: Line drawings of seismic sections along lines PB/031 and PB/021 across Prydz Bay and adjacent slope and rise (after Stagg, 1985). Interpreted Oligocene unconformity is marked by an arrow.

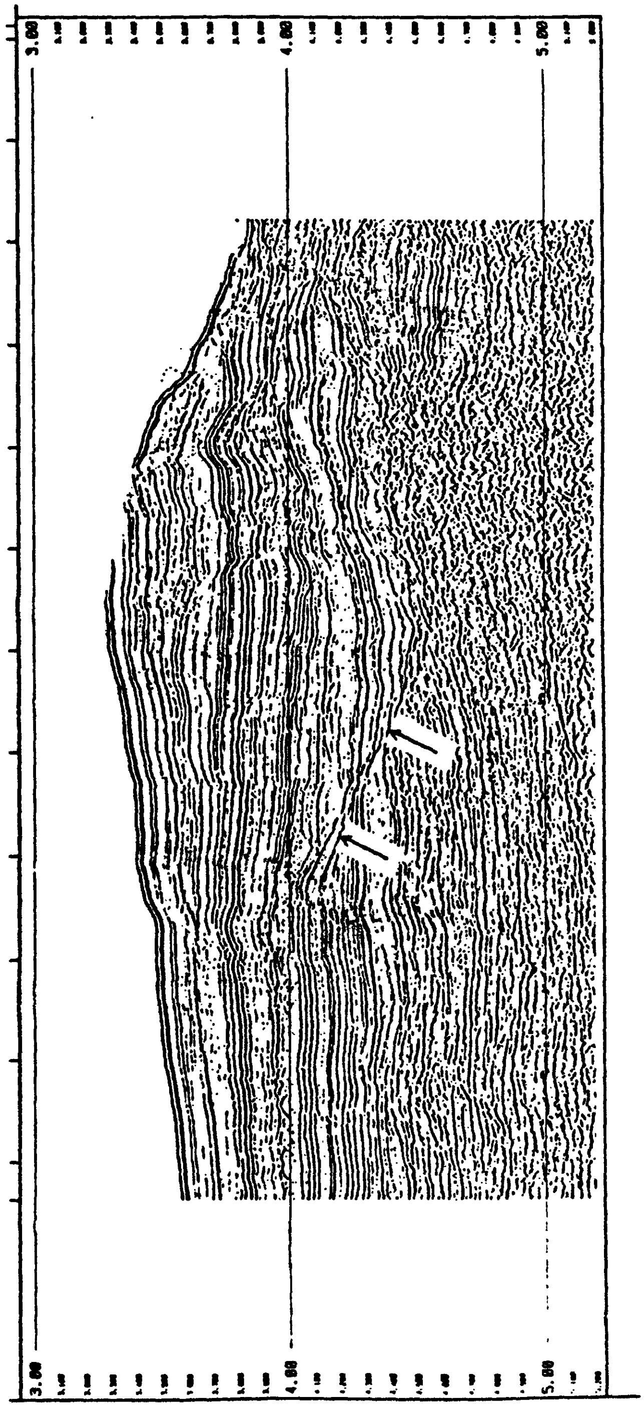


Figure 4: Seismic section along line PB/012, northeast of Prydz Bay, showing seismic character of levee deposits adjacent to canyon interpreted to consist of alternating glacial and inter-glacial sediments, and syn-sedimentary faulting. Trace of possible abandoned channel shown by an arrow.

Japanese Expedition Data in Weddell Sea and Off Queen Maud Land

Manabu Tanahashi
(Geological Survey of Japan)

Weddell Sea

TH81 cruise was devoted to the marine geological and geophysical survey in the Weddell Sea. Seismic survey was carried out with an Airgun and 24 channels mini-streamer as a seismic source and receiver, respectively. 1,860 km long multichannel reflection profiles were collected in continental slope to rise and abyssal plain area to Maud Rise in central-eastern part of the Weddell Sea during TH81. Survey lines are grouped into 1) lines from Maud Rise to Princess Martha coast (4 - 6 and 8 -14 SMG) and 2) lines in central Weddell abyssal plain (17 - 20 SMG). Five stratigraphic sequences (A to E) were identified based on some paleontological evidence on dredge samples. They are A: Upper Pliocene to Quaternary, B: Miocene to Upper Pliocene, C: Oligocene, D: Paleogene and E: Pre-Tertiary. Some stratifications are observed in acoustic basement beneath sequence E.

Bathymetric and subbottom profiling and gravity measurement were carried out along whole survey tracks during the cruise. Magnetic measurement was carried out along whole survey tracks in the survey area.

Three dredges were tried on the wall of submarine canyons. Samples of all three sites contain many of drop stones and recent mud or silt. D202 and D203 also contain some in-situ mudstone fragments. D202 sample contains Uppermost Pliocene to lowermost Pleistocene diatom fauna and Lower Pliocene radiolarian fauna. D203 sample contains Upper Eocene to Lower Oligocene diatom fauna.

Nine corings were operated on the abyssal plain and continental slope and rise. Total core length is 2,132 cm. Paleontological (foraminiferal, diatom and radiolarian) analyses were applied to the samples which were taken at every 20 cm of cores in principle. Most part of the cores is estimated as Upper Quaternary in age. Upper and lower parts of cores predominantly contain benthic arenaceous and planktonic foraminifera faunas, respectively, in general.

Five heatflow measurements were carried out with piston coring during the cruise.

Off Queen Maud Land

TH85 cruise was devoted to the survey Off Queen Maud Land area. Seismic survey was carried out with two Watergun and 24 channels mini-streamer as seismic sources and receiver, respectively. 2,432 km long multichannel reflection profiles were collected in continental rise and slope area off Queen Maud Land. The survey lines are long N-S line from abyssal plain to the upper continental rise off Syowa Station (2SMG), E-W line from continental rise to N-S trending Gunneras Ridge, which consists of submarine basement spur (3SMG), N-S line along the ridge crest of the Gunneras Ridge (4SMG), NE-SW line from north end of the Gunneras Ridge to continental rise in Riiser-Larsen Sea (5SMG), short N-S line in the Riiser-Larsen Sea (6SMG) and short NE-SW line in lower continental rise (7SMG).

The Gunneras Ridge is the most prominent structural feature in the survey area. It is the northward continuation of Riiser-Larsen Peninsula. The basement of the ridge consists of faulted and folded sedimentary sequences with high reflectivity. It is covered by thin (< 0.7 sec) younger undeformed sedimentary sequences. It shows northward thickening in general. It thinned out on the northern end of the ridge. The deep basement of the ridge is interpreted as continental one based on low magnetic anomaly.

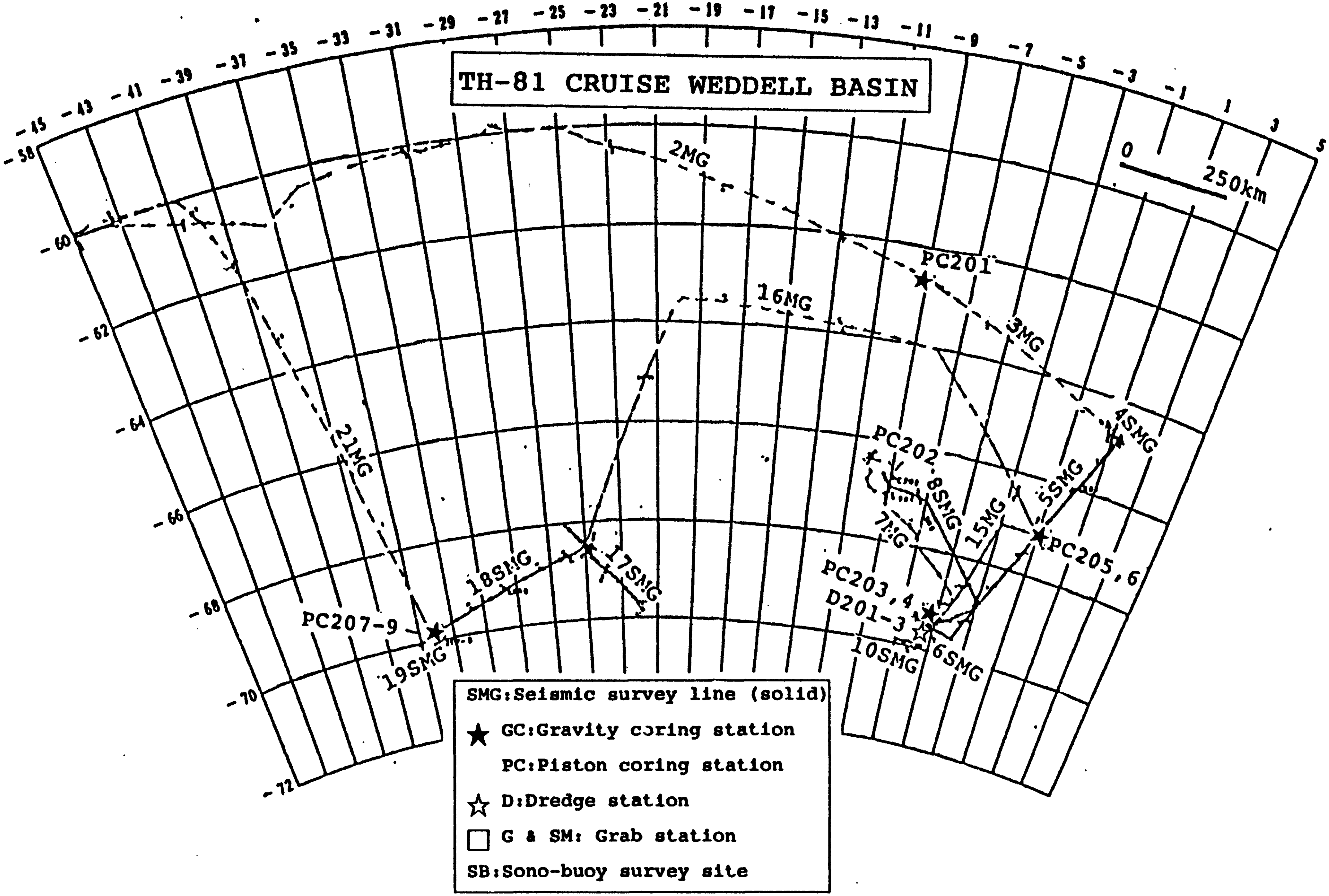
Bathymetric and subbottom profiling and gravity measurement were carried out along whole survey tracks during the cruise. Magnetic measurement was carried out along whole survey tracks in the survey area.

Four dredges at upper continental rise off Syowa Station (D601), northern slope of the Gunneras Ridge (D602, D603) and eastern slope of the ridge (D604). Most of the samples are drop stones of metamorphic and plutonic rocks and some sedimentary rocks. Only D603 contains some probable in situ rock fragments. They are mainly weathered gneissose granite and some conglomerate fragment. They are partly covered by 5 to 25 mm thick manganese coating.

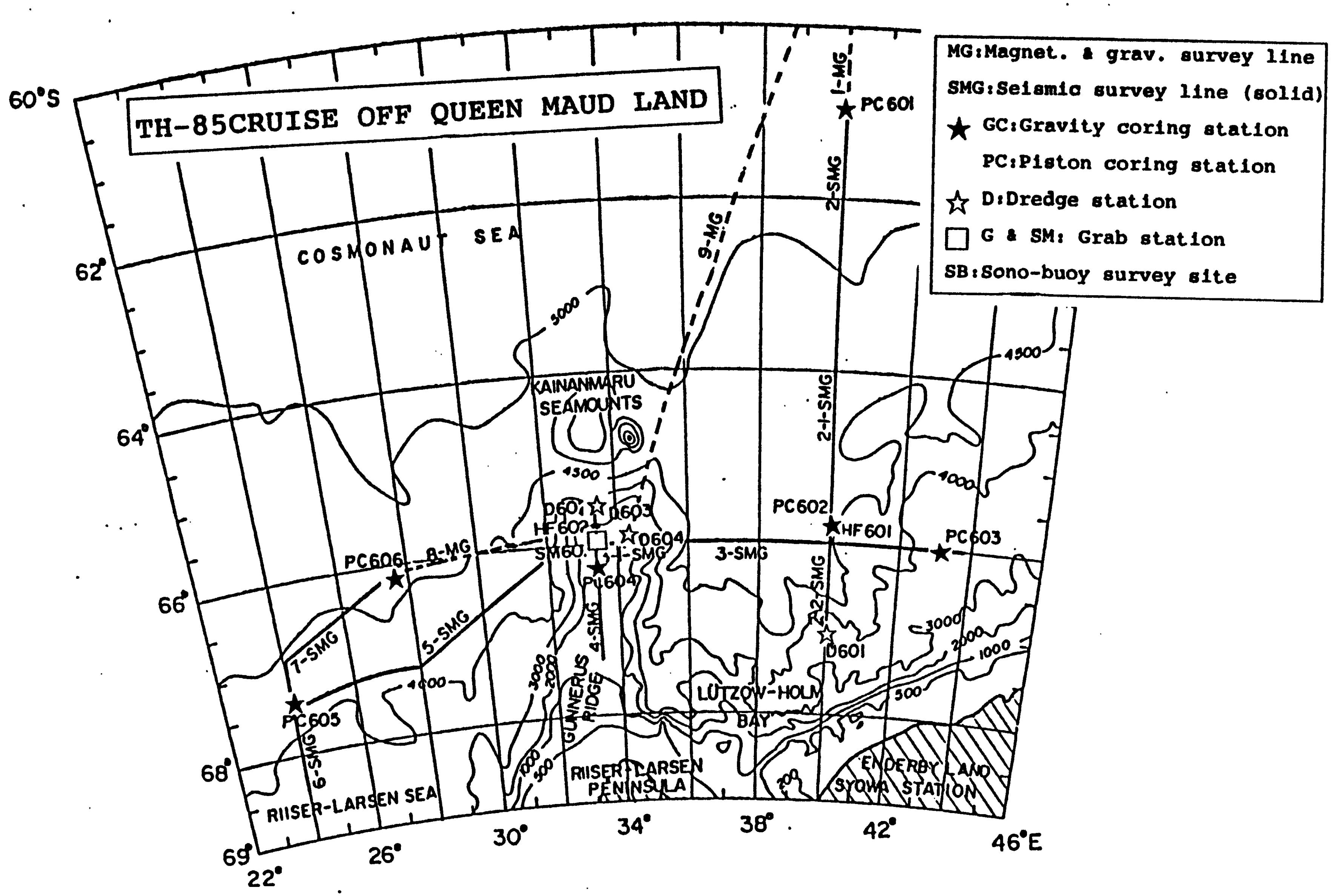
Six piston coring were tried and total samples core length is 3,847 cm. PC601, 602, 603 were operated in the abyssal plain and continental rise off Syowa Station. The sampled sediments are mainly composed of siliceous ooze and siliceous clay. PC604 was operated on the Gunneras Ridge. The sample mainly consists of calcareous ooze. PC605 and 606 are operated in the continental rise in the Riiser Larsen Sea. They are composed of alternation of siliceous clay and pelagic clay (PC605) and siliceous clay and ooze (PC606).

Paleontological (foraminiferal, diatom and radiolarian) analyses were applied to the samples which were taken at every 20 cm of cores in principle. Every identified planktonic foraminifera consists of sinistral *Globigerina pachyderma* fauna. PC604 contains few *Globorotalia puncticuloides* and *G. scitula.* Three zones were identified from diatom analysis. They are *Nitzschia kerguelensis* Zone (0 - 0.195 Ma), *Hemidiscus karstenii* Zone (0.195 - 0.35 Ma) and *Rouxia isopolica* Zone (0.35 - 0.66 Ma). All the sampled sediments age are ranging from Upper to Middle Pleistocene.

Seven heatflow measurements were carried out with piston coring (5) and without coring (2) during the cruise.



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN WEDDELL SEA (TH-81)



LOCATIONS OF ACOUSTIC AND SAMPLE DATA OFF QUEEN MAUD LAND (TH-85)

Manabu Tanahashi
(Geological Survey of Japan)

Off Wilkes Land

TH82 cruise was devoted to the marine geological and geophysical survey of Dumont d'Urville Sea and Ross Sea. Seismic survey was carried out with an Airgun and 24 channels mini-streamer as a seismic source and receiver, respectively. 680 km long multichannel and 140 km long single channel seismic reflection profiles were collected in abyssal plain, continental rise and shelf area of Dumont d'Urville Sea (around 140°E) during the first leg of TH82 cruise. The lines are long N-S line 3SMG from abyssal plain to the continental shelf, short N-S single channel line 5SMG in the continental shelf and slope and short E-W line 8SMG in the continental rise.

TH83 cruise was devoted to the marine geological and geophysical survey of Off Wilkes Land area between 140°E and 100°E. 3,700 km long multichannel reflection profiles were collected in abyssal plain, continental rise and shelf area. The survey lines are E-W line (2 and 3 SMG) to cross TH82-3SMG, NW-SE line to the upper continental rise (4SMG), E-W line along continental rise (7, 18, 17, 12SMG), N-S or NW-SE lines from continental rise to slope or shelf (10, 11, 13 and 19SMG), and some short connecting lines of them.

The geologic structure of this margin is rather simple. The continental shelf has 300 to 700 m water depths. It has shallow shelf edge and has extremely gentle landward flat floor (< 0.1°). The 150 m high mound, which has steep slope on ocean-side and gentle slope on landward side, is developed at the landward end of the flat floor. Distinct oceanward divergent prograding reflectors are commonly observed on whole continental shelf profile. The continental slope is steep (about 10°). Lower continental slope and uppermost continental rise show gentle smooth bottom feature. The sea bottom suddenly change very rough at 2700 to 2800 m depth, 25 to 50 km off from shelf edge. Extensive erosional and redepositonal sedimentary features are developed at oceanward from this boundary. Considerably thick (2 - 3 sec) sedimentary sequences are developed in lower continental rise.

Bathymetric and subbottom profiling and gravity measurement were carried out along whole survey tracks during the cruise. Magnetic measurement was carried out along whole survey tracks in the survey area.

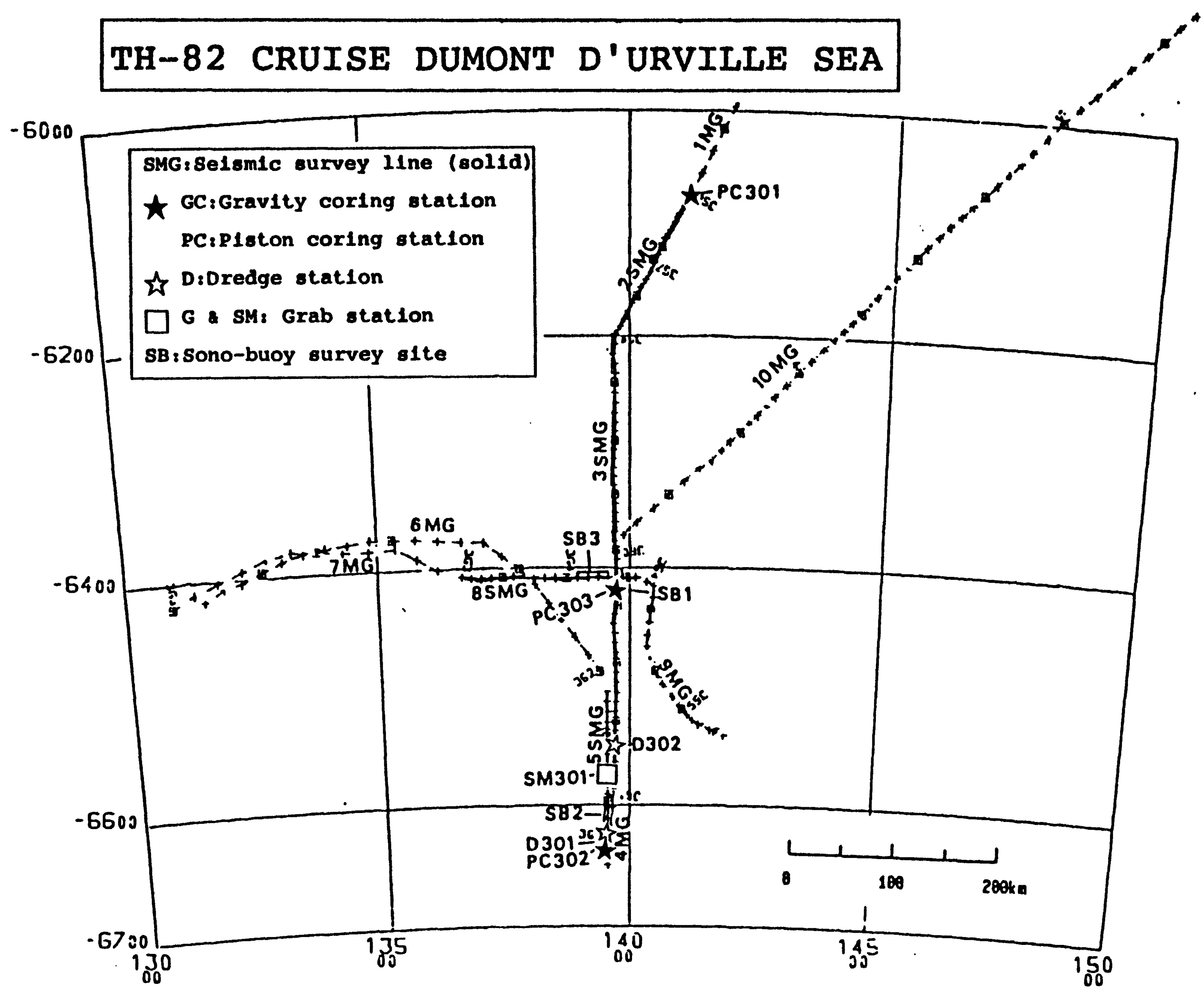
Seven piston corings (PC401- PC407), five gravity corings (G401 - G405), eight dredges (D401 - 408), and one grab sampling (SM401) were carried out during the cruise.

Dredge sample was mainly composed of drop stones. D401 contains abundant manganese nodules. D402 and D405 contains some possible in situ semi-consolidated mudstones. The mudstones contain uppermost Pleistocene diatom fauna. D407 and D408 contains some possible in situ diamictite. They contain some older (Early Miocene to Pliocene) diatom fauna in matrix and fragment.

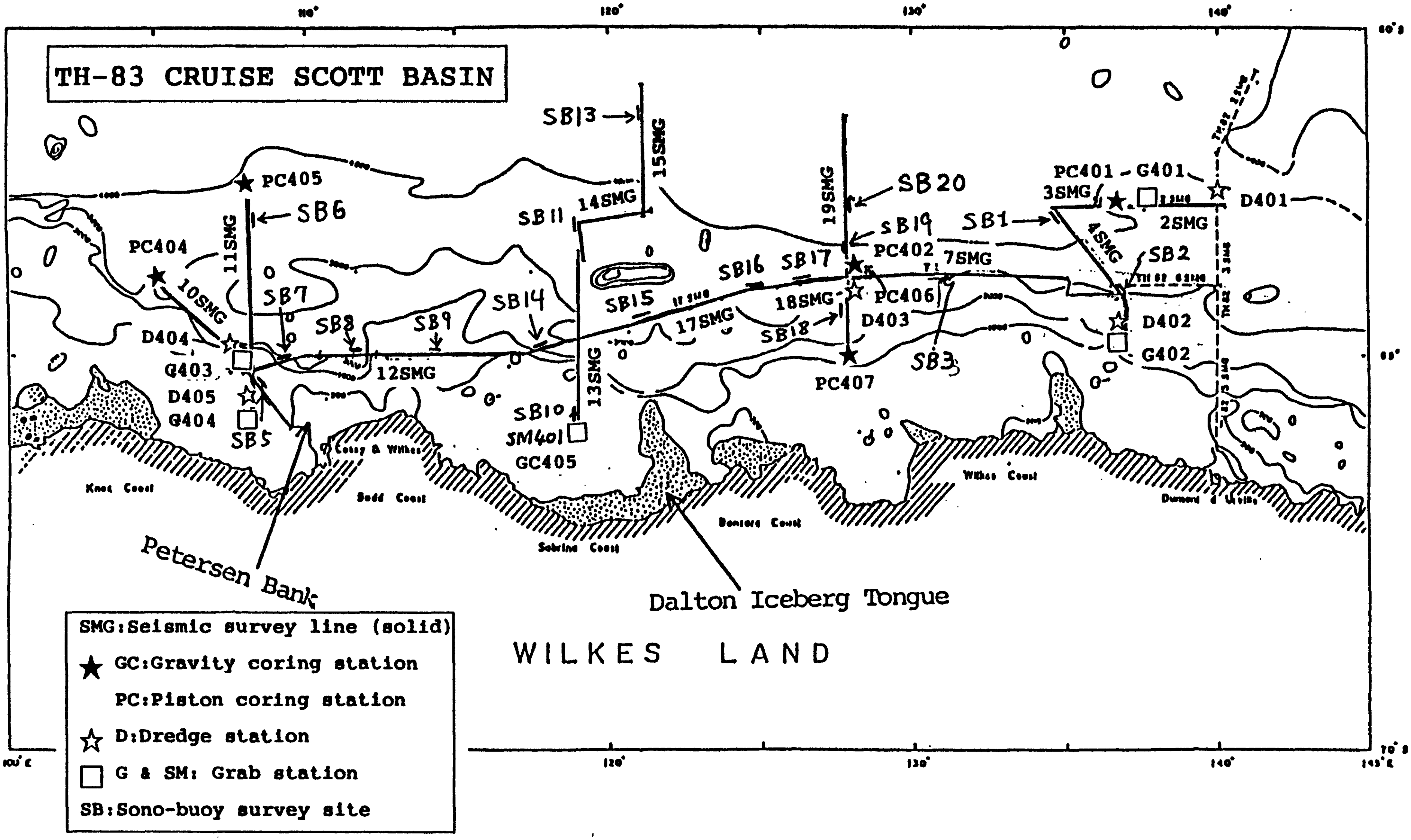
Sediments of all seven piston cores consist mainly of diatomaceous silt. The bottom part of PC403 sample is fine sand bearing silt. Lower 67 cm of PC404 is reddish siliceous ooze. Gravity core samples (G401 to 404) are predominantly composed of siliceous silt. G403 contains coarse sand layer. G405 is composed of an alternation of silt and sand with gravels.

Paleontological (foraminiferal, diatom and radiolarian) analyses were applied to the samples which were taken at every 20 cm of cores in principle. Three Late Pleistocene diatom zones were identified from cores PC402, 403, 404, and 406, i.e. *Nitzschia kerguelensis* Zone (0 - 0.195 Ma), *Hemidiscus karstenii* Zone (0.195 - 0.35 Ma), and *Rouxia isopolica* Zone (0.35 - 0.66 Ma). Three Late Pliocene to middle Early Pleistocene diatom fauna were identified from PC401 core, i.e. *Rouxia isopolica* Zone (0.35 - 0.66 Ma), *Actinocyclus ingens* Zone (0.66 - 1.67 Ma) and *Rhizosolenia barboi* Zone (1.67 - 2.48 Ma). Five Late Pliocene to Late Pleistocene diatom zones were recognized in G401 core, i.e. *Nitzschia kerguelensis* Zone to *Rhizosolenia barboi* Zone. Peculiar planktonic foraminifera species which specify warm water conditions were identified from G401 core, i.e. *Globorotalia inflata, G. praeinflata, G. puncticuloides, G. cf. spericomiozea.* PC407, G403 and 404 yield only diatoms in *Nitzschia kerguelensis* Zone.

Eight heat flow measurements were carried out with piston and gravity corings (7) and independently (1).



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN DUMONT d'URVILLE SEA (TH-82)



LOCATIONS OF ACOUSTIC AND SAMPLE DATA OFF WILKES LAND (TH-83)

Manabu Tanahashi
(Geological Survey of Japan)

Ross Sea

TH82 cruise was devoted to the marine geological and geophysical survey of Dumont d'Urville Sea and Ross Sea. Seismic survey was carried out with an Airgun and 24 channels mini-streamer as a seismic source and receiver, respectively. 1,980 km long multichannel reflection profiles were collected in abyssal plain and continental slope and shelf area of Ross Sea during the second leg of TH82 cruise. Survey lines are grouped into 1) lines in abyssal plain area off Cape Adare (12 - 14SMG) and 2) lines on western and central part of Ross Sea continental shelf and northeastern part of continental slope (16 - 22 SMG).

Eight stratigraphic sequences (A to F and F') were identified and correlated with DSDP results in the continental shelf area. They are A: Quaternary, B: Quaternary to Pliocene, C: Late Miocene to Pliocene, D: early Late Miocene to Late Miocene, E: Middle Miocene to early Late Miocene, F: Late Oligocene to early Middle Miocene, and F': Oligocene.

The quality of seismic profiles in the continental shelf area was not good mainly by the strong seabottom multiples. The short source-receiver offset and few CMP foldings (6) limited the improvement of the signal to multiple noise by the conventional signal processing sequence. Then some further optional processes were applied to the selected record in 1987. Its principal method is semblance filtering process. The processed data were reinterpreted and four stratigraphic sequences were identified in the continental shelf area. They are U1 (previous A), U2 (B and C), U3 (D and E) and U4 (F and F').

Two sedimentary basins were recognized. Western one (Central Trough by Davey, 1983) consists of U3 and U4 and lack upper sequences. The thickness of the sequences is fairy constant, c.a. 2.0 sec in average, 2.5 sec in maximum. Eastern one (Eastern Basin by Davey, 1983) consists of U1 to U2. The sequences show east or northeastward divergent sedimentary configuration. The maximum thickness of the total sequences is 3.0 sec. The southwest ends of the sequences are exposed on the shelf floor sequentially.

Bathymetric and subbottom profiling and gravity measurement were carried out along whole survey tracks during the cruise. Magnetic measurement was carried out along whole survey tracks in the survey area.

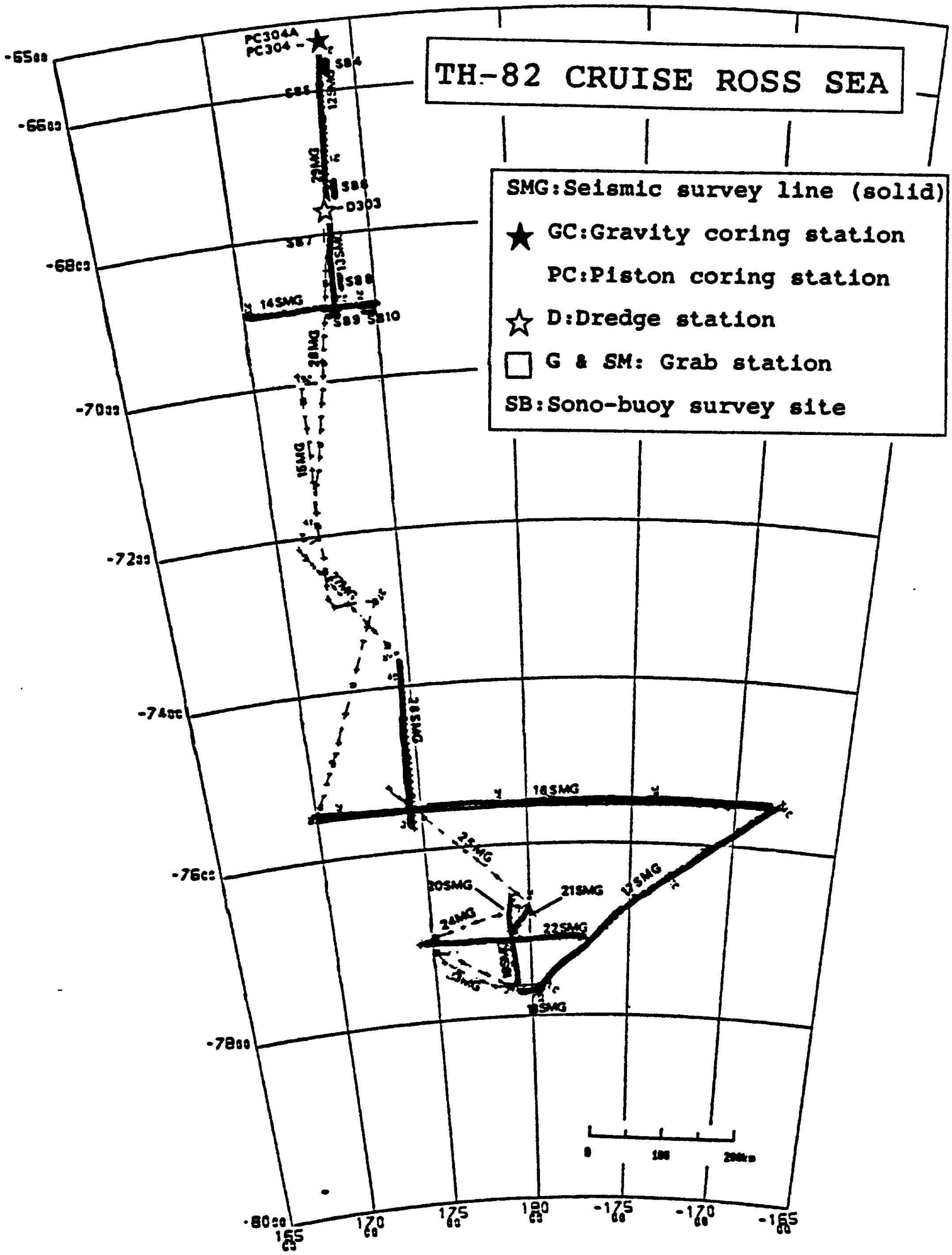
One dredge (D303) and two piston corings (PC304 and 304A) were operated off Cape Adare. One piston coring (PC305) and nine gravity corings (G301 - 309) were operated in the continental shelf and slope area.

Dredge sample was composed of drop stones only.

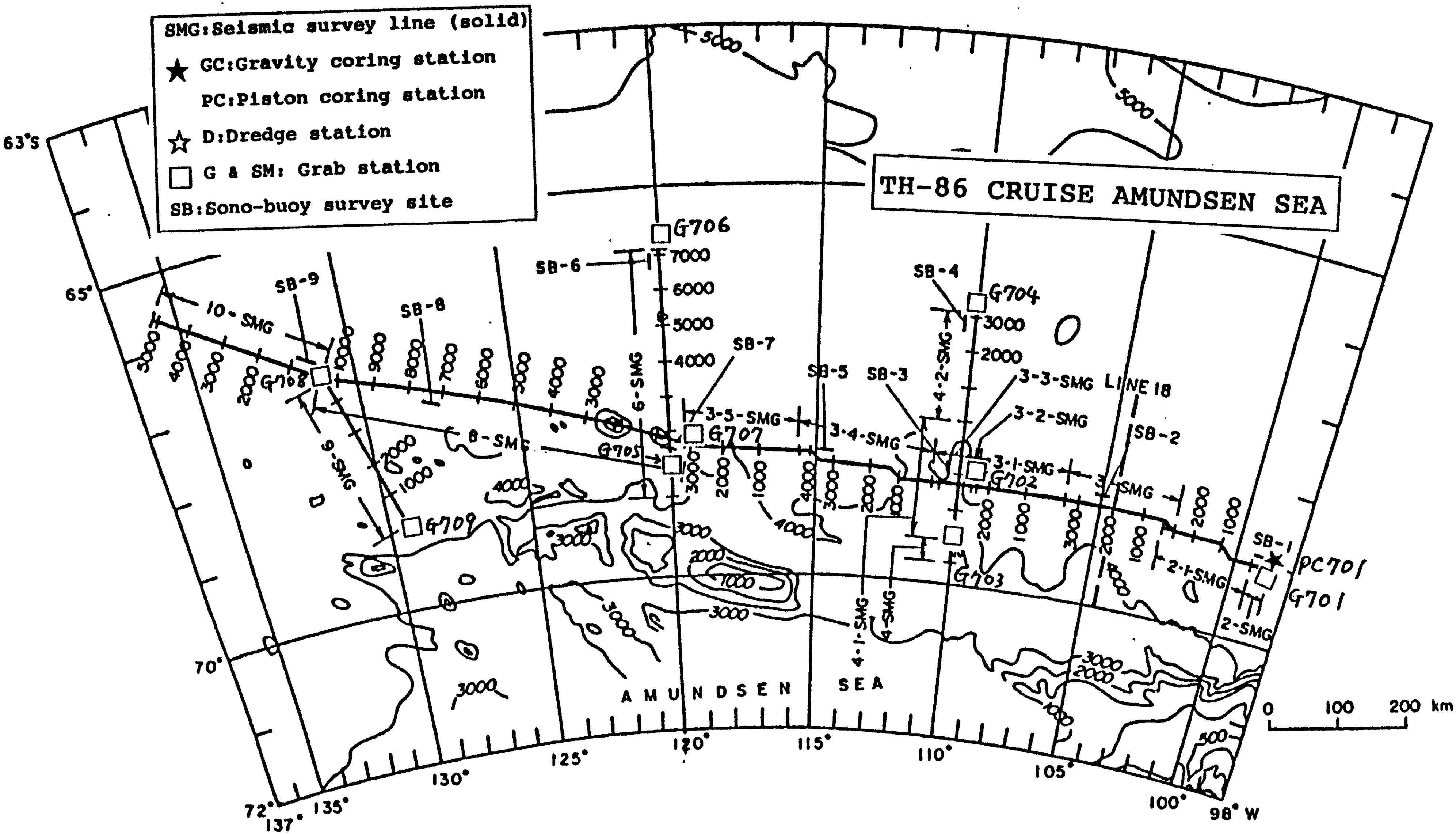
Sediments of PC304 and 304A consist of diatomaceous silt. PC305 sample from the northeastern continental slope shows rhythmic fine alteration of silt and fine sand. Gravity core samples are predominantly composed of sandy silt and silt with some gravels.

Paleontological (foraminiferal, diatom and radiolarian) analyses were applied to the samples which were taken at every 20 cm of cores in principle. Three zones were identified from diatom analysis of PC304. They are *Nitzschia kerguelensis* Zone (0 - 0.195 Ma), *Hemidiscus karstenii* Zone (0.195 - 0.35 Ma) and *Rouxia isopolica* Zone (0.35 - 0.66 Ma). Upper part of PC305, G301, 302, 303, 304 and 305 belong to *Nitzschia kerguelensis* Zone. Lower part of them and G307, 308 and 309 do not yield enough diatom to identify the geologic ages.

Six heatflow measurements were carried out with piston coring (2) off Cape Adare and without coring (4) on the continental shelf during the second leg of the cruise.



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN ROSS SEA (TH-82)



LOCATIONS OF ACOUSTIC AND SAMPLE DATA IN AMUNSEN SEA (TH-86)

FACTORS AFFECTING THE CHARACTERISTIC BATHYMETRY OF ANTARCTIC CONTINENTAL MARGINS: PRELIMINARY MODELING RESULTS FROM PRYDZ BAY.

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Continental margins around Antarctica are often characterized by a trough of up to 1 km deep near the coast and an unusually deep shelf (400-700 m deep at the shelf edge). In some places (e.g. Prydz Bay) the water depth increases monotonically from the shelf edge toward the coastal trough while in others (e.g., Weddell Sea, Haugland et al., 1985) a central high is located between the shelf edge and the trough.

Several factors may determine the geometry of the sea floor and the underlying stratigraphy in Antarctic margins. These are: 1. The load of the ice cap. 2. The isostatic response of the lithosphere. 3. The pattern of erosion. 4. The pattern of sedimentation. 5. Sea level changes. 6. Thermal and tectonic subsidence of the margin. 7. Possible compaction of the sedimentary section by an ice cap which has periodically covered the margin.

The effects of these factors (with the exception of compaction) were investigated using simple numerical models to simulate the sea floor bathymetry along a transect across Prydz Bay (Cooper et al., in press). In these models we assume that prior to the existence of ice cap in East Antarctica the margin had a depth profile typical of low-latitudes margins, which gradually deepen from the coast to ~150 m at the shelf edge. The supply of water-suspended sediments to the margin has to a large extent terminated when the ice cap developed on land suggesting that further erosion and sedimentation on the shelf were caused by glacial advancement and retreat across the shelf (Hambrey et al., in press). In the absence of quantitative relationship between characteristic properties of the ice cap and erosion and sedimentation (e.g, Drewry, 1986, Brown et al., 1987), we measured the distribution of eroded and deposited material from the seismic section (Cooper et al., in press), but also explored hypothetical distributions of erosion and sedimentation. We further assumed that glacial advancement and retreat across the shelf occurred at cycles with periods ≥10,000 y implying that residual deformation of the asthenosphere from these movements is negligible (e.g., Cathles, 1975). Isostatic compensation to ice loading, erosion, sedimentation, and sea-level change was therefore, assumed to be limited to the lithosphere and in our models was either local (Airy model) or regional (flexure) with variable rigidity across the margin. Following Hughes (1981, and pers. comm., 1990) the height (flow line) of the ice cap was calculated using an initial-value finite difference formulation with a basal shear stress of 0.3 bar. Regional isostatic response to ice loading was incorporated by iteratively calculating the ice flow and flexure until convergence was achieved. Lastly, we assumed that the margin has been undergoing residual thermal subsidence (e.g., Dunbar and Sawyer, 1989) because it was formed by rifting from Australia some 120 Ma (Lawver et al., in press). We assumed for simplicity linearly increasing subsidence from the coast (extension factor, β=1, no subsidence) to the shelf-edge (extension factor, β=6). A maximum of 460 m of thermal subsidence is expected to have occured in the last 40 Ma, but only 90 m in the last 10 Ma.

Since we modeled only one chrono-stratigraphic horizon (i.e., the sea floor) and the effect of compaction was not investigated, the models consist of only one time step, which is the present situation. We can make the reasonable assumption that lithospheric rigidity has not changed significantly in Prydz Bay since the commencement of Antarctic glaciation and, therefore, the effects of erosion, sedimentation, and sea level can be considered cumulative. (This assumption may fail in more recently active margins, such as the Ross Sea).

For the first set of models we used the observed distribution of glacial sediments starting 64 km from the coast (hereafter x=64 km) and thickening to 600 m at the pre-Oligocene shelf edge (x=176 km). In addition, a large thickness (up to 4000 m) of observed prograding glacial sediments was modeled between x=176 km and x=224 km (the present-day shelf edge) and beyond (Cooper et al., in press). A triangle of eroded material was modeled, where observed (between x= 0-64 km) with a maximum amplitude of 500 m at x=16 km. The only model which successfully predicted the observed profile of the sea floor was one where the margin has a very high rigidity (elastic thickness, Te=100 km). Models with lower rigidity (including the extreme case of local isostasy) produce a central high in the middle of the shelf and increasing depth both landward and seaward. Moreover, a good-fit was achieved only if thermal subsidence has been negligible (<100 m) along the transect.

While an elastic thickness on the order of 100 km was determined for East Antarctica (Stern and ten Brink, 1989), the rigidity (i.e., elastic thickness) of continental margins is, usually thought to be considerably smaller (e.g., ten Brink and Stern, submitted). The thickness of post-rift pre-glacial sediments in the margin under this profile is possibly, very small (0.5-2.5 km) (Cooper et al., in press) indicating little thermal subsidence and β, which is probably <<6. This may indicate little thermal perturbation of the lithosphere along the transect and therefore, no appreciable reduction in flexural rigidity from land toward the margin. Models with lower rigidity across the margin may, on the other hand, fit better margins such as Weddell Sea (Haugland et al., 1985) with a local high at the center of the shelf.

The second set of tested models allows for any hypothetical distribution of erosion and sedimentation which fits the sea floor geometry but assumes a linear thermal subsidence across the margin (β from 1 to 6) in the last 40 Ma. A variety of distributions can be composed depending on the variation in flexural rigidity across the margin. A conservative distribution of erosion and sedimentation can be achieved using the assumption of local Airy isostasy because the shelf geometry in this case is not affected by the ice load on land or by the large prograding sequence of glacial sediments at the outer shelf. In this model erosion is more than double than in the first set of models, with a maximum of 1100 m and areal distribution between x=0-128 km. Topset flat-lying sedimentation for the Airy model is much smaller than observed both in amplitude (max. of 275 m) and areal extent (x=128-176 km).

In summary, the following factors are suggested to affect the deeper than usual continental margins in Antarctica: 1. Thermal subsidence of margins which are "starved" of sediment supply. 2. The depression by a large pile of prograding deposits at the shelf edge (provided the lithosphere has a finite non-zero rigidity). 3. The depression by the near-by ice sheet (provided the lithosphere has a finite non-zero rigidity). Possible factors affecting the landward tilt of the continental margins (with and without a local high) are: 1. The pattern of erosion close to shore and sedimentation in the outer shelf. 2. The load of the continental ice sheet (provided the lithosphere is rigid). 3. Compaction of the pre-glacial sequence which may be proportional to the elevation of the ice cap (not tested). Possible factors creating a local high in the mid-shelf include the combination of a large pile of prograding sediments at the shelf edge and low flexural rigidity there. More detailed seismic and down-hole observations and more sophisticated models, which include additional sedimentary interfaces other than the sea floor, are needed to tackle the questions of the past extent of the ice cap, glacial processes of erosion and sedimentation, and the flexural rigidity of continental margins.

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PRELIMINARY RESULTS OF THE FIRST MARINE GEOPHYSICAL INVESTIGATIONS IN THE NORTH-WESTERN WEDDELL SEA

The studied area is situated between 40° and 56° W and 64°-66° S. Despite its key position at the junction of major South Atlantic tectonic units, this area has not been covered by systematic marine geophysical surveys and remained largely unknown with respect to its crustal structure.

In February - March 1990 R/V " Geolog Dmitry Nalivkin " from the Arctic Expedition for the marine exploration at Murmansk accomplished here approximately 4500 km of MCS (48-channels, 24- and 48-fold) accompanied by gravity, magnetic and high-resolution seismic measurements; the survey was done as part of the scientific program of 35 Soviet Antarctic Expedition. The following parts in north-western Weddell Sea were crossed: Powell Basin, Jane Basin, South Orkney microcontinent and, significantly, the shelf off the north-eastern Graham Land and adjacent continental slope and rise. Most of the lines were concentrated south-eastwards of the South-Orkney Archipelago and eastwards of the James Ross Island Group; these were connected by reconnaissance lines crossing the Powell Basin and adjacent deep-water Weddell Sea.

The South Orkney shelf is underlain by a relatively thin sedimentary cover (usually 0.5-1.5s TWT). Where the acoustic basement is recorded in high-resolution seismic data, its paleotopography is well preserved, especially if it is buried by some thickness of cover sediments. In the south-eastern part of the shelf the cover thickens to 2.0-2.2 s TWT; the continental slope here is underlain by buried down faulted basement steps which can be traced farther to the south-east into Jane Basin.

The adjacent Endurance Ridge is believed to represent a fragment of magmatic arc transitional between the Antarctic Peninsula and South Sandwich arcs.

An extensive back-arc basin with thick sedimentary cover is present offshore north-east Graham Land. On the shelf edge at 64°40'S in 0.95 km water depth there is the following seismic column (thickness, km / layer velocity, km/s):

0.6/1.93; 0.7/3.3o; 1.5/3.70; 3.9/4.30; 2.6/5.10 - over 9 km in total thickness. Apparently this great body of sediments represents a distal continuation of the Late Mesozoic-Cenozoic essentially molassic sequence exposed along the south-east coast of Graham Land.

Farther seawards, below the continental slope and rise the thickness of basin fill is at least 5s TWT. In the vicinity of 4000 m isobath the reworked continental basement underlying that fill shows an extremely complex transition into oceanic-type basement overlain by a much lesser thickness of sediments. This is the first seismic evidence in support of earlier observations by J. LaBrecque and M. Gidella (personal communication) made on the basis of USAC aeromagnetic data with respect to distribution of thick non-magnetic sequences in western Weddell Sea.

East of Joinville Island two well preserved volcanic centers were observed on subbottom rise probably representing the submerged continuation of the Antarctic Peninsula magmatic arc. We bellieve that these volcanoes are related to the same extensional zone the axis of which is marked by the Seal Nunataks - Robertson Is., James Ross Is. and Paulet Is. basaltic rocks ("Larsen Rift"). Thus the total length of the young volcanic line on the Atlantic side of the Antarctic Peninsula is at least 700 km.

The origin of Powell Basin is enigmatic. Our preliminary results seem to disagree with a simple opening model postulated in some reconstructions. A single refraction site in the center of Powell Basin (3400 m water depth), indicated according to raw data, the crust thickness in order of 10 km with about 2 s TWT of sediments above the acoustic basement. No geomorphic features which could be attributed to spreading activity were observed, as well as any linear magnetic anomalies showing reliable correlation. There is also a considerable difference in magnetic anomalies pattern between the Antarctic Peninsula shelf and the South Orkney microcontinent.

A special attention was given to the study of subbottom glacial sequences. Each of the ODP sites in vicinity of the South Orkney Islands was crossed by two lines, and unconformities drilled at sites 695 and 696 were continuosly traced on connecting seismic line.

On the South Orkney outer shelf no progradational glacial forms typical for Antarctic continental margin were recognized, rather the bottom strata become more older towards the shelf break. On the whole the South Orkney shelf seems to belong to the type intermediate between "normal" low-latitude shelves and repeatedly glaciated Antarctic shelf.

Indistinct evidence of AP-sequences in the upper 600 m of sedimentary section was obtained by high-resolution seismic profiling near the Antarctic Peninsula shelf edge.

After the processing the data collected during the 1990 cruise will significantly contribute to better insight into crustal history of hitherto unknown part of the South Atlantic.

FINNISH MARINE GEOLOGY ON THE SOUTHEASTERN CONTINENTAL SHELF, WEDDELL SEA, ANTARCTICA

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The Finnish Antarctic Expedition (FINNARP 89/90) on board r/v ARANDA has just returned from a fruitful multidisciplinary research cruise to the Weddell Sea. The three man marine geology group had to share very limited ship time with other activities. Despite of this we do consider the trip to have been a success. During the short time alloted to us, we acquired some 50 nm of single channel seismics plus a further 30 nm of echo-sounding profiles across the shelf, from the ice edge at the Kvitkuven Ice Rise, Riiser-Larsen Ice Shelf, to the shelf break. Two piston corer (6 m) samples were taken from the shelf slope and 3 vibro-hammer coresamples were acquired on the shelf.

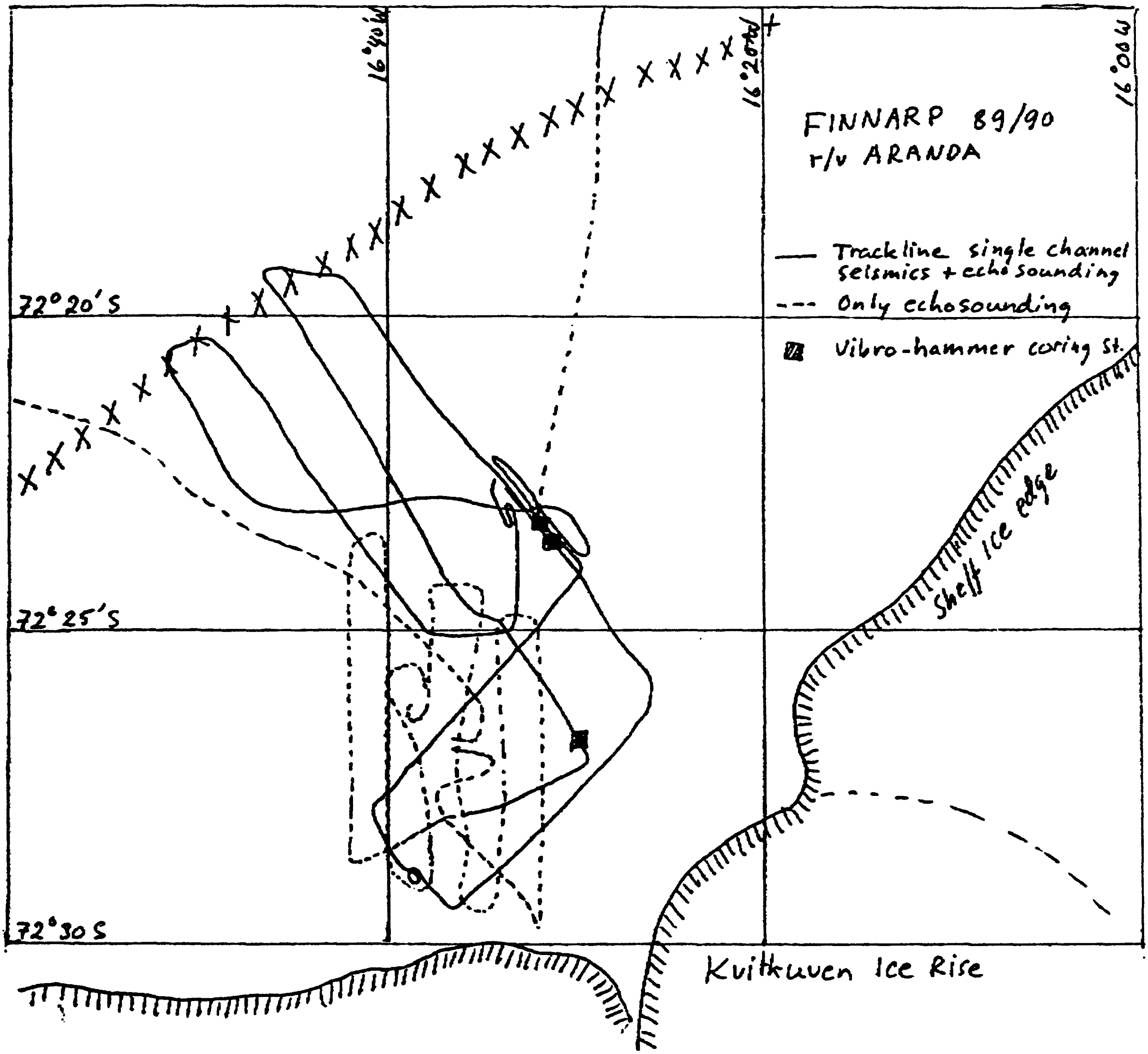
A Bolt 5 cu.in air gun and an implosion type electromagnetic sound source were used as sound sources for the continuous reflection profiling. Atlas Deso 25 echo-sounder (15 kHz) was run continuously. Due to unforseen electric noise on the newly commissioned r/v Aranda prohibited the use of the side scan sonar unit on board.

The electrically powered vibro-hammer drill, designed for work in the formerly glaciated Baltic Sea, and built at the Geological Survey of Finland, worked to our full satisfaction. Three cores 0.9 to 1.5 m in length were acquired in depths ranging from 157 m to 317 m. The fact that core barrel penetration was severly limited must be due to permafrost, since the type of till acquired from the shelf is quite similar to that sampled normally in the Baltic Sea environment with core retrievals of several meters, includig full six meter cores. Further study of the acquired cores, currently located in cold storage on the r/v ARANDA, will have to await the return of ship to Finland in the beginning of April.

The shoal area of 157 m (vibro-hammer core station), off the ice edge at the Kvitkuven Ice Rise, was viewed with a ROV (Benthos MiniROVER Mk II). The very ambundant faunal colonies found on the bottom was rather astonishing, especially considering the great abundance of icebergs moving in the area.

This having been the first Finnish oceanographic expedition to the Antarctic, it is obvious that a second cruise will follow in the near future, since too many questions were left unanswered. The first hand information now gathered on the conditions in the Weddell Sea, will permit a more effective planning of future cruises. The merging of this new knowledge with many years of experience in marine geology and geophysics in the Baltic Sea will be the basis for future planning.

The marine geology group at the Geological Survey of Finland, will try to commit itself to detailed marine geological and geophysical work on a limited stretch of continental shelf from ice edge to shelf break. The area would logically be the seaward extension of land studies conducted at the Finnish ABOA station on Heimfrontfiella Queen Maud Land.


FINNARP 89/90
r/v ARANDA
Trackline single channel seismics + echo sounding
Only echosounding
Vibro-hammer coring st.
16°40'W
16°20'W
16°00'W
72°20'S
72°25'S
72°30'S
Shelf ice edge
Kvitkuven Ice Rise

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THE SOVIET GEOPHISICAL RESEARCH IN THE ROSS SEA

In 1987 and 1989 R/V "Geolog Dmitry Nalivkin" of the North Branch for marine geologic exploration "SEVMORGEOLOGIA" of the Ministry of geology, USSR conducted marine geophysical investigations in the Ross Sea. The survey extended primarily over the central and eastern parts of the shelf and included 7500 km of 24-fold MCS profiling, over 3100 km of HRS lines and a 212-km line of sonobuoy refraction measurements; all seismic lines were accompanied by gravity and magnetic observations (Fig.1).

The results of previous studies [Cooper et al., 1987; Hayes a. Frakes, 1975; Hinz and Block, 1983] and our data are summarized in Fig.2. Density modeling along the seismic lines indicates reversed correlation between the acoustic basement topography and the Moho behaviour. According to sonobuoy refraction data, in the Central Trough the Moho is about 18 km deep which agrees well with gravity evidence and confirms a rift nature of the Ross Sea basins.

A general sublongitudinal structural pattern is interrupted by sublatitudinal regional faults. The northern fault is represented in seismic data as narrow graben separating the Central High from the Iselin High and bounding from the north the Victoria Land Basin where it is also clearly reflected in aeromagnetic data. The central latitudinal fault is reflected mainly in regional gravity gradient, while the southern fault is the least pronounced in both bathymetric and gravity data. Along the shelf boundaries all three faults are marked by appearance of young volcanic constructions - Mt.Melbourne, Ross Island, Mt.Discovery, Roosevelt I., Minin High (Fig.3a).

The top of acoustic basement is identified within the 0-4.2 s TWT subbottom depth interval. On majority of seismic profiles it is characterized by very rugged topography and high-amplitude reflections; according to refraction measurements and velocity analysis of MCS data the basement velocities range from 5.0 to 6.3 km/s. High variability of magnetic and gravity fields, onshore geologic evidence, drilling data and acoustic features of the basement suggest that the latter is very heterogeneous and may include both the recent volcanic rocks and a wide range of older strata, from relatively undisturbed Beacon/Ferrar sequences to strongly deformed metasedimentary and/or crystalline (pre) Ross units [Hayes a.Frakes,1975].

In the East Basin the greatest thickness of sedimentary fill reaches 8-9 km; in the Central Trough it does not exceed 5-6 km. Seven seismic sequences are recognized (table) which can be grouped into three major tectono-stratigraphic units.

The lower unit (R7) is acoustically semitransparent and poorly stratified. There is a marked difference in configuration of its lower and upper boundaries represented respectively by a highly dissected basement surface (B) and a relatively flat reflector VI (Figs. 3b,4). Apparently this unit is a Late Mesozoic to Early Cenozoic synrift sequence whose thickness is essentially controlled by a horst-graben topography of the underlying basement. Despite persistent correlation of reflector VI which forms the unconformity at the top of synrift unit throughout much of the Ross Sea shelf uncertainties still exist with respect to regional relationship between that boundary and U6 unconformity of Hinz and Block, 1983 with the top of V5 unit of Cooper et al., 1987.

The middle unit (R6) is acoustically similar to the synrift sequence and also lacks consistent internal stratification. However, unlike the synrift unit it forms an almost continuous cover whose thickness usually does not exceed 1-2 km. Only in axial parts of the basins it increases to 2.5-3.0 km which indicates that during accumulation of that unit predominant subsidence still involved the deepest basement depressions.

The upper unit (R5 - R1) occurs mostly on the outer shelf of the East Basin where it forms an extensive glacial progradational wedge of Late Cenozoic age (Fig.4). Its thickness here varies from 1.0 km to about 4.0 km; elsewhere this unit is very thin. An important seismic feature of that unit is clear internal stratification with a sigmoid configuration of reflectors. Because of sufficiently close line spacing in the northern part of the East Basin it appeared possible to determine the areal extent of progradational wedge and to recognize that glacial transportation of its clastic components occurred essentially in two major directions - across the Central High and also from the southward continuation of the East Basin. A combination of repeated glacial unloading with high productivity of biogenic accumulation led to avalanche sedimentation impulses separated by periods of slower depositional rates during glacial retreats. Location of large progradational delta was, perhaps, additionally controlled by intensive subsidence which involved the eastern Ross Sea due to final onset here in late Cenozoic time of an extensional (passive margin) regime. Features of possible compressional origin which locally affect the pre-glacial part of the section below reflector V (Fig.3b, right) may indicate the existence of an earlier active margin regime.

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FIGURE CAPTIONS

Fig.1. Location map for the Soviet seismic data in the Ross Sea.

Fig.2. Generalized structure of the Ross Sea Shelf. Onshore geology after Cooper et al., 1987. Small asterisks - boreholls (1 - for MSSTS-1 and CIROS-1 sites, 270-273 - for DSDP sites). Large asterisks - volcanoes (MM-Mt. Melbourne, ME - Mt.Erebus, MH - submarine Minin High). Areas of shallow acoustic basement are shaded. Arrows in progradational delta indicate direction of sediment transportation. CH - Central High, ISH - Iselin High, CLH - Coulman High, VR - volcanic ridge, VLB - Victoria Land Basin, CT - Central Trough, EB - East Basin.

Fig.3. Fragments of multichannel seismic reflection profiles.
a) Line 87002 showing volcanic - related features at the continental slope (Minin High);
b) Line 890015 demonstrating relationship of tectonostratigraphic units on the outer shelf and upper slope of the eastern Ross Sea;
c) Line 890023 illustrating a local anticline possibly productive for hydrocarbons.

Fig.4. Stratigraphic correlation of seismic sequences on the Ross Sea shelf based on drill data (Hayes and Frakes, 1975) and global sea level changes (Vail et al., 1977). Gondwana reconstruction at 65 Ma after Kennet, 1982.

TABLE. CHARACTERISTICS OF SEISMIC SEQUENCES (SS)

SS	THICKNESS (km)	INTERVAL VELOCITY (km/s)	AGE	UNCONFOR-MITY	FACIES	TECTONO-STRATIGRAPHIC UNITS
R1	<0.13	1.75-1.9	Q	I	glacial-marine	PROGRADA-TIONAL
R2	<0.6	1.85-2.1	N_2 - Q	II	glacial-marine	
R3	<1.5	1.9-2.3	N_1^3 - N_2	III	glacial-marine	
R4	0.1-1.5	2.0-2.8	N_1^3	IV	glacial-marine	
R5	0.2-1.5	2.0-3.4	N_1^2 - N_1^3	V	glacial-marine	
R6	0.7-3.0	2.7-4.2	$₽_3^2$ - N_1^3	V-A VI	marine, glacial-marine	POST - BREAKUP
R7	<7.0	3.6-5.4	K_2 - $₽_3$	B	continen-tal-shal-lowmarine	SYNRIFT
		5.0-6.3	PЄ - MZ_1		metamor-phic, igneous	BASEMENT

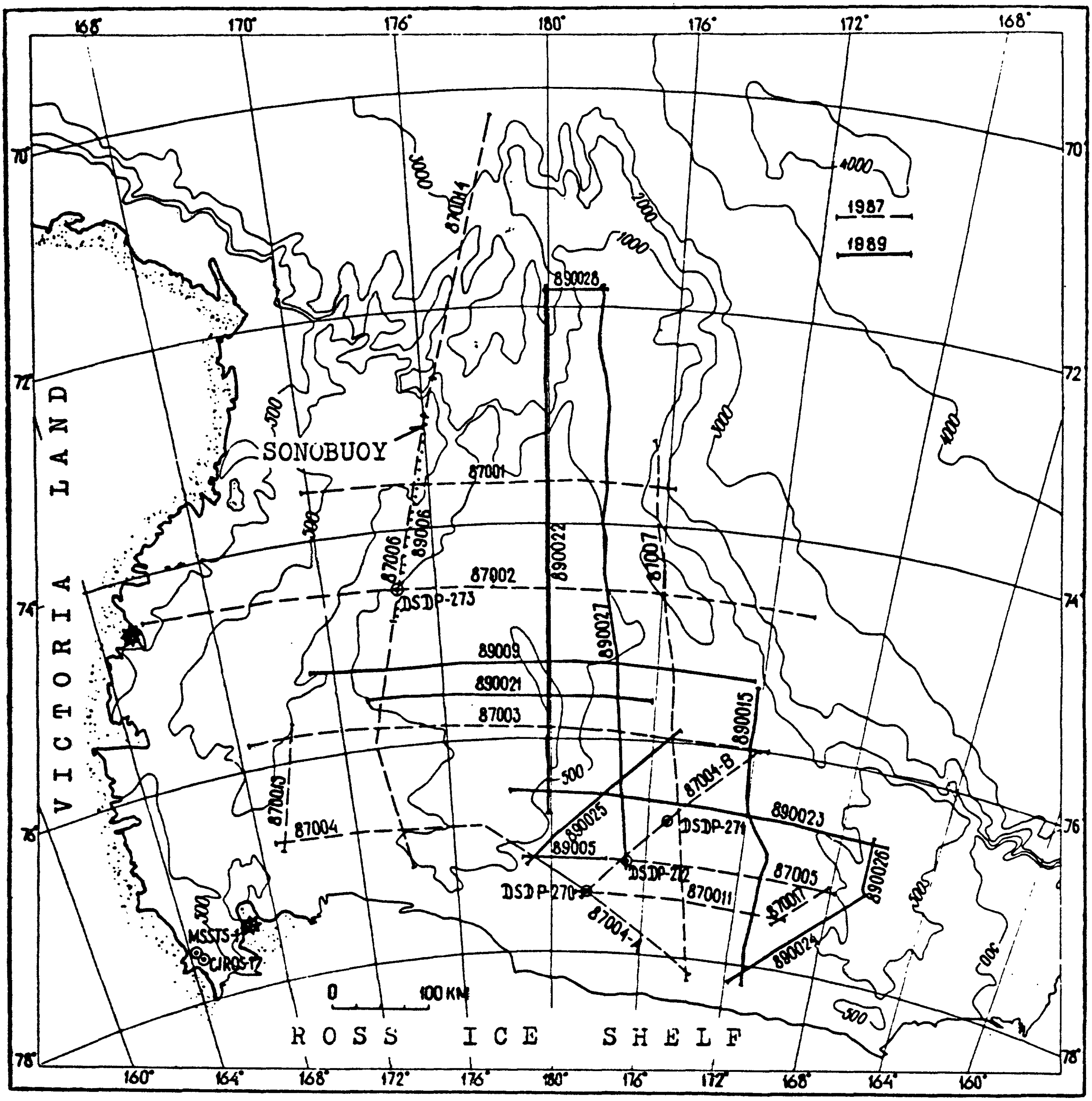
VICTORIA LAND
ROSS ICE SHELF
SONOBUOY
1987
1989
0 100 KM
DSDP-273
DSDP-271
DSDP-272
DSDP-270
MSSTS-1
CIROS-1
87001
87002
87003
87004
87005
87006
87007
870011
87004-A
87004-B
870014
870013
89005
89006
89009
890015
890021
890022
890023
890024
890025
890026
890027
890028
70°
72°
74°
76°
78°

Figure 1

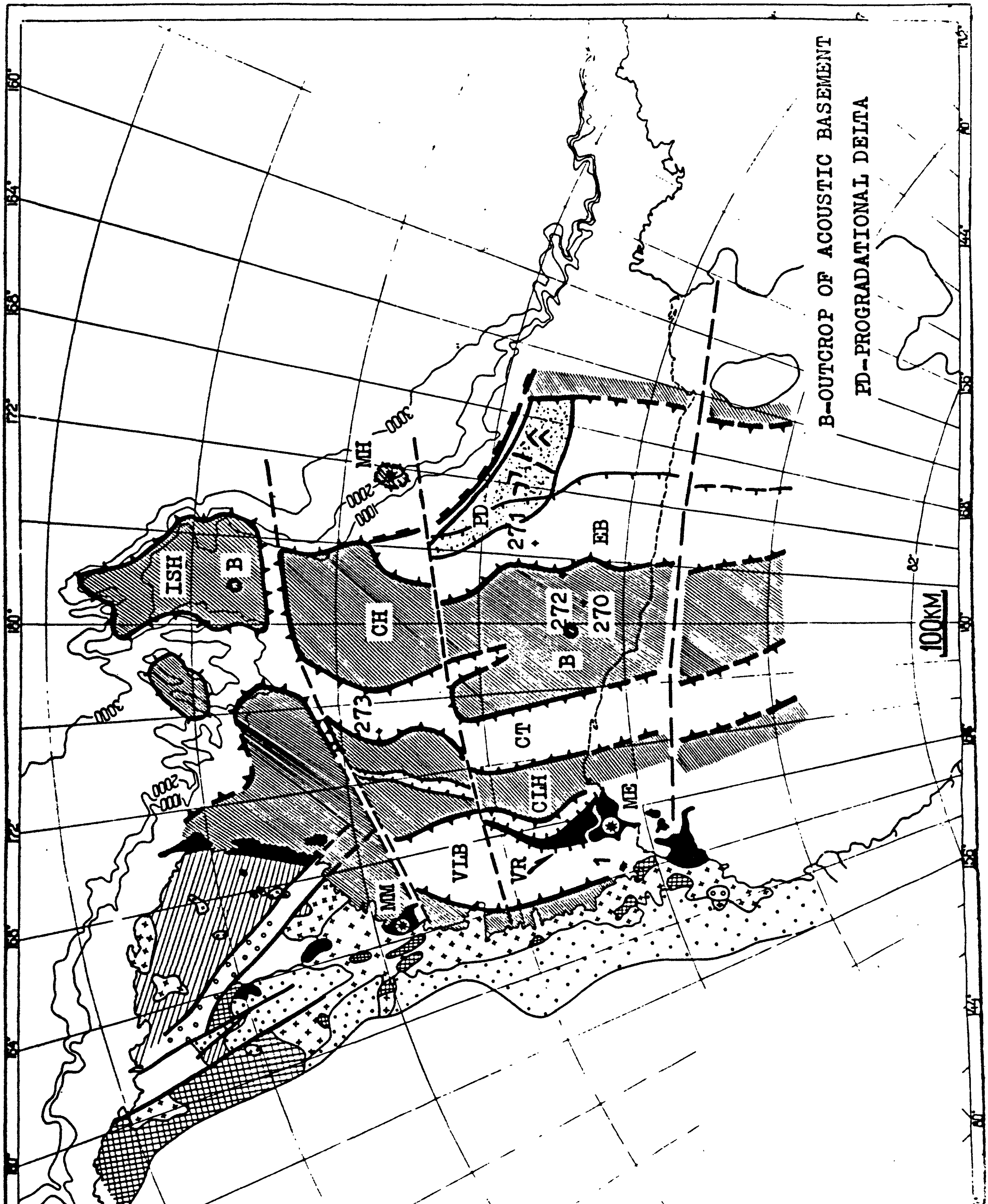
B-OUTCROP OF ACOUSTIC BASEMENT
PD--PROGRADATIONAL DELTA
100KM
ISH
B
CH
273
CT
CLH
VLB
VR
MM
ME
272
270
271
EB
PD
MH

Figure 2

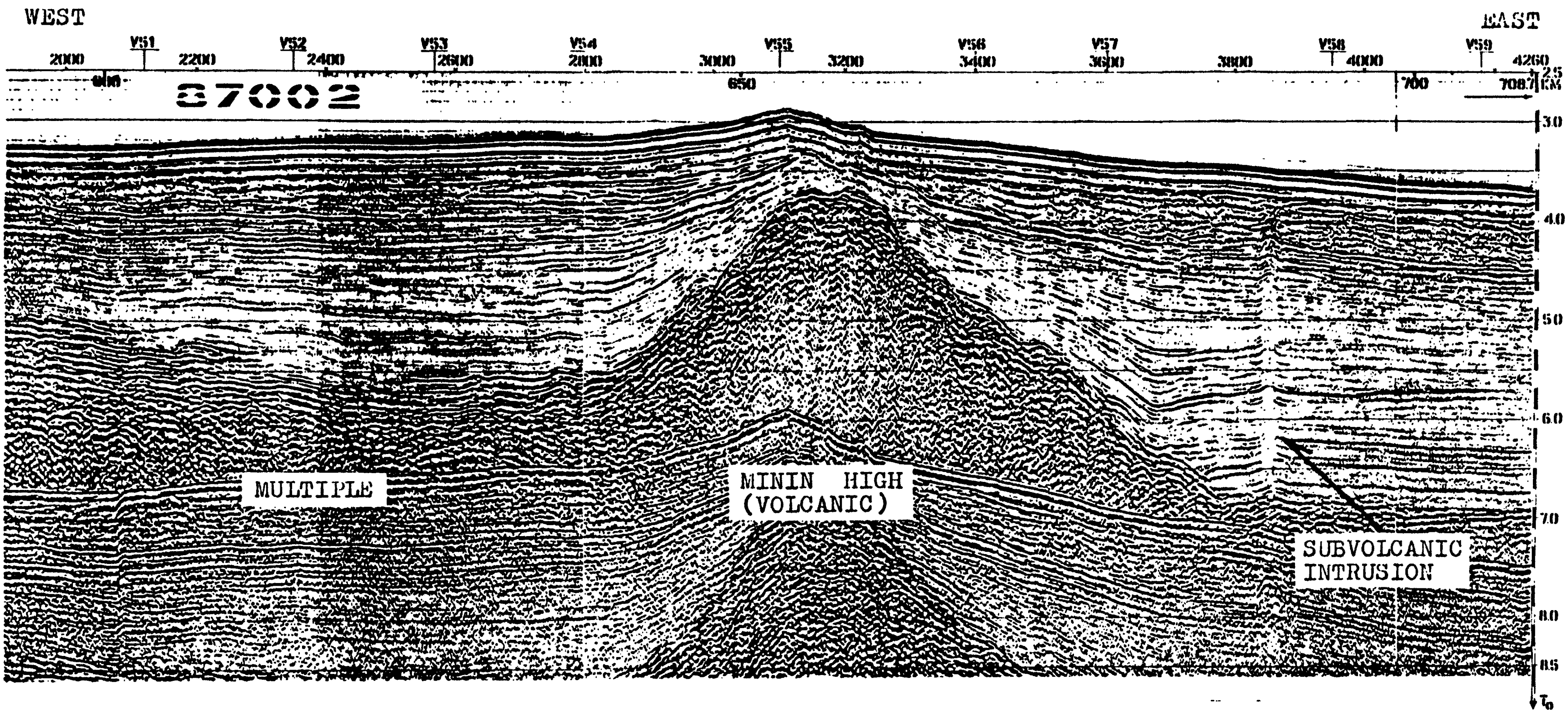
WEST
EAST
87002
MULTIPLE
MININ HIGH
(VOLCANIC)
SUBVOLCANIC
INTRUSION

Figure 3A

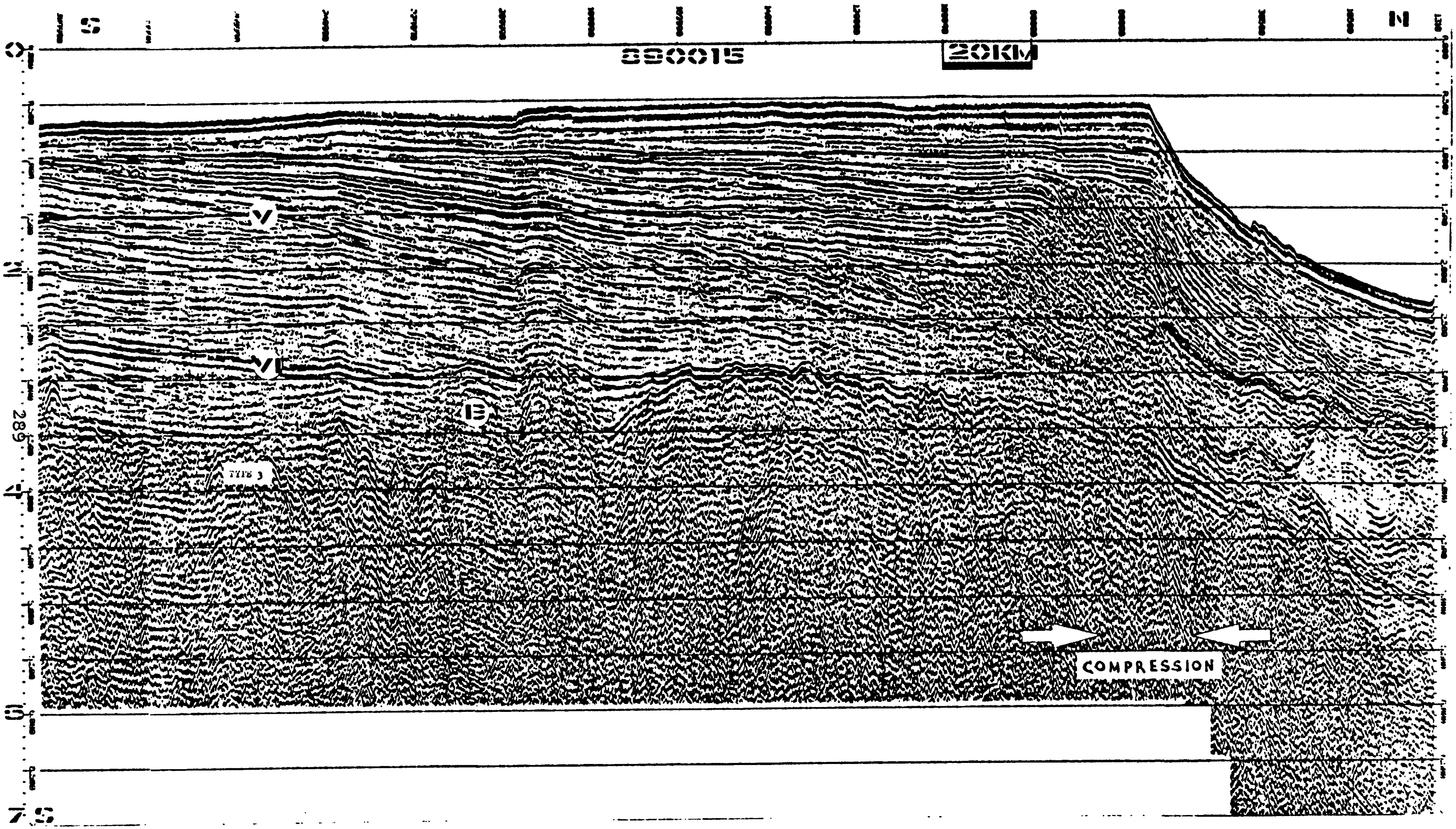

Figure 3B

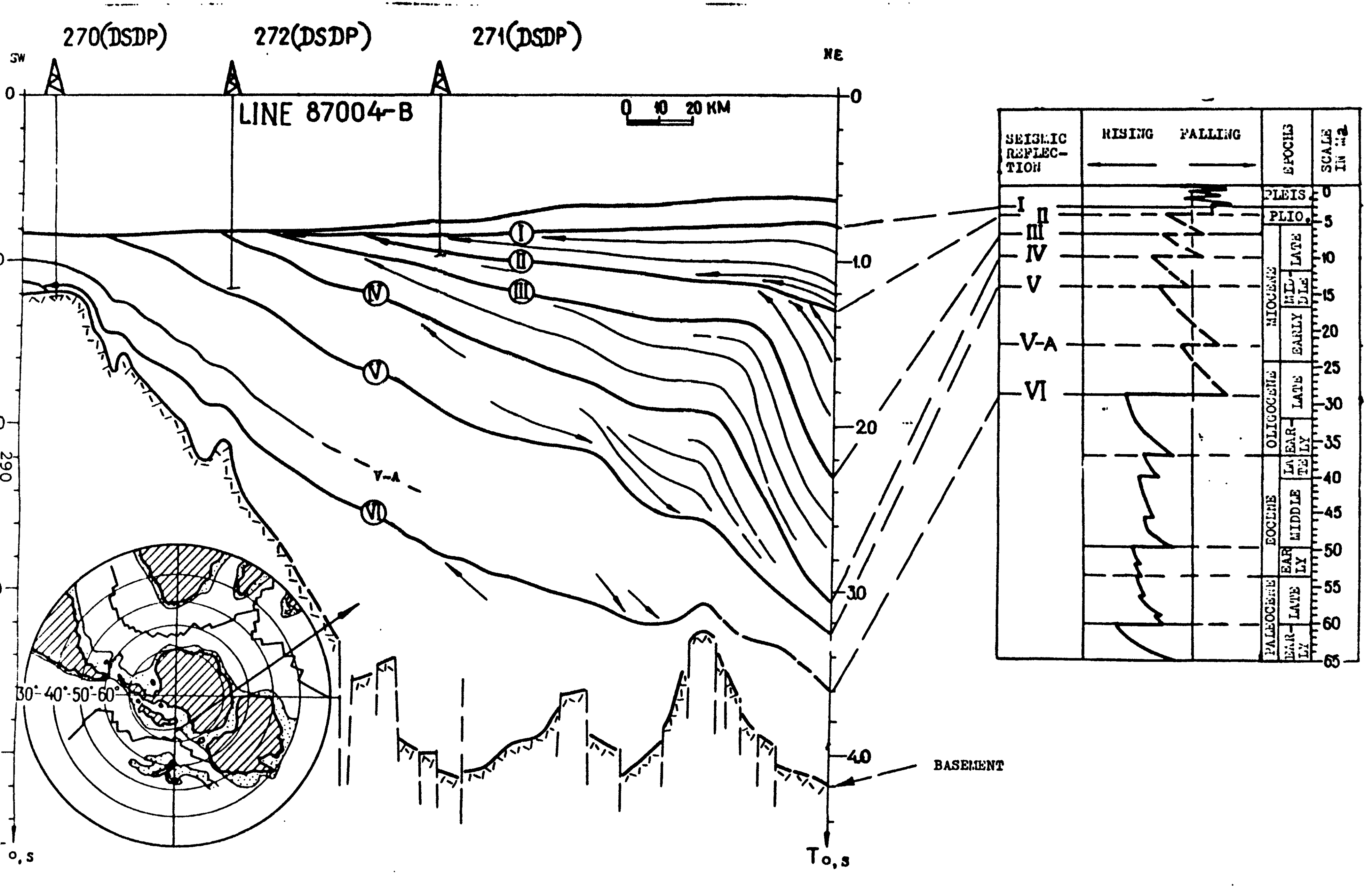
270(DSDP)
272(DSDP)
271(DSDP)
SW
NE
LINE 87004-B
0 10 20 KM
0
1.0
2.0
3.0
4.0
To,s
I
II
III
IV
V
V-A
VI
BASEMENT
30° 40° 50° 60°
SEISMIC REFLECTION
RISING
FALLING
EPOCHS
SCALE IN m.y.
PLEIS.
PLIO.
MIOCENE
LATE
MID-DLE
EARLY
OLIGOCENE
LATE
EAR-LY
EOCENE
LA-TE
MIDDLE
EAR-LY
PALEOCENE
LATE
EAR-LY
0
5
10
15
20
25
30
35
40
45
50
55
60
65

Figure 4