Marine Geological and Geophysical Investigations of the Antarctic Continental Margin, 1984

U.S. GEOLOGICAL SURVEY CIRCULAR 935

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By Stephen L. Eittreim, Alan K. Cooper, and Scientific Staff

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INTRODUCTION

The Antarctic continental margin is geologically the least known continental margin of the world. Although the National Science Foundation has for many years supported reconnaissance-style marine geophysical and geological studies on the Research Vessel Eltanin, the coverage of Eltanin tracks in the Southern Ocean is sparse, and the vast majority of tracks do not cross the mostly ice-covered continental margin but concentrate in deeper and farther-offshore areas. Other marine geophysical and geological studies have dealt with only limited areas on the continental margin. Therefore, knowledge about the geologic framework of the margin has been pieced together by extrapolating between widely spaced observations and by inferring from the geology that is known of better studied passive continental margins, particularly those conjugate margins of the Gondwana group.

A few Deep Sea Drilling Project (DSDP) holes have been drilled on the lower continental rise off East Antarctica and on the Ross Shelf (Hayes and Frakes, 1975; Hollister and Craddock, 1976). Sedimentologic and geomorphic studies also have been done in limited areas on the shelves of East Antarctica and in the Ross Sea (Anderson end others, 1980). Recently, Germany, France, Australia, Japan, Norway, and the USSR have conducted seismic surveys aimed particularly at characterizating sediment bodies of the Antarctic margin. Behrendt (in press; 1983) reviews the knowledge regarding petroleum resources for the Antarctic continental margin including the more recent seismic surveys. Our studies on the Wilkes Land margin and in the Ross Sea are adjacent to recent seismic surveys by France (French Petroleum Institute, IFP), Federal Republic of Germany (Federal Institute for Geosciences and Natural resources, BGR) and Japan (Japanese National Oil Corporation, JNOC) and have been planned cooperatively with these institutions to produce a more comprehensive data base for this part of the Antarctic continental margin.

The initial breakup of Antarctica, Australia, and New Zealand occurred approximately 100 m.y. ago, with an early phase of very slow spreading between Australia and Antarctica, and was probably preceded by a period of rift-basin formation along the rift margins (Weissel and Hayes, 1972; Falvey and Mutter, 1981; Cande and Mutter, 1982). Because the Antarctic margin is relatively young and has probably been sediment starved during the latter part of the Tertiary, due to presence of the ice cap, the mantle of sediment is thin, and the resultant breakup structures and stratigraphy are easily accessible to study.

Drilling by the DSDP on the Tasman Rise, conjugate to the Antarctic margin, has demonstrated that until about 38 m.y. ago, the opening sea between Antarctica and Australia had a restricted circulation with deposition of organic carbon-rich silt and clay and with abundant diagenetic and authigenic components (Andrews and Ovenshine, 1975). The basin's restriction was due to the Tasman Rise that topographically connected the two continents at their eastern edges during the early seafloor-spreading phase.

Climatic influence on Antarctic sedimentation is obviously important. The drastic cooling during the Terminal Eocene Event 38 m.y. ago and the major expansion of the ice sheet during the Miocene at 15 m.y. ago (Kennett, 1982) are likely to imprint profound effects on the stratigraphic record. Also of interest is the record of climate change on the morphologic development of the shelf, slope, and rise and what kind of environment of sedimentation, in terms of sediment stability and transport, prevails today.

This report is a summary of our surveys (Fig. 1) during 1984 and includes a description of the types of data collected and a brief discussion of preliminary results based primarily on shipboard analyses of unprocessed seismic and other geophysical data. Participants on the scientific crew of the U. S Geological Survey Research Vessel S.P. Lee for the two legs, including scientists from academic and government institutions of Australia and New Zealand, are listed on the facing page.

LEG 1—WILKES LAND CONTINENTAL MARGIN

Operations

Leg 1 commenced in Christchurch (Lyttleton Harbor) on January 5, 1984, and ended at McMurdo Station, Antarctica, on February 2. Transit to and from the work area off the Wilkes Land coast consumed about 9 days and 5 days, respectively. During the 13 days spent in the survey area between longtitude 130, and 150, E, we collected multichannel-seismic (MCS) and other geophysical data, sampled the seafloor by gravity corer and rock dredge, and mapped the shelf seafloor by side-scan sonar. The area of work is adjacent to and mostly west of the 1982 survey by the French Petroleum Institute. During our survey, weather conditions were favorable but sea-ice conditions were not, affording only limited access to the continental shelf (figs. 2 and 3).

During non-MCS operations, the Lee at times moved through loose multiyear, 3 m-thick ice floes of approximately five-tenths seasurface coverage to locate sites for sampling (fig. 4). Although such ice-maneuvering proved to be possible for the Lee, the process of searching for leads and pushing through the ice was an inefficient and wasteful use of time. All MCS profiling was carried out in ice-free areas, although some of the inshore lines, due to the necessity of skirting the ice front, contained dog legs. Entry into McMurdo Sound was attempted via the ice channel that was cut through the fast ice by the U.S. Coast Guard. Passage proved to be impossible for the Lee, however, due to wind-pressured brash ice which filled the ice channel. The Lee was beset in the ice of the channel for 12 hours, and with assistance from the U.S. Coast Guard icebreaker Polar Sea was finally extricated and an exchange of crew and replenishment of supplies was accomplished.

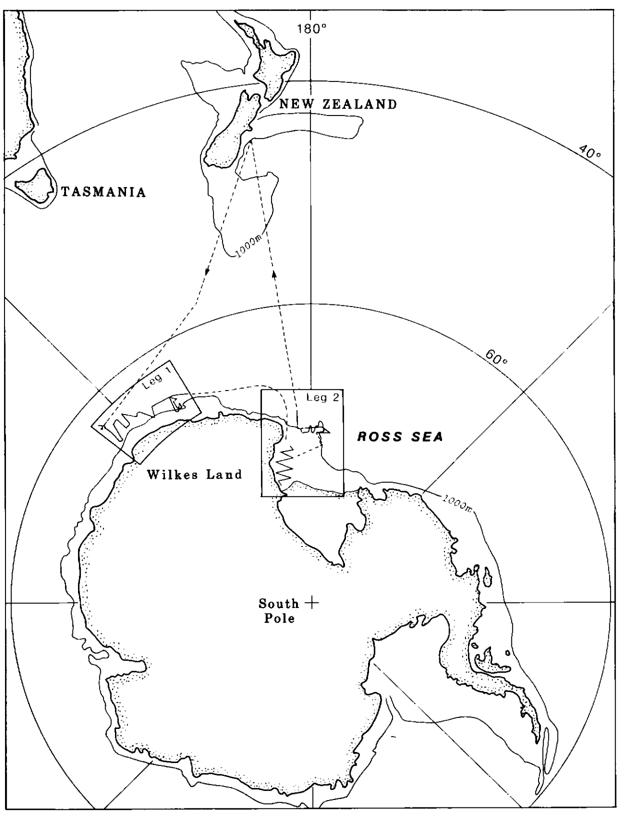

Figure 1. Regions where the two 1984 surveys were carried out by the S.P. Lee.

Data Collected

During Leg 1, 1,800 km of 24-fold seismic-reflection data was recorded using a 2,400-m-long hydrophone streamer and a 1300 cubic inch airgun array. Shot intervals of 50 m provide 24-fold coverage. An additional 400 km of single-channel seismic reflection data was recorded using one 80 cubic inch airgun. Also, 33 sonobuoy-refraction profiles were recorded. Along all lines, including most of the transit lines, gravity and magnetics, and 3.5 and 12 kHz acoustic-reflection profiles were recorded. Magnetic measurements were made with a two-sensor system to measure along-track magnetic gradients. During lines run on the continental shelf, Uniboom (1 kHz) acoustic profiles were recorded and one 30-km long side-scan-sonar record was made. Nine gravity cores of bottom sediment were obtained with a 3-m corer in various sedimentary environments on the shelf, slope, and rise. Physical engineering properties were measured on these samples and gas analyses were made in the ship's laboratory. Two dredge hauls for rocks were made on the shelf and upper slope respectively. Navigation was by "Transit" satellite, supplemented by high-accuracy "Global Positioning System" (GPS) satellite for 9 hours each day.

Preliminary Results

The five north-south lines in the western part of the survey span the region from the continental shelf break or slope out across the continent-ocean boundary (COB). The COB is typically characterized by a ridge that forms the southern boundary of oceanic basement (fig. 5) Two lines of the survey penetrate onto the continental shelf. Based on single-channel monitor records from the MCS system, and seismic velocities from sonobuoys, the sediment wedge of the slope and rise ranges from about 3 to 6 km in thickness. Thicknesses measured on the shelf are greater than 3 km, but are difficult to ascertain from the unprocessed seismic data.

The continental rise wedge consists of a lower unstratified sequence which is largely confined to the region landward of the COB, and a stratified upper sequence that extends out over oceanic crust, beyond the COB (fig 5). The older unstratified sequence may be a synrift deposit, laid down during early rifting and crustal thinning, before significant movement between Antarctica and Australia occurred. The younger stratified sequence was deposited in an environment of active bottom currents that have shaped and eroded the deposits, and turbidity currents that have dissected

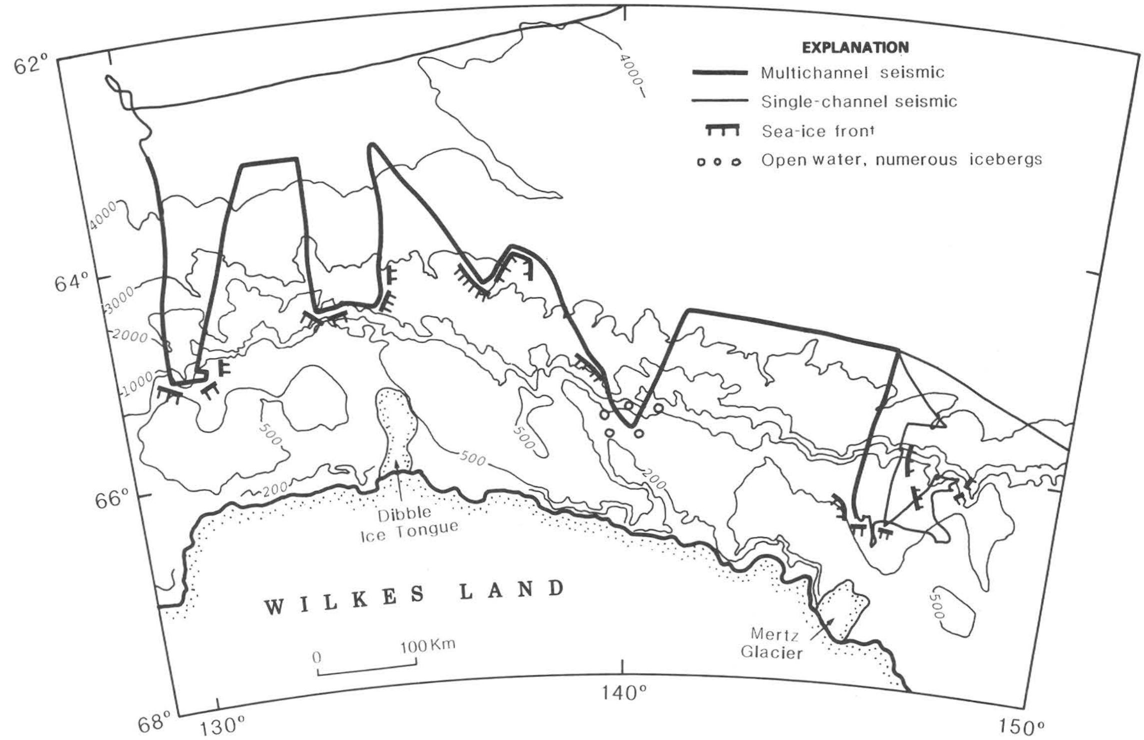

Figure 2. Leg 1 tracklines of the S.P. Lee. Generalized bathymetry in meters from Gebco chart no. 5-18. Sea-ice edge indicated is from visual observation.

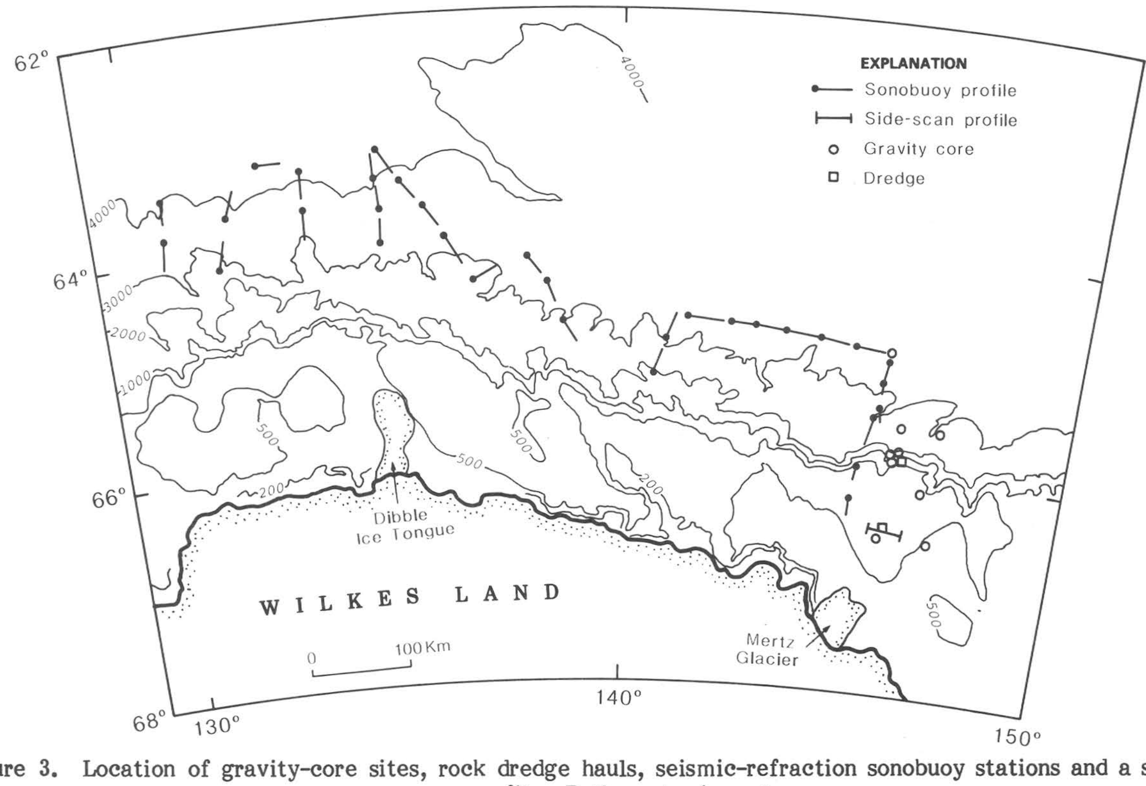

Figure 3. Location of gravity-core sites, rock dredge hauls, seismic-refraction sonobuoy stations and a side-scan-sonar profile. Bathymetry in meters.

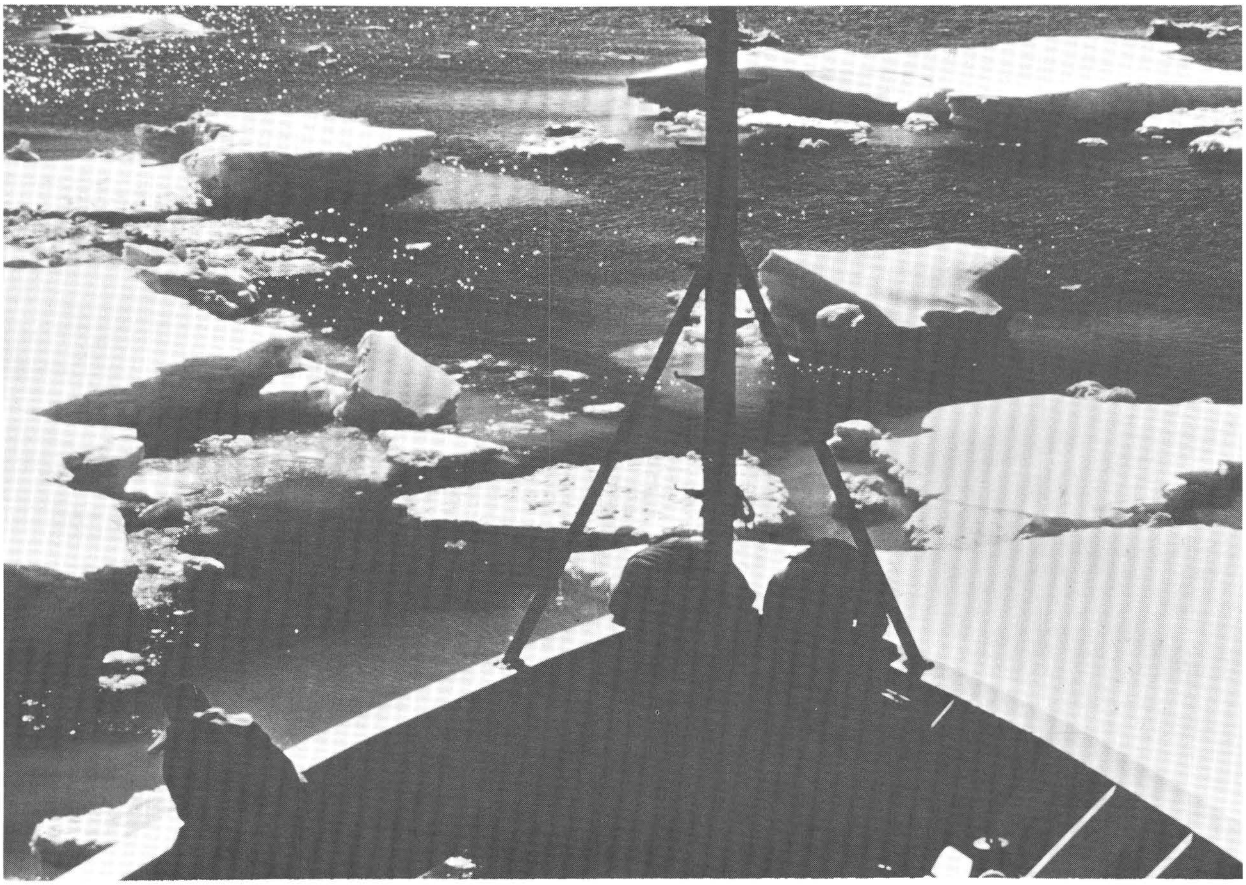

Figure 4. Ice types commonly encountered at the southern ends of our survey lines. The ice cakes in this photograph have a freeboard of about 1 m. The Lee was able to move through such ice at an average speed of about 4 knots.

the upper rise and slope to form many submarine canyons. Seafloor truncation of beds of this stratified sequence on the upper continental rise indicate that the erosion is recent (fig. 6).

Capping this upper stratified sequence, sharp-crested depositional ridges spaced about 35 km apart, with canyons cut into some of the valleys between them, dominate the morphologic fabric of the seafloor on the upper continental rise. The seismic stratigraphy indicates that the ridge crests have migrated eastward through time (fig. 7).

On the continental shelf, side-scan-sonar images of the seafloor reveal that ice gouges produced by large tabular icebergs occur in water depths greater than 500 m (fig. 8). Ice-gouge features are typically multiple grooved incisions a few meters deep and tens of meters in width. Semicircular to circular depressions about 100 m in diameter (30 to 150 m) are also common on shelf bank tops and slopes. Commonly these depressions appear as an overlapping sequence forming a linear feature. These depressions in places are associated with the grooved features that are more obviously identifiable as ice gouges. Coast-perpendicular ridges and furrows a few meters high and spaced about 100 m apart are believed to be related to glacial advances onto the shelf. During the cruise, the observed alignment of tabular icebergs on the shelf indicated their grounding along the flanks of seafloor ridges. It seems that modern and ancient ice-related processes are dominant in determining the shape and character of the seafloor in this shelf environment.

The sediment core samples collected on the continental shelf consist of: (1) diatom ooze from a deep-shelf basin, probably deposited in this quiet sedimentary environment by modern biogenic processes; (2) a pebbly mud on the flank of the basin, probably emplaced by Pleistocene glacial or glacial-marine processes; and (3) sand on a bank top that either is material deposited in shallow water during a Pleistocene low stand of sea level or is a modern winnowing product of poorly sorted Pleistocene glacial sediment. Cores from the continental slope and rise contain sandy mud.

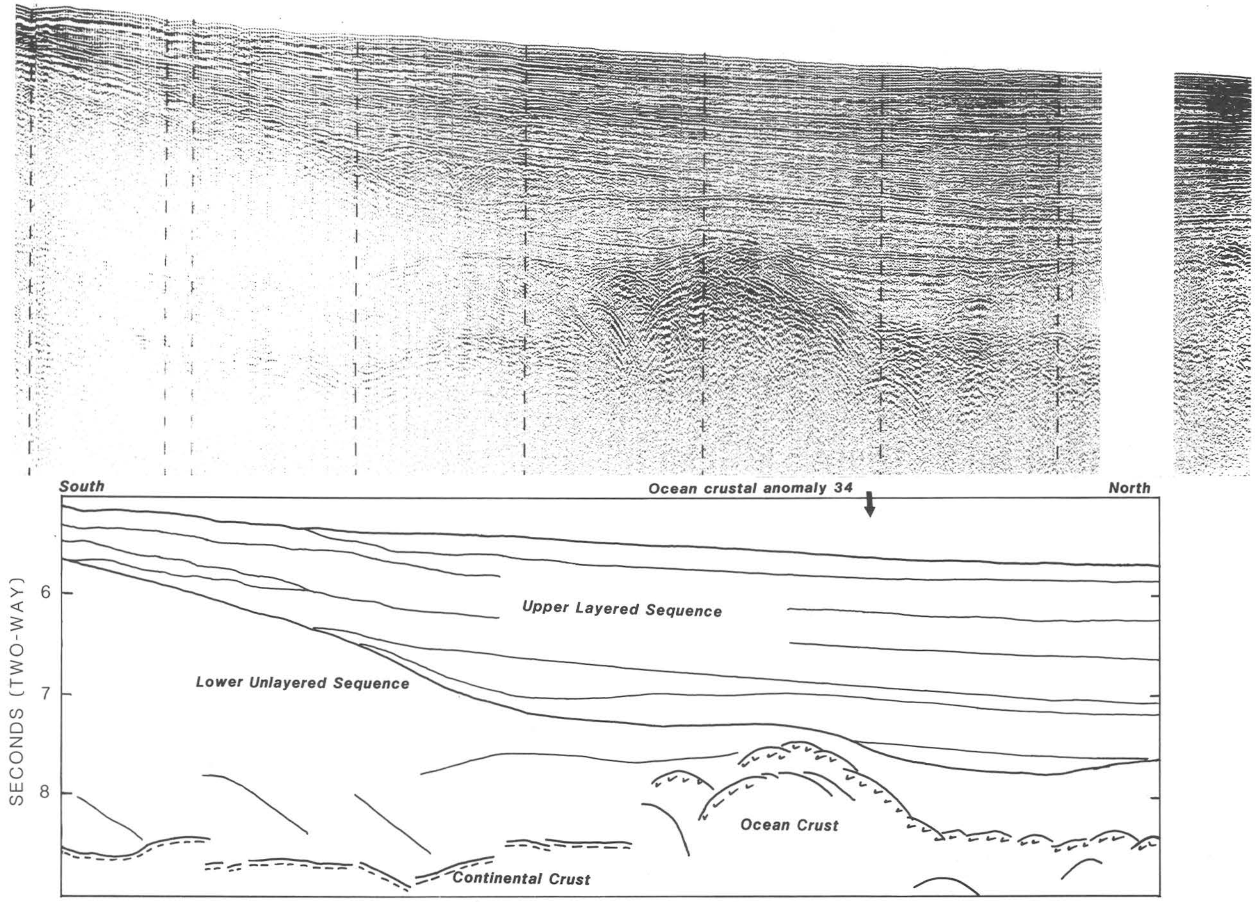

Figure 5. Unprocessed single-channel seismic record made from one channel of the MCS system across the presumed continent-ocean boundary. One second of reflection time equals approximately 1 km; less for the shallower sediment and more for the deeper strata. Location given in Figure 2.

Gases were extracted from the nine sediment cores and analyzed for hydrocarbons. Samples from tops and bottoms of cores, which in length are as much as 3.8 m, showed methane to be the most abundant hydrocarbon, with concentrations typical of shelf environments. The other higher hydrocarbon gases occur in much lower concentrations. The source of all of the hydrocarbons is likely biogenic. No obvious evidence was found for thermogenic gas migration or diffusion and no gas seeps were observed. Thus the gases were probably generated in place by low-temperature bacterial decay.

LEG 2—ROSS SEA

Leg 2 commenced at McMurdo Station, Antarctica, on February 2, 1984, and ended in Christchurch (Lyttleton Harbor), New Zealand, on March 3. The general operating area (figs. 1 and 9) included the western Ross Sea (Victoria Land basin) and Iselin Bank, where geophysical surveys and geological sampling were conducted. A single multichannel seismic-reflection trackline also was recorded along the western side of McMurdo Sound and crossed existing (MSSTS-1, McMurdo Sound Sediment and Tectonic Studies) and planned (CIROS, Cenozic Investigation in Western Ross Sea) shallow drilling sites.

In contrast to Leg 1, the second (29 day) leg was characterized by bad weather conditions, with frequent periods of high-velocity winds and rough seas. The inclement weather at times halted station operations in the central Victoria Land Basin and multichannel seismic operations across the continental margin near Cape Adare. Ice conditions, however, were exceptionally good in the western Ross Sea, and multichannel seismic tracklines were continued to within a few miles of the shore line in the southern part of the survey area. Occasional brash ice, "bergy bits," and tabular icebergs were encountered, but usually only near the edge of the ice shelf and pack ice.

Operations were delayed near the beginning of the cruise when the tail buoys on the multichannel hydrophone streamer snagged on an automobile-sized "bergy bit," and the entire 2,400-m streamer broke away from the ship. By good fortune, the streamer was recovered, and, although it had sunk 900 m to the seafloor, after minor repairs it continued to function normally throughout the remainder of the cruise.

Data Collected

During Leg 2, several thousand kilometers of geophysical trackline data and geologic samples were collected (fig. 9). The geophysical data included multichannel (2,350 km) and single-channel (850 km) seismic reflection, high-resolution seismic reflection (1,850 km), sonobuoy seismic (39 stations), gravity (3,950 km), magnetic gradiometer (3,100 km), and 3.5 kHz and 12 kHz bathymetry (4,500 km).

Sampling operations (fig. 9) included 3-meter gravity coring (15 cores), chain-bag dredging (2 stations), and heat flow measuring (3 sites). Six days were dedicated to these operations and to a detailed high-resolution seismic reflection survey of an area of irregular seafloor bathymetry. The gravity cores range in length from 20 to 258 cm. Several hundred kilograms of rocks were recovered at both dredge stations. Several sub-seafloor temperature measurements were also made at each of three gravity-core sites in the Victoria Land basin to determine heatflow.

Analytical measurements of organic gas concentration and sediment shear strength were routinely made on the gravity cores immediately after core recovery. Thermal conductivity determinations were also done on cores from heat flow stations.

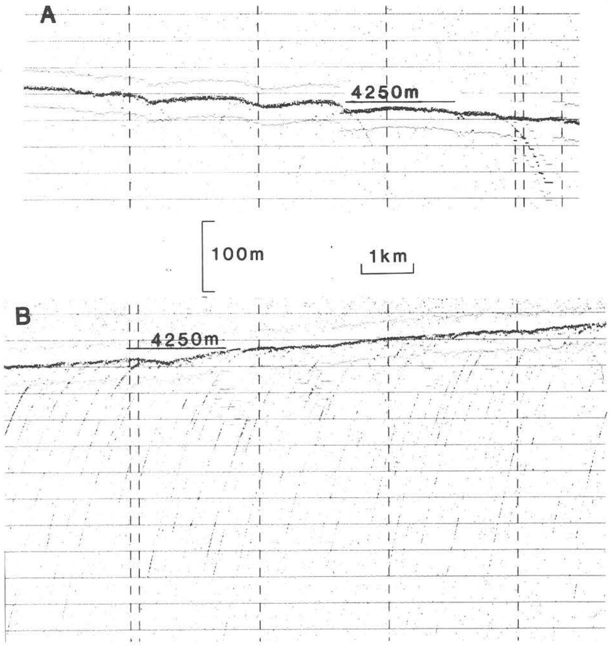

Figure 6. Examples of 12-kHz reflection records that show erosional effects on the seafloor of the continental rise: (A) cuestas or steps caused by the outcrop of eroded strata of the upper stratified layered sequence; (B) hyperbolic echos indicative of energy focused by linear furrows, probably of erosional nature, on the seafloor.

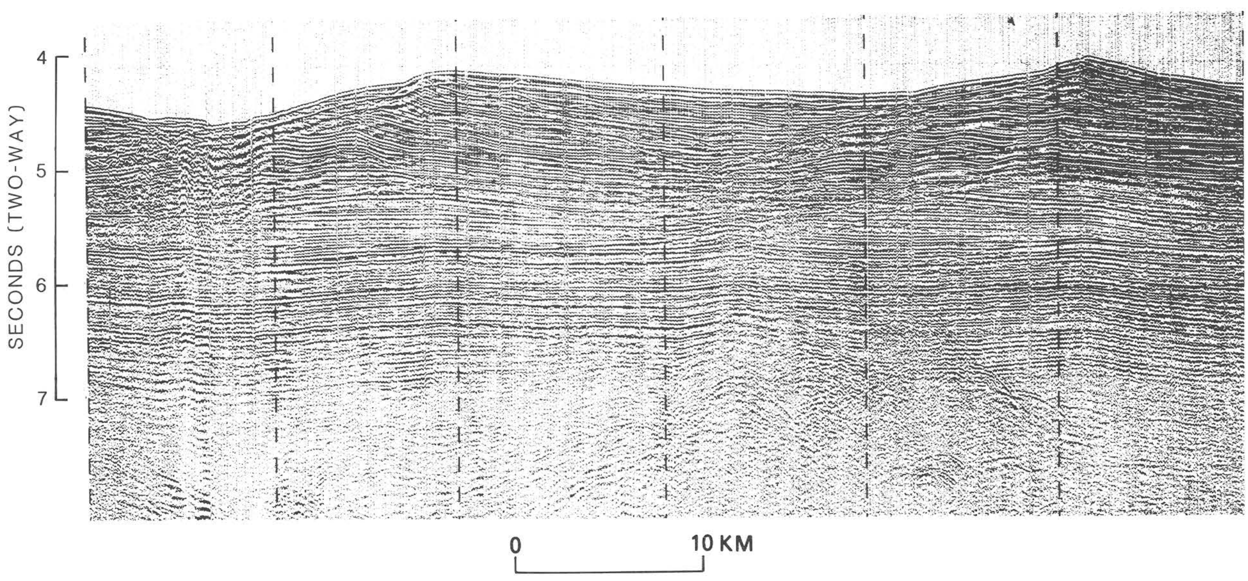

Figure 7. Depositional ridges, which strike generally downslope, recorded on the upper continental rise.

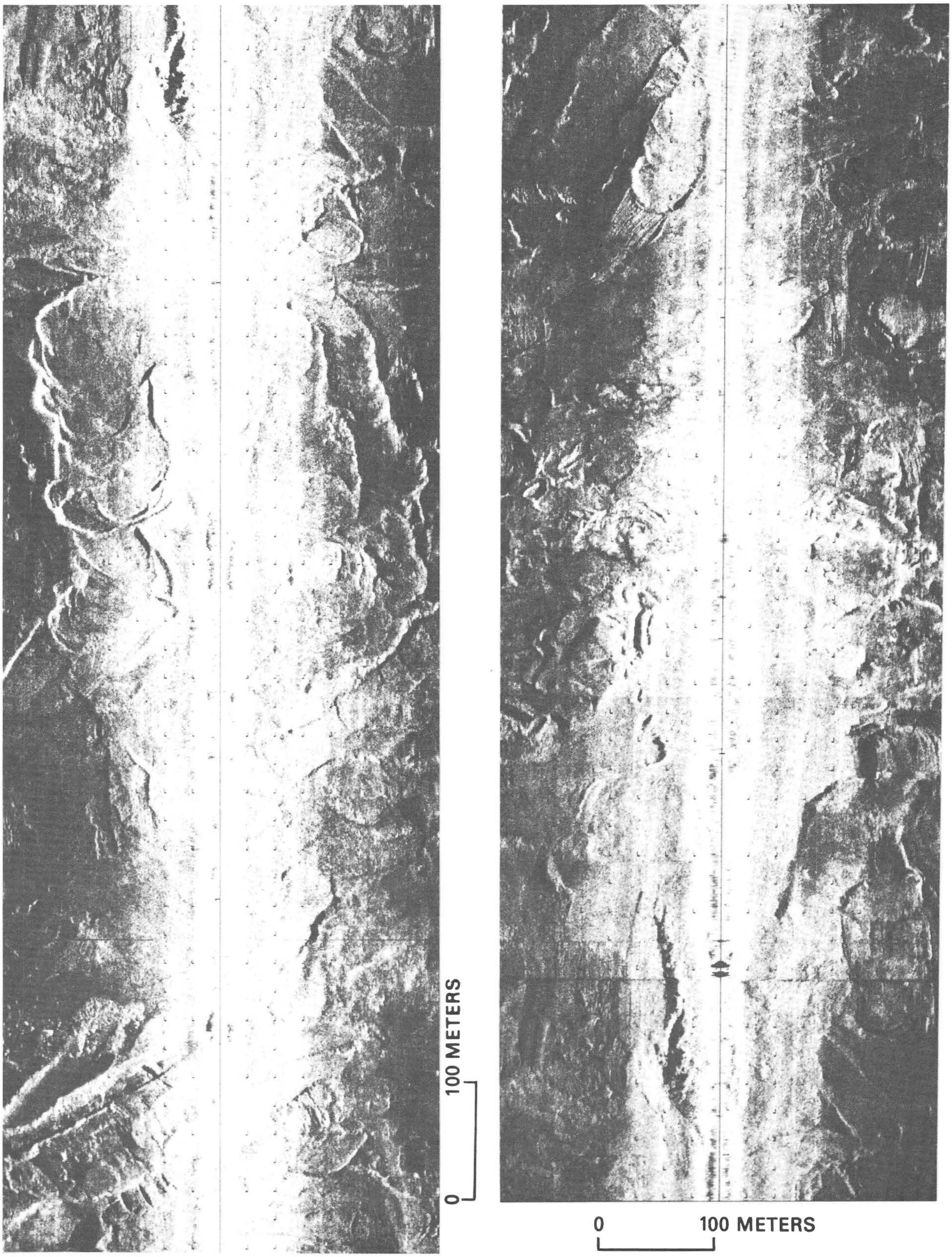

Figure 8. Sample of side-scan-sonar record collected along track shown in figure 3. Most of the relief features seen are believed to be due to ice scouring.

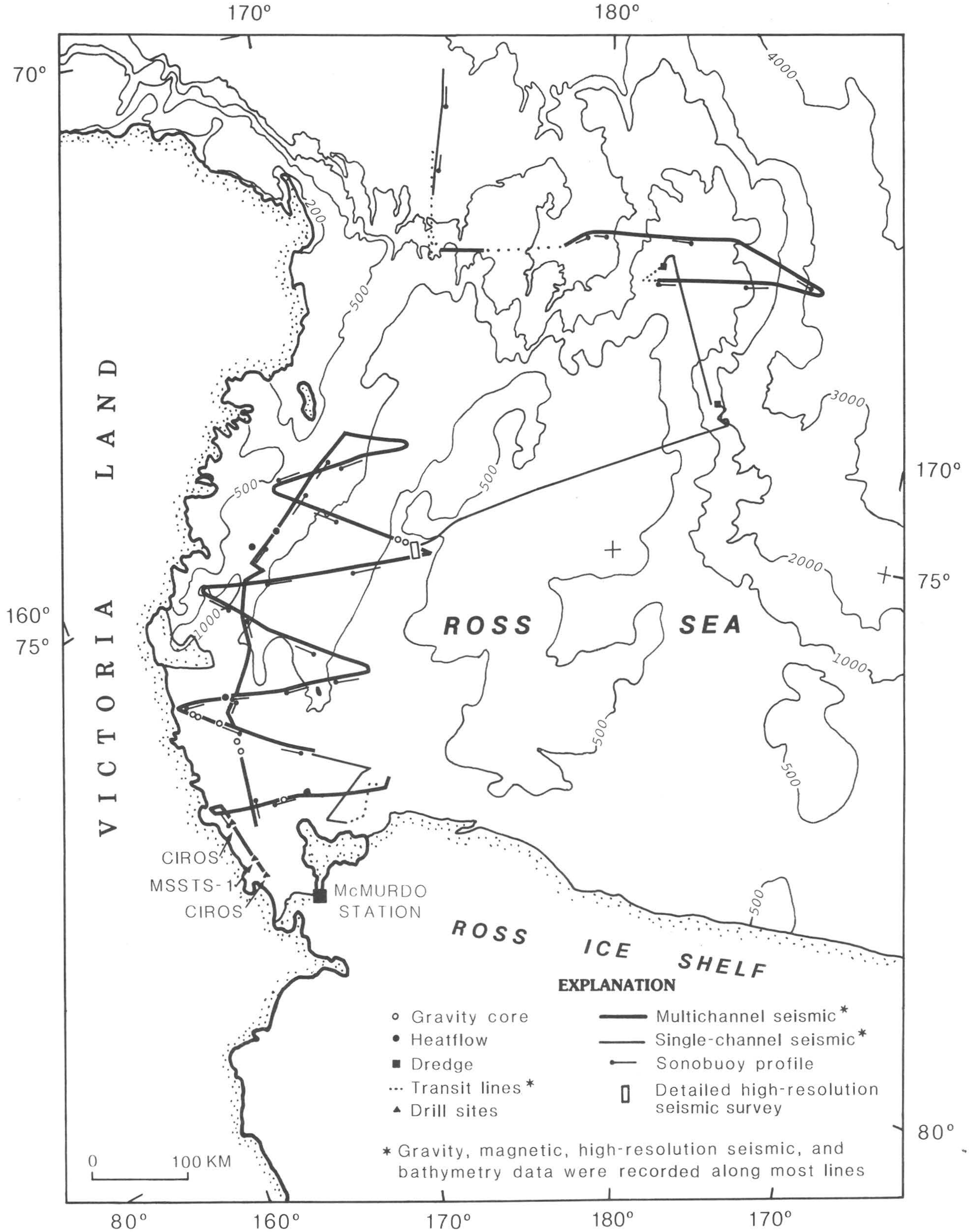

Figure 9. Index map of the Ross Sea, Antarctica, showing location of geophysical tracklines and geologic sampling sites occupied by the S.P. Lee during February 1984. Bathymetry in meters.

Preliminary Results

The Ross Sea is a large embayment in the coastline of Antarctica and is floored by a broad continental shelf that is covered by 400 to 1,100 m of water. To the west, the Ross Sea is bordered by the Transantarctic Mountains, the feature commonly accepted as the structural boundary between the Proterozoic shield rocks of East Antarctica and the younger Phanerozoic microplates of West Antarctica (fig. 10). To the south, the edge of the extensive Ross Ice Shelf marks the boundary of the Ross Sea. Three major structural troughs beneath the Ross Sea trend north-south, subparallel with the Transantarctic Mountains.

Previous multichannel seismic-reflection surveys (fig. 11), sonobuoy-refraction measurements, and DSDP drilling data from the two easternmost sedimentary basins of the Ross Sea, Eastern basin and Central basin, show they contain 4 to 5 km of Cenozoic (mostly post-Oligocene) sedimentary rock believed to be of predominately glacial origin (Davey, 1983; Hinz, in press). However, the westernmost basin, the Victoria Land basin had no previous multichannel seismic surveys, yet is believed to be filled with similar thicknesses of possibly older sediment (Davey, 1983).

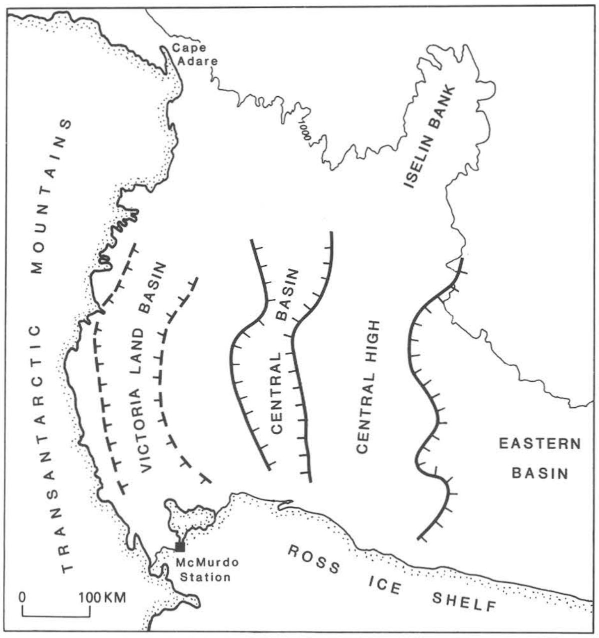

Figure 10. Map showing approximate location of structural features in the Ross Sea region. Modified from Hinz (1983). Bathymetry in meters.

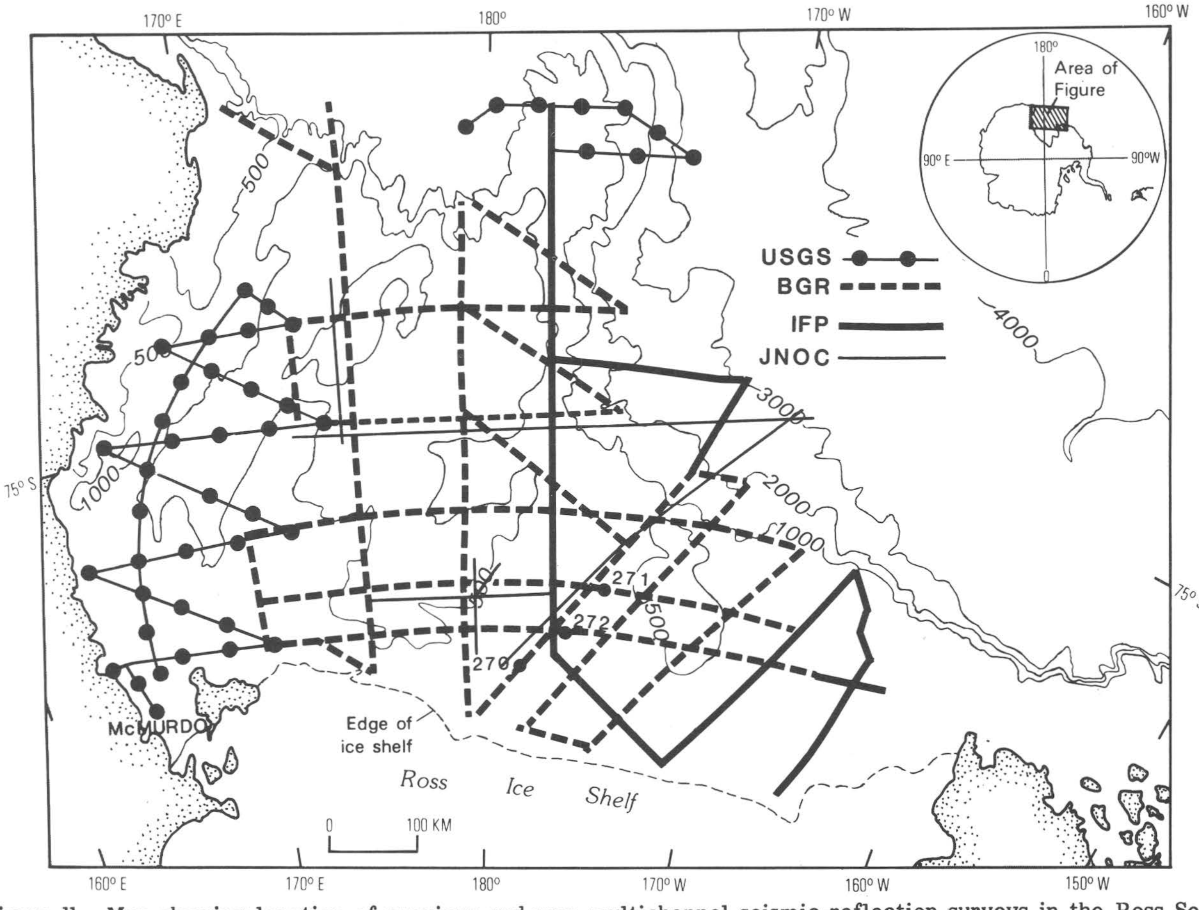

Figure 11. Map showing location of previous and new multichannel seismic-reflection surveys in the Ross Sea. Modified from Behrendt (1983). Bathymetry in meters.

Structural highs separate the basins and form bathymetric ridges. Iselin Bank is the northward projection of one of these basement highs and is believed to be a feature of probable continental origin. In pre-Gondwana reconstructions, Iselin Bank lies at the junction of Australia, Antarctica, and New Zealand.

The objective of Leg 2 was to study the crustal structure of the Victoria Land basin and the Iselin Bank areas. The new multichannel seismic-reflection data recorded over the Victoria Land basin suggest that the basin has had a more complex history of deformation than the other two basins and that the Victoria Land basin's history is closely tied to that of the Transantarctic Mountains. Figure 12, a line drawing of a seismic-reflection profile across the Victoria Land basin, shows regional unconformities and faulting that may be related to the uplift of the Transantarctic Mountains in late Cenozoic time. The enlarged seismic section in the same figure illustrates the presence of at least two unconformities, possibly one at the top of bedrock.

Sonobuoy-refraction measurements made during the cruise also confirm a 2 to 5 km thickness of sedimentary rock in the Victoria Land basin and the existence of distinct refraction horizons, possibly unconformities or older Tertiary rocks within the sedimentary section. Basement rocks which have a velocity of 4.9 to 5.4 km/s can be followed throughout most of the Victoria Land basin, based on the sonobuoy refaction data.

A high-velocity (1.9 km/s) refractor is recorded along the seafloor in areas where stiff indurated glacial sediment has been sampled in the 3-m cores. This sediment is marked by high shear strength, high thermal conductivity, and a low concentration of only biogenic methane gas. Temperature measurements made in the upper 3 to 4 m of this sediment show a large thermal gradient, suggestive of high heat flow.

High-resolution seismic-reflection profiles from the Victoria Land basin indicate that areas of 265- to 725-m-deep seafloor are covered by hummocky features with 5 to 25 m of relief (fig. 13). The origin

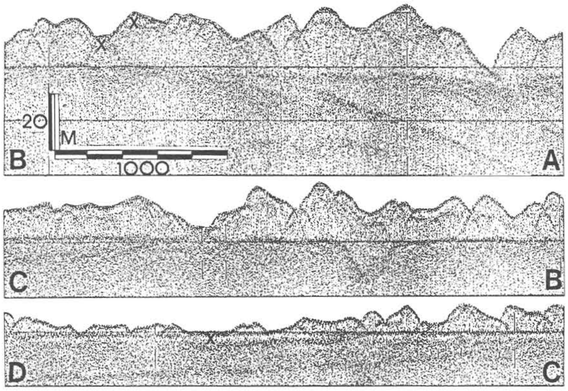

Figure 13. Example of high-resolution seismic-reflection data recorded across an area of hummocky seafloor topography of about 500 m water depth. Dipping reflectors and a shallow unconformity can be seen on the record. "X" marks the location where gravity cores were collected. See figure 9 for location of the detailed high-resolution seismic survey.

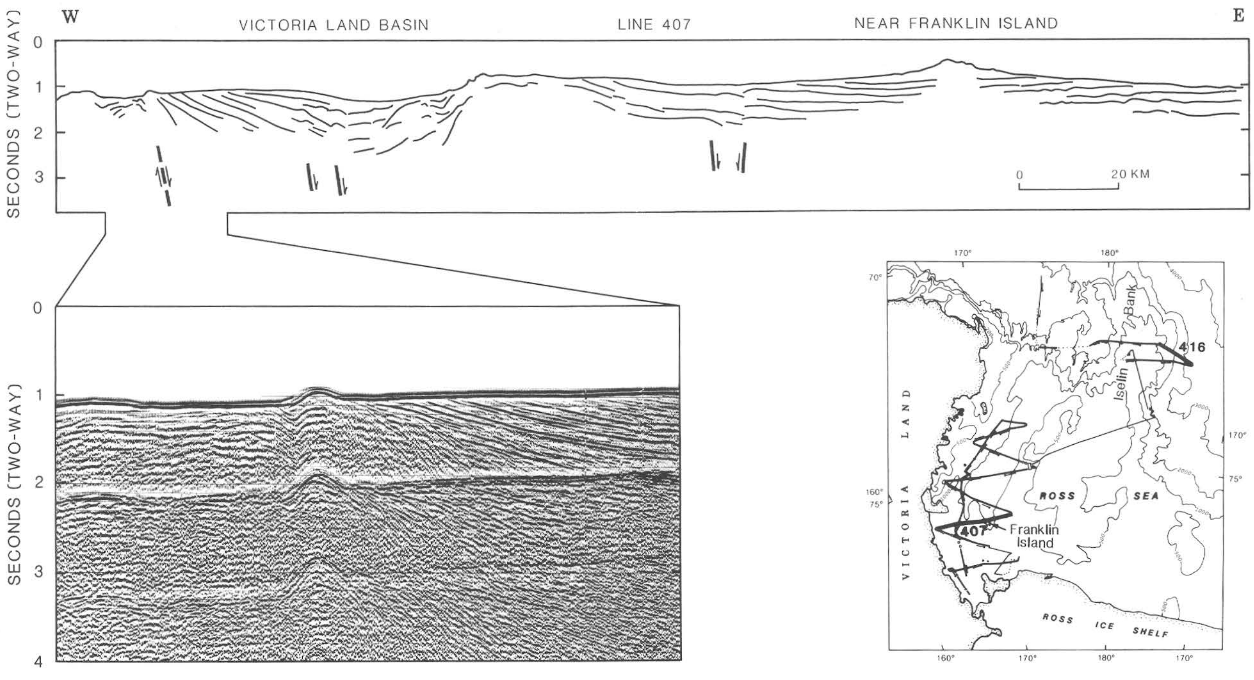

Figure 12. Line drawing and multichannel seismic-reflection data from line 407 across the Victoria Land basin in the western Ross Sea. Faults and uncomformities are found in the sedimentary section and reflect relative vertical displacement in the western Ross Sea region. Bathymetry in meters.

of these features is likely to be related to glacial processes, however, the mechanism is not fully understood.

Multichannel seismic-reflection profiles across the eastern flank of Iselin Bank indicate that basement rocks of the Ross Sea Shelf crop out along the bank (fig. 14). The steep-sided bank is covered by a thin sedimentary section that is separated from deep-water sedimentary rocks, of the Southern Ocean by an outer basement high. Rocks dredged from the basement high include volcanic, plutonic, metamorphic, and sedimentary rocks; although most are rounded and appear to be glacial erratics. A significant number of angular quartzite clasts may be from the local "basement." These clasts are provisionally correlated with Paleozoic quartzite units of the Transantarctic Mountains. A different assemblage of rocks, which includes large quanties of well-rounded volcanic and granitic cobbles, was dredged from a fault scarp along the crest of Iselin Bank.

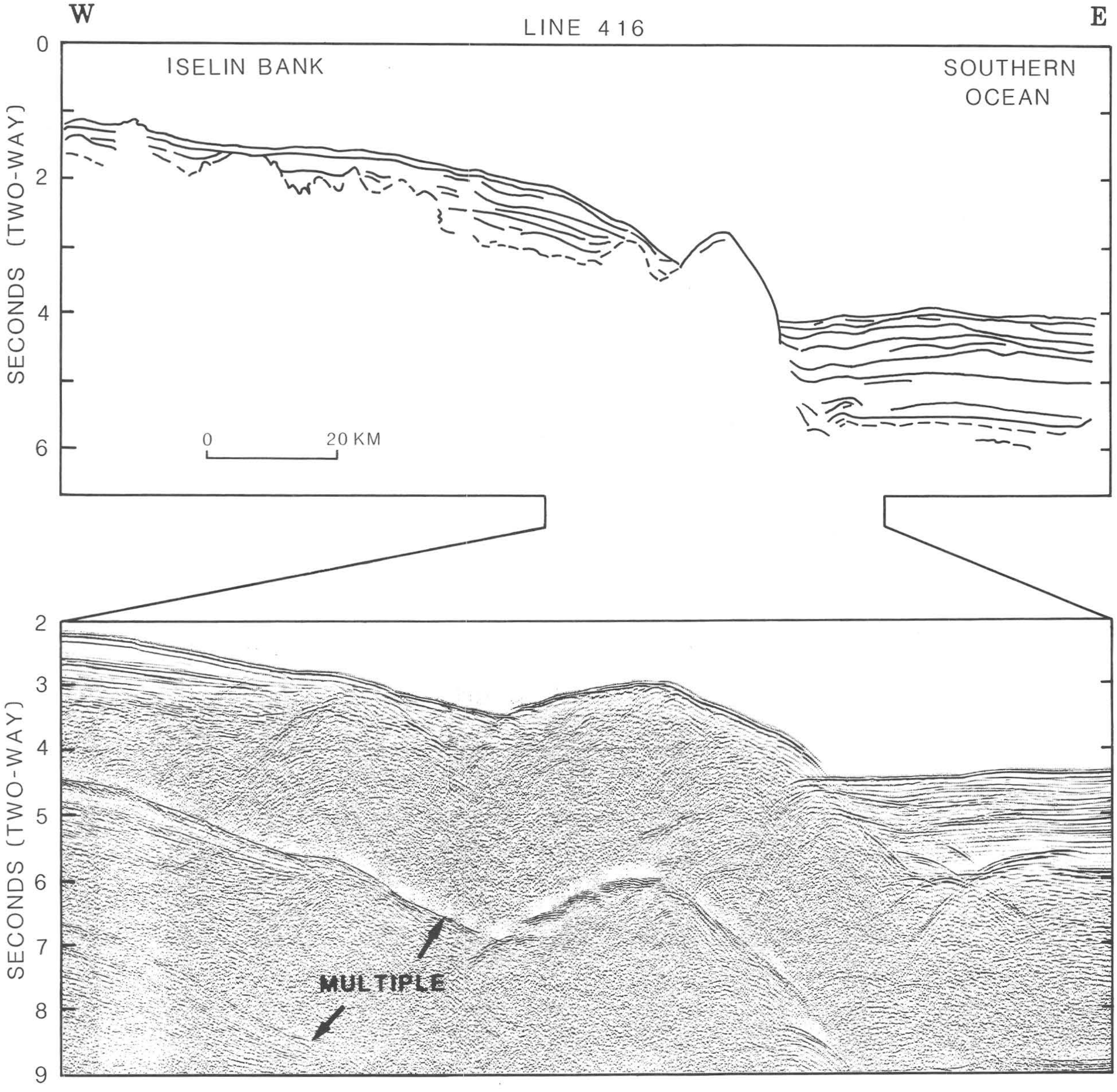

Figure 14. Line drawing and multichannel seismic-reflection data from line 418 across the eastern side of Iselin Bank. The basement ridge at the edge of Iselin Bank was dredged about 150 km south of line 418, and a diverse suite of volcanic, plutonic, and sedimentary rocks was recovered. See figure 12 for location of profile.

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U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

U.S.G.S. EXPEDITION TO ANTARCTICA

LEG I WILKES LAND MARGIN

LEG II ROSS SEA

SP LEE

JAN-FEB 1984

THE LAST FRONTIER