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PRELIMINARY REPORT OF GEOLOGICAL AND GEOPHYSICAL SURVEYS OFF QUEEN MAUD LAND, EAST ANTARCTICA

Takao SAKI*[1], Yasuo TAMURA, Shuichi TOKUHASHI*[2], Toshio KODATO, Ikuro MIZUKOSHI*[3] and Hiroshi AMANO

Technology Research Center, Japan National Oil Corporation, Fukoku Seimei building, 2–2, Uchisaiwai-cho 2-chome, Chiyoda-ku, Tokyo 100

Abstract: The geological and geophysical surveys off Queen Maud Land, East Antarctica were carried out during the 1985–1986 season using R/V HAKUREI-MARU. The survey covered areas of Gunnerus Ridge and the upper continental rise to the abyssal plain off Syowa Station. The basement of Gunnerus Ridge is supposed to be continental crust by magnetic data, gravity data, sonobuoy data and dredged rocks. The oceanic basement is confirmed in seismic and gravity data to have a deepening trend and to form a thickening sedimentary basin toward the foot of the continental slope. The maximum depth and thickness exceed 9.0 s in two-way time from sea level and 3.0 s in two-way time between sea bottom and acoustic basement, respectively on seismic lines. The age difference of the oceanic crust is discussed using seismic character difference of the top of acoustic basement. The sediment section of the basin is divided into three prominent sequences and discussed in terms of seismic stratigraphy. The heat flow data show slightly lower values than a world ocean average value, and this may suggest that the age of the oceanic basement in this area is relatively old.

1. Introduction

Since 1980, the Technology Research Center of Japan National Oil Corporation (TRC, JNOC) has been conducting marine geological and geophysical surveys in offshore areas around Antarctica. In succession to the first three-year phase having surveyed off West Antarctica, the second three-year phase to survey off East Antarctica started in 1983.

The offshore area of Queen Maud Land shown in Fig. 1 was surveyed in the 1985–1986 season as the last investigation area of the second phase after the past surveys in the offshore areas of Wilks Land and Enderby Land. The result of this survey is reported in the present paper.

The results of previous five surveys have already been published by KIMURA (1982), OKUDA *et al.* (1983), SATO *et al.* (1984), TSUMURAYA *et al.* (1985) and MIZUKOSHI *et al.* (1986).

Present address:
*[1] Technical Department, Japan National Oil Corporation.
*[2] Geological Survey of Japan, 1–3, Higashi 1-chome, Yatabe-machi, Tsukuba-gun, Ibaraki 305.
*[3] Japan Petroleum Exploration Co., Ltd., Akasaka Twin Tower, East Wing, 17–22, Akasaka 2-chome, Minato-ku, Tokyo 107.

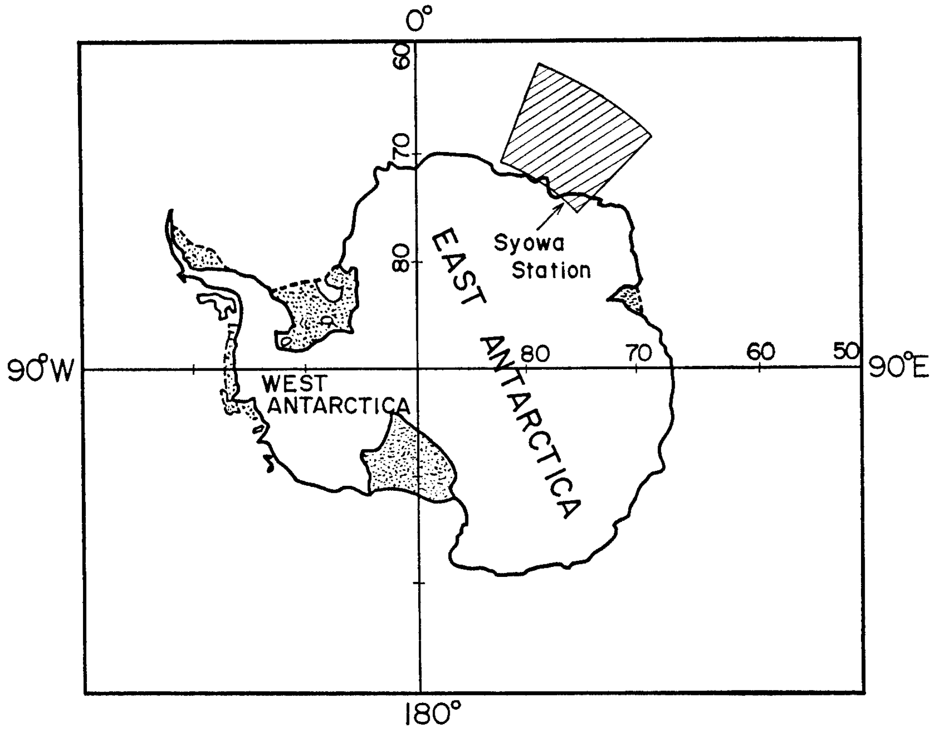

Fig. 1. Location of the survey area.

This survey was carried out as TH-85 cruise (TRC HAKUREI-MARU cruise in 1985) using the Japanese scientific research vessel R/V HAKUREI-MARU, and covered Gunnerus Ridge and the surrounding continental rise to the abyssal plain. This area is typically interpreted as a passive continental margin formed by breakup of Gondwanaland. This implies development of a thick sedimentary basin in the boundary area between the oceanic crust and the continental crust. Gunnerus Ridge seems a submarine peninsular ridge of the Antarctic continental basement.

Although previous studies of this area have been done using paleomagnetic data (*e.g.* BERGH, 1977; LAWVER *et al.*, 1985), geological data (*e.g.* KATZ, 1978) and gravity data (*e.g.* SEGAWA *et al.*, 1984), a multichannel seismic reflection study is newly carried out in this survey.

2. Outline of Survey

The TH-85 cruise conducted seismic reflection survey, "sonobuoy" refraction survey, gravity survey, magnetic survey, terrestrial heat flow measurement and bottom sampling.

Seismic reflection survey was performed with a 6-fold coverage using a short streamer cable with 24 channels and a water gun seismic source system. Heat flow was measured concurrently with piston coring except two stations. The 3.5 kHz subbottom profiler, the 12 kHz precision sounding and gravity survey were operated throughout the survey period.

The statistics of the survey is summarized in Table 1 and the methods and the main instruments of the survey are listed in Table 2. Main specifications of R/V

Table 1. Summary of the TH-85 cruise.

	Total
Survey period	24 days
Seismic reflection survey	2432 km
Sonobuoy refraction survey	10 sites
Magnetic and gravity survey	11750 km
Heat flow measurement	7 sites
Piston coring	6 sites
Smith-McIntyre grab	1 site
Dredging	4 sites

Table 2. Summary of survey instruments.

Survey name	Instrument		Remarks
Multichannel seismic reflection	Source:	H400 water gun (400 cu. in.) × 2	Record length: 5 s
			Sampling rate: 4 ms
	Receiver:	SEC ministreamer cable (24 ch × 25 m)	Shot interval: 50 m
			CDP coverage: 600%
	Recorder:	TI DFSV	
Seismic refraction (Sonobuoy)	Source:	H400 water gun (400 cu. in.) × 2	
	Receiver:	OKI OC-1 Sono-radio-buoy OKI SZ 1038 Sonobuoy receiver	
Gravity	LaCoste & Romberg S-79 sea-air gravimeter		Normal gravity: IGSN 71
Magnetic	Geometrics G-866 proton magnetometer		Reference field: IGRF 1985
Navigation	Magnavox MITI-1 Integrated satellite navigation system		Geodetic datum: WGS-72
Bottom sampling	Piston corer Cylinder dredger Smith-McIntyre grab		
Heat flow	Nichiyu Giken NTS-11 geothermal recorder Showa Denko QTM-D II thermal conductivity meter		

HAKUREI-MARU are as follows: no ice-class, overall length: 86.95 m, gross tonage: 1821.60 t, main engine 3800 ps × 230 rpm × 1 set, and winches: 5 sets.

This survey covers the area between 22°E and 46°E in longitude and between 60°S and near 68.5°S in latitude, where water depth is over 3500 m in the deep sea area and is about 1200 m on Gunnerus Ridge (Fig. 1).

Lines of the geophysical surveys and locations of the bottom samplings are shown in Fig. 2 with a general bathymetric feature. The shotpoint map with sonobuoy locations is shown in Fig. 6. Line 2-SMG and 2-1-SMG run successively along the 40°E meridian and traverse the abyssal plain to the upper continental rise. Line 3-SMG runs along the 66°S parallel and intersects 2-1-SMG. Lines 3-1-SMG and 4-SMG traverse Gunnerus Ridge from the east to the west and from the south to

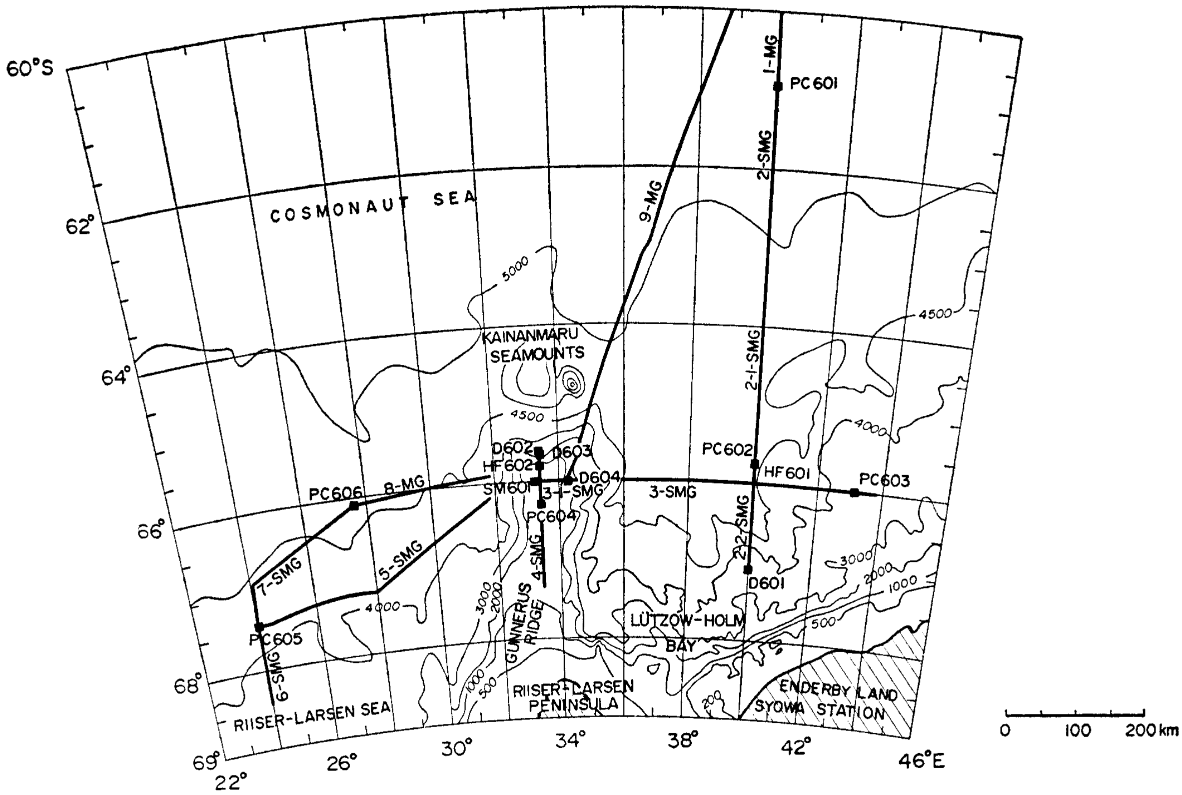

Fig. 2. Lines of geophysical survey and sampling stations off Queen Maud Land SMG: seismic, magnetic, gravity; MG: magnetic, gravity; PC: piston core; D: dredge; SM: Smith-McIntyre grab; HF: heat flow.

the north, respectively. Line 5-SMG crosses this ridge from NE to SW and changes the direction to WSW at 28°E in longitude. Line 6-SMG runs along the 24°E meridian, and Line 7-SMG starts from the end of Line 6-SMG with an NE direction.

3. Gravity and Magnetic Surveys

Free air gravity anomaly and total magnetic intensity anomaly in the surveyed area are respectively shown in Figs. 3 and 4. Regarding Lines 2-1, 2-2, 3-1, 4-SMG and a part of Line 5-SMG, these anomaly profiles are integratedly displayed on seismic sections as shown in Figs. 8 to 12. Data seem interpretively valid except for the total magnetic intensity anomaly profile of Line 5-SMG which is noisy data.

On profiles along the 40°E meridian in the offshore of Lützow-Holm Bay, the free air gravity shows a regional decreasing trend which shows the higher values of 10–15 mgal in the northern part of the block and lessens southwardly to zero near the site of 65°S parallel, then further lowers to negative anomaly values toward the Antarctic Continent. This remarkable gravity trend is well correlated with the deepening trend of the acoustic basement toward the continent from the sea side. This correlation agrees with the widely confirmed relation between the free-air gravity anomaly trend and the depth of acoustic basement in other passive continental margins.

A remarkable positive and negative set of free-air gravity anomaly on the profile

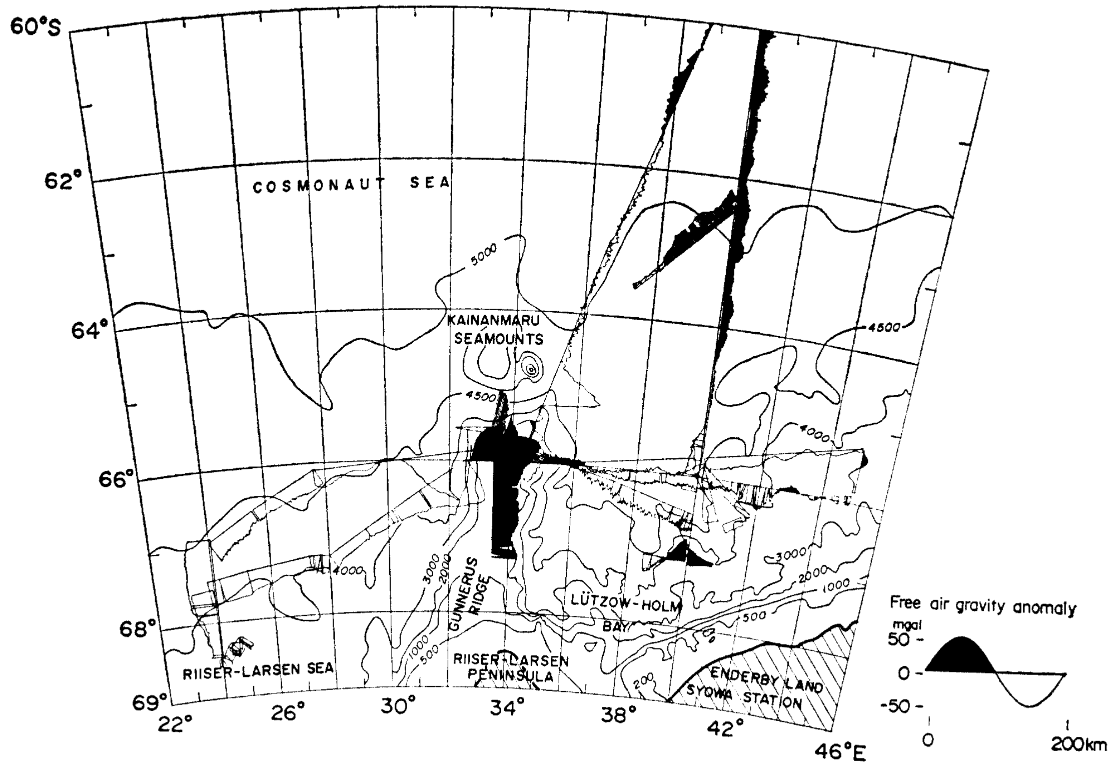

Fig. 3. Free air gravity anomaly profiles along the ship's tracks. Reference field: IGSN 71.

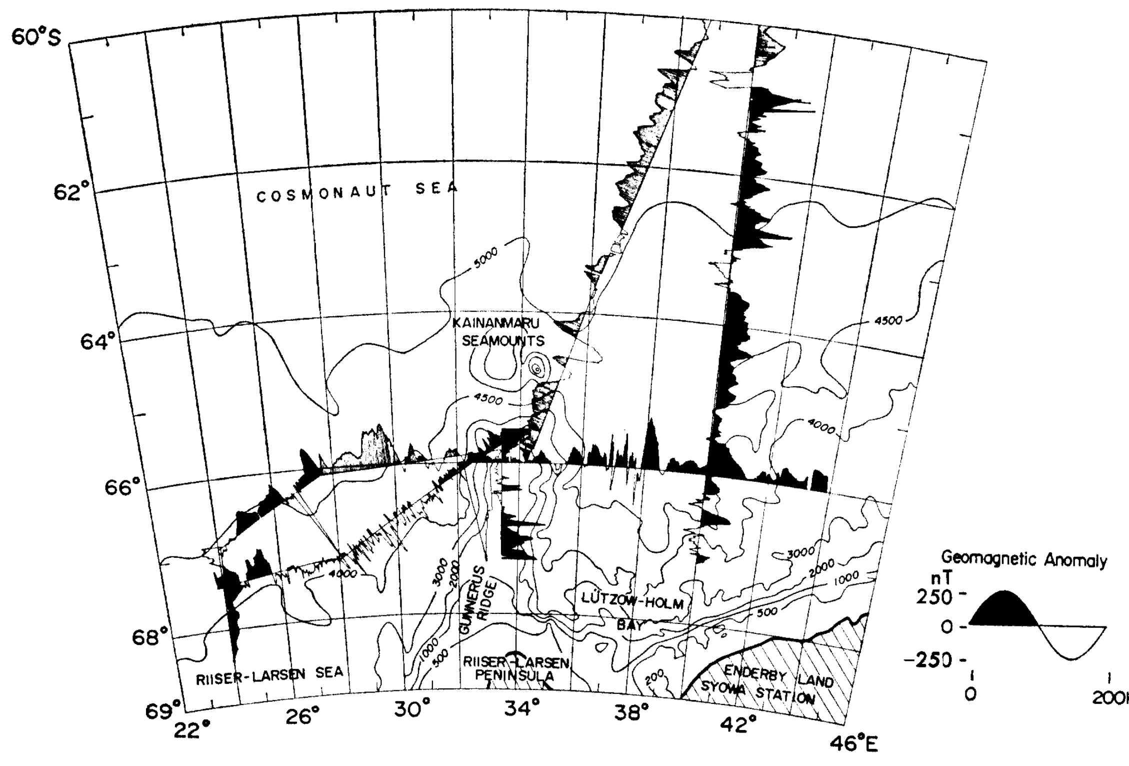

Fig. 4. Total magnetic intensity anomaly profiles along the ship's tracks. Reference field: IGRF 1985.

across Gunnerus Ridge reflects clearly the topographic high of the ridge and gravity edge effects due to rather abrupt changes of the basement depth and materials (Figs. 10 and 12).

In the area of the central continental rise with water depth of 4000–4500 m, extensive negative free-air gravity anomalies with smoothed variation are observed on profiles in both Riiser-Larsen Sea and the Lützow-Holm Bay blocks, which possibly corresponds to such a deep and smoothed basement as observed in seismic section of Lines 3, 5 and 6-SMG.

The total magnetic intensity anomaly in the surveyed area shows a relatively strong amplitude with about 100–300 nT possibly corresponding to existence of underlying oceanic basement, except for a relatively calm and small anomaly across Gunnerus Ridge which is scarcely correlated to the basement topography possibly due to difference of basement materials between the ridge and its surroundings.

4. Bottom Samplings

Sampling by a piston corer was carried out at 6 stations. Sampling by a dredger was carried out at 4 stations on relatively steep slopes. Although a Smith-McIntyre grab was tried at 1 station, only sea-bottom photographs (7 sheets) were taken.

Table 3. Summary of bottom samples of sediments and rocks.

Station	Lat. (S)	Long. (E)	Depth (m)	Description	Fossils	Recovery (m/m)
PC601	60°55.8′	40°00.6′	5281	silic. clay	diatom abundant	7.80/8
PC602	65 34 9	39 58 8	4674	silic. ooze (upper) alter. silc. clay/ pelag. clay (lower)	diatom common	6.43/8
PC603	66 00 1	43 08 0	3157	alter. pelag. clay/ silic. clay/ silic. ooze	diatom common	7.32/8
PC604	66 16 2	33 25 5	1309	calc. ooze	foraminifera abund.	2.50/8
PC605	67 24 9	24 02 4	4418	alter. silic. clay/ pelag. clay	diatom common	6.69/8
PC606	66 05 9	27 33 1	4791	silic. clay/ silic. ooze	diatom abundant	7.73/8
D601	67 05 2	39 56 1	3535	gneiss, granite, mylonite, sandstone,		
	67 05 9	39 56 5	3474	shale		
D602	65 35 7	33 22 1	3222	gneiss, dolerite, amphibolite (covered		
	65 36 4	33 21 1	2980	by manganese layer)		
D603	65 38 4	33 24 9	2363	gneiss (covered by manganese layer) pegmatite-granitic rock, gneiss (possible		
	65 39 2	33 25 4	2009	basement rocks, covered by manganese layer)		
D604	66 00 6	34 15 9	2917	gneiss, amphibolite, ultramylonite,		
	66 00 7	34 11 7	2654	sandstone		
SM601	66 00 1	33 12 9	1332	no rock samples, 7 sheets of sea-bottom		
	66 00 5	33 12 8	1338	photographs		

PC: piston core, D: dredge, SM: Smith-McIntyre grab.

The sampling localities are shown in Fig. 2 and partly in Fig. 11 (for PC 604, D 602, D 603). The results of these sampling works are summarized in Table 3.

The unconsolidated sediments except for PC 604 are mostly composed of siliceous ooze and siliceous clay. The PC 604 core from Gunnerus Ridge (water depth: 1309 m) consists of calcareous ooze, dominantly comprising planktonic foraminifera, *Globigerina pachyderma*. In terms of the diatom assemblage zones, the cored samples except for PC 601 and PC 603 comprise 3 assemblage zones. They are the *Nitzschia kerguelensis* Zone (0–0.195 Ma), the *Hemidiscus karstenii* Zone (0.195–0.35 Ma) and the *Rouxia isopolica* Zone (0.35–0.66 Ma) in descending order, whereas those of PC 601 and PC 603 represent only the *H. karstenii* Zone and the *N. kerguelensis* Zone, respectively. All of these diatomaceous zonations are based on AKIBA (1982).

The dredged rocks from D 601 and D 604 are possibly ice rafting rocks. They are round to subround pebbles and some of them have glacial striae on their surfaces. All dredged rocks from D 602 and part of dredged rocks from D 603, which were taken on the northern slope of Gunnerus Ridge, are also possibly allochthonous rocks. They are completely covered by a manganese layer, less than 5 mm in thickness. However, some rocks of D 603 are possibly autochthonous rocks. They are covered by a relatively thick manganese layer, 20 to 30 mm in thickness, and each sample has a fresh rock surface with sharp edge. This suggests that they were scraped off from the submarine outcrops of autochthonous basement rocks.

The possible allochthonous rocks from the sites are mostly composed of gneiss of upper amphibolite to granulite facies (HIROI and SHIRAISHI, 1986). They commonly occur on the land of Antarctica behind the surveyed sea area. The possible autochthonous rocks are pegmatite or coarse-grained granitic rocks, and gneiss. The manganese layer consists of vernadite (δ-MnO_2) which precipitated slowly from sea water. The chemical composition of the layer is characterized by Fe, Mg concentrations from 10 to 20% each and Cu, Ni values of less than 0.2% each.

5. Terrestrial Heat Flow Measurement

Terrestrial heat flow measurement was carried out at 7 stations (Fig. 5). The heat flow values were calculated from multiplication of the geothermal gradient in the bottom sediment and the thermal conductivity of the bottom sediments.

Geothermal gradient was measured by a core-installed equipment (sensor length 3.6 m with 6 sensors) at 5 stations, and by a violin bow type equipment (sensor length 2.4 m with 4 sensors) at other 2 stations and geothermal gradient data were recorded by a digital recorder. Thermal conductivity for the bottom sampled sediment was measured by a transit heat transfer type thermal conductivity meter.

The results of heat flow measurement are shown in Fig. 5. In the abyssal plain 53 mW/m^2, Lützow-Holm Bay and Riiser-Larsen Sea region 43 to 60 mW/m^2 and on Gunnerus Ridge 57 mW/m^2 heat flow were obtained.

Those values were slightly lower than a world ocean average heat flow value and this means the floor of the ocean of the survey area is relatively old.

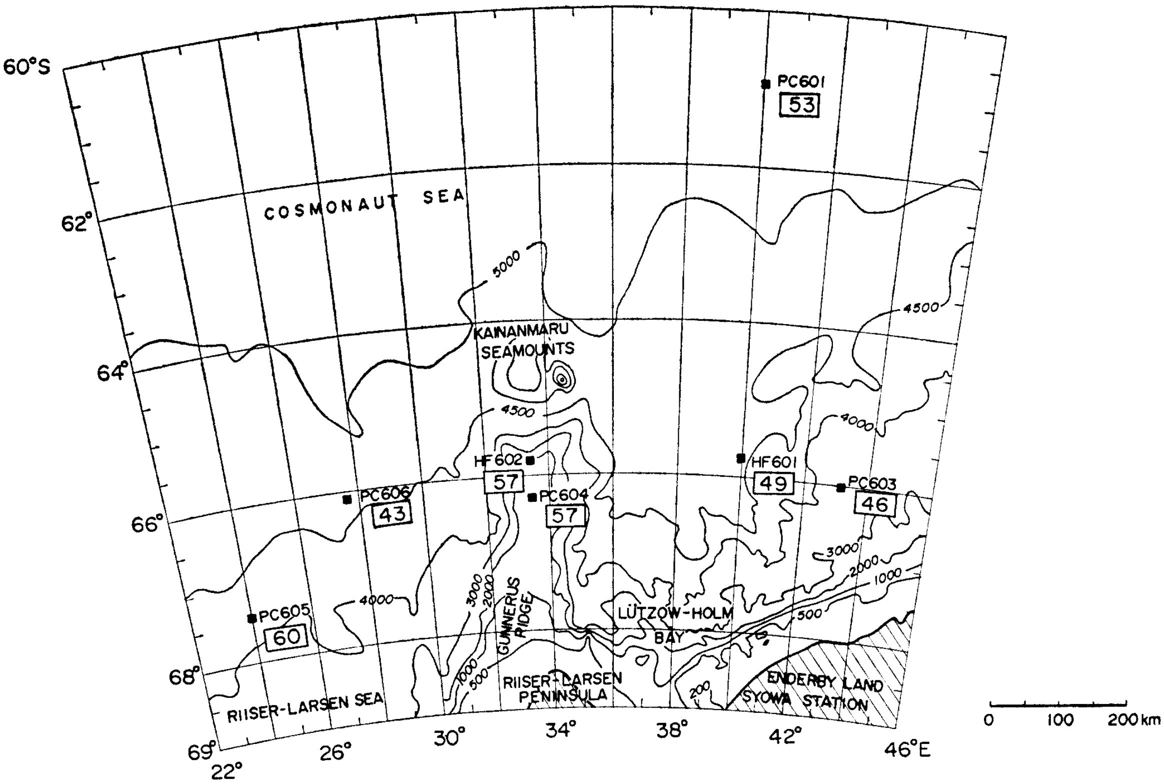

Fig. 5. Terrestrial heat flow distribution off Queen Maud Land (unit: mW/m²).

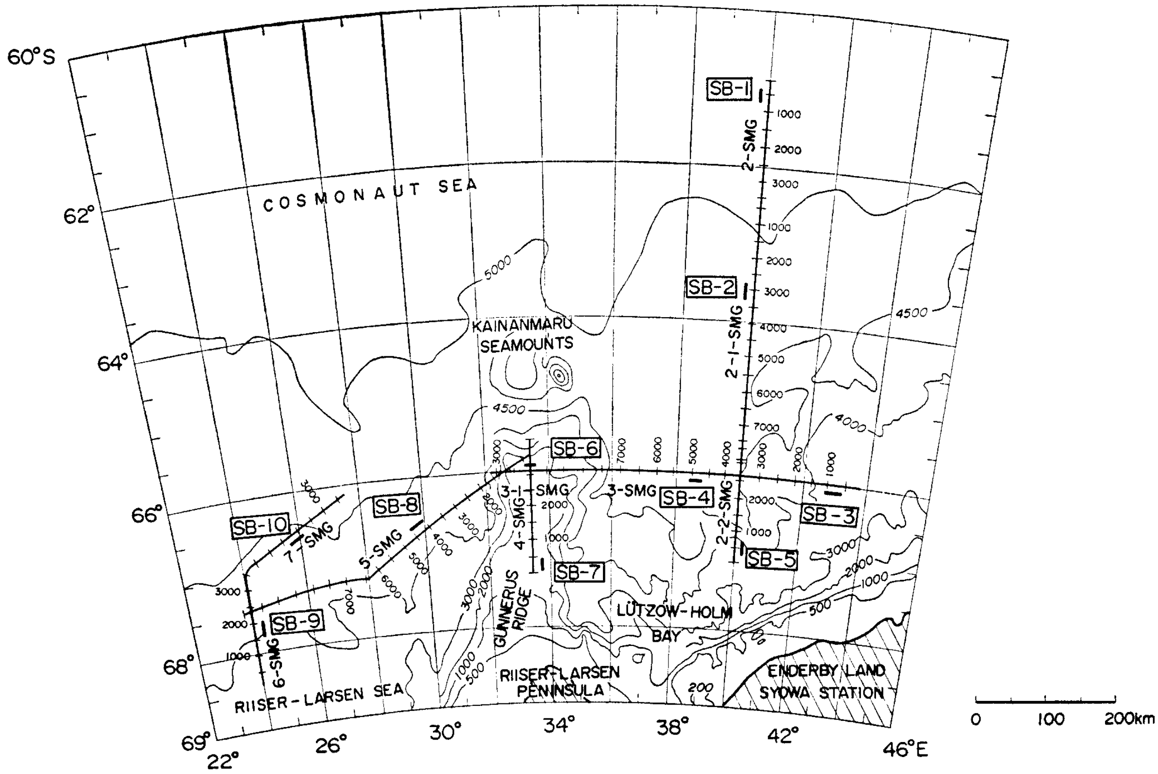

Fig. 6. Lines of seismic reflection survey and sites of sonobuoy seismic survey off Queen Maud Land. SB: Sonobuoy.

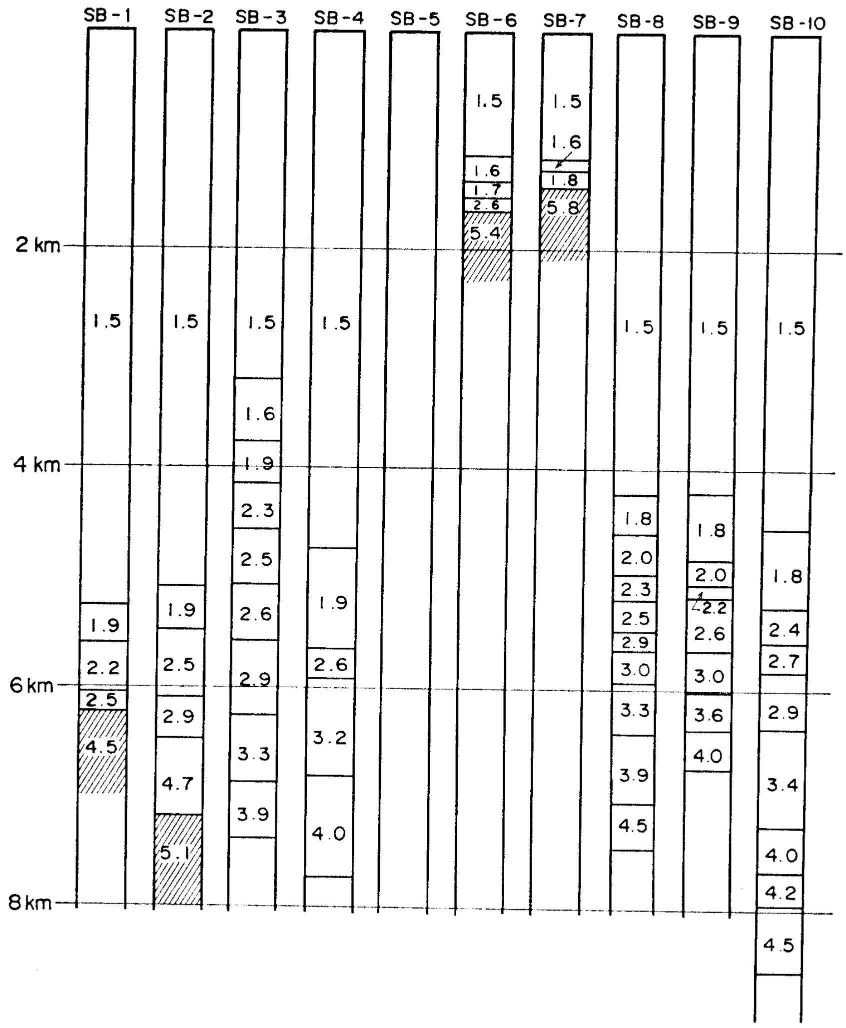

Fig. 7. Velocity-depth profiles derived from sonobuoy survey. The acoustic basement is shown by hatching in each profile.

6. Sonobuoy Velocity Survey

Sonobuoy refraction and wide angle reflection surveys were carried out at 10 stations on lines of seismic reflection survey as shown in Fig. 6. All the data except those of SB-5 which are poor of quality were analyzed by means of the conventional refraction method and the "velocity scan" method. The results are profiled in Fig. 7.

The velocity of acoustic basement obtained at 2 sites (SB-6, 7) in Gunnerus Ridge area is calculated to be 5.4 and 5.8 km/s respectively, and these values seem to be comparable to the average velocity (6.0 km/s) of the Antarctic continental basement (Ito *et al.*, 1984; Ikami *et al.*, 1985). The velocities of the deepest layers observed at some sites in the offshore areas of Lützow-Holm Bay and Riiser-Larsen Sea are calculated to be 4.5 km/s (at SB-1) and 5.1 km/s (at SB-2) which suggest those layers as "layer 2" in oceanic crust (4.5–5.5 km/s: Fox *et al.*, 1973).

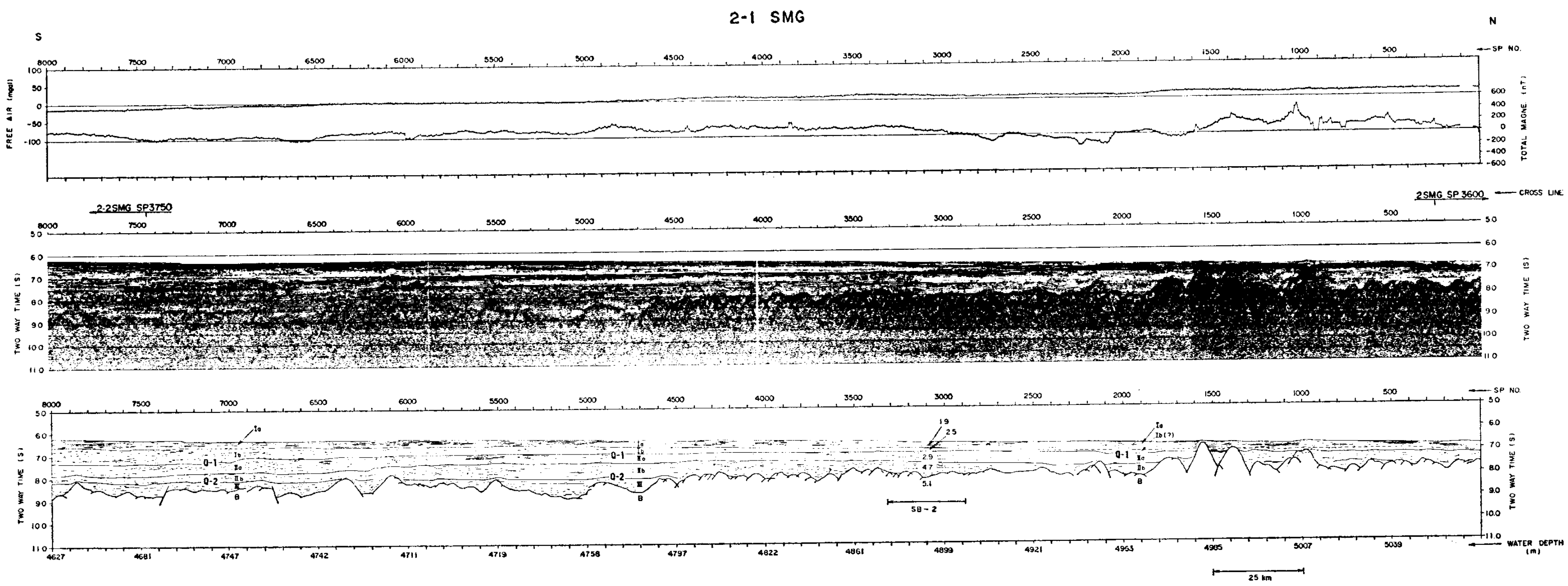

Fig. 8. Conventionally stacked and interpreted section of Line 2-1-SMG with the profiles of the free-air gravity anomaly and total magnetic anomaly.

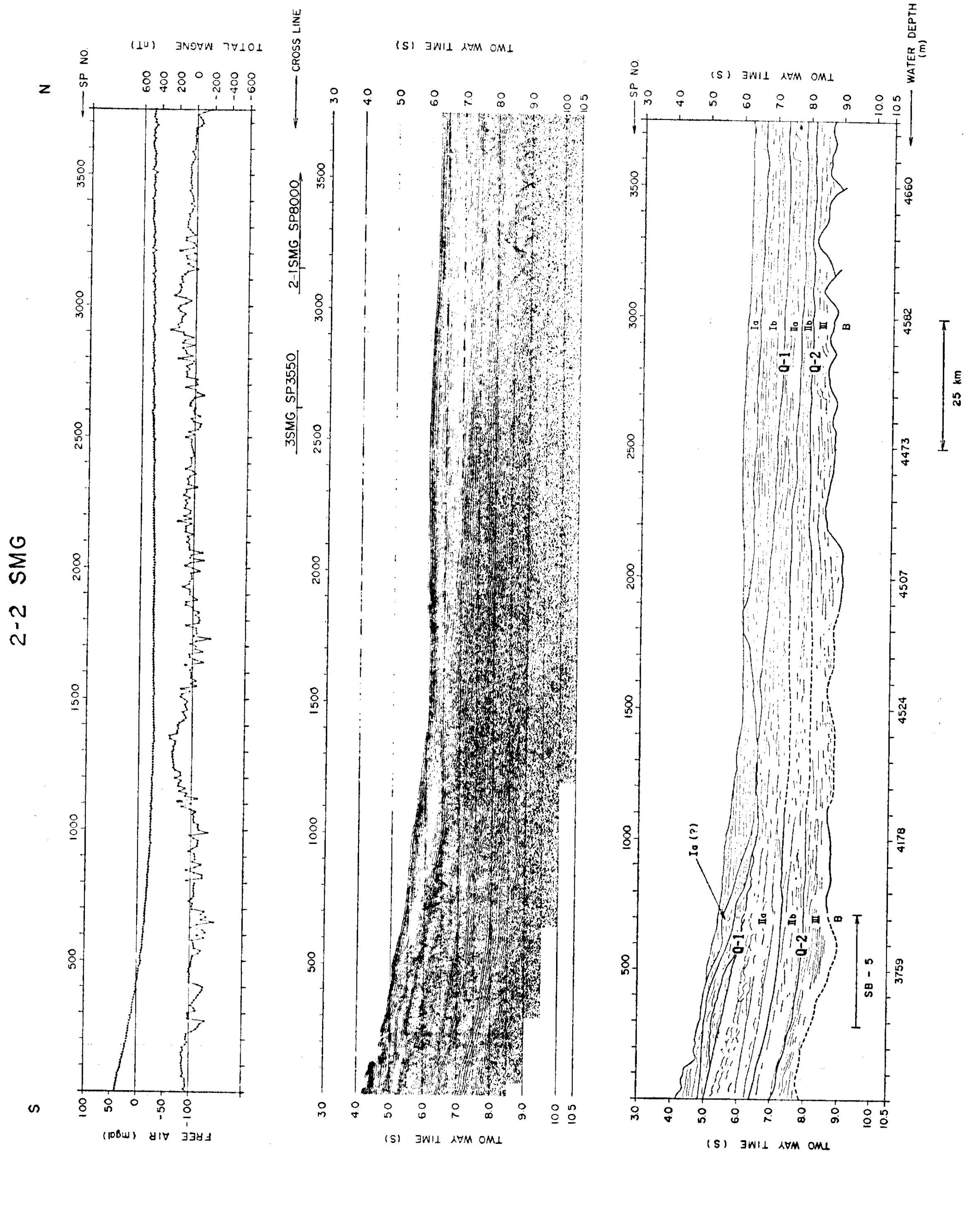

Fig. 9. Conventionally stacked and interpreted section of Line 2-2-SMG with the profiles of the free-air gravity anomaly and total magnetic anomaly.

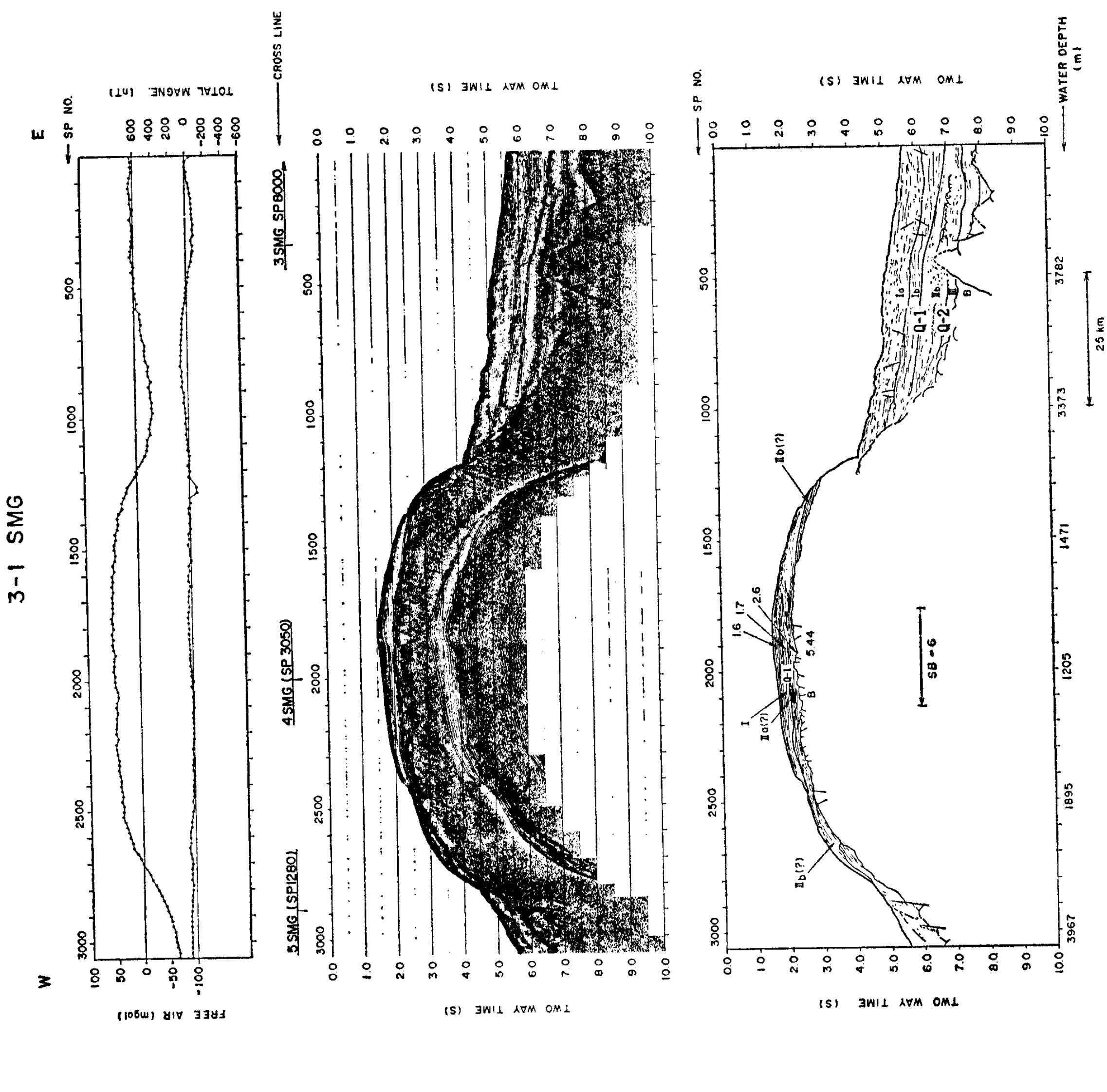

Fig. 10. *Conventionally stacked and interpreted section of Line 3-1-SMG with the profiles of the free-air gravity anomaly and total magnetic anomaly.*

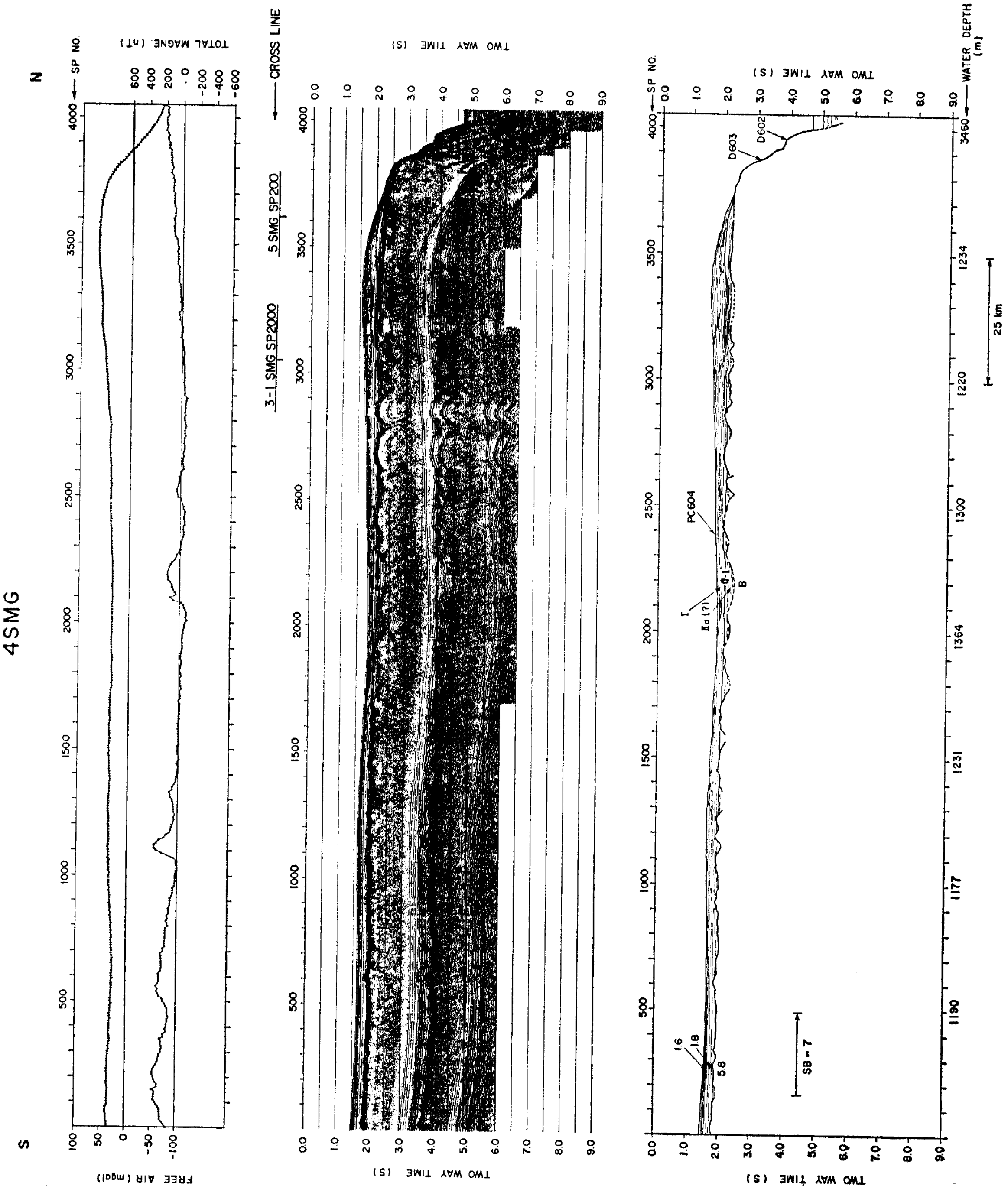

Fig. 11. Conventionally stacked and interpreted section of Line 4-SMG with the profiles of the free-air gravity anomaly and total magnetic anomaly.

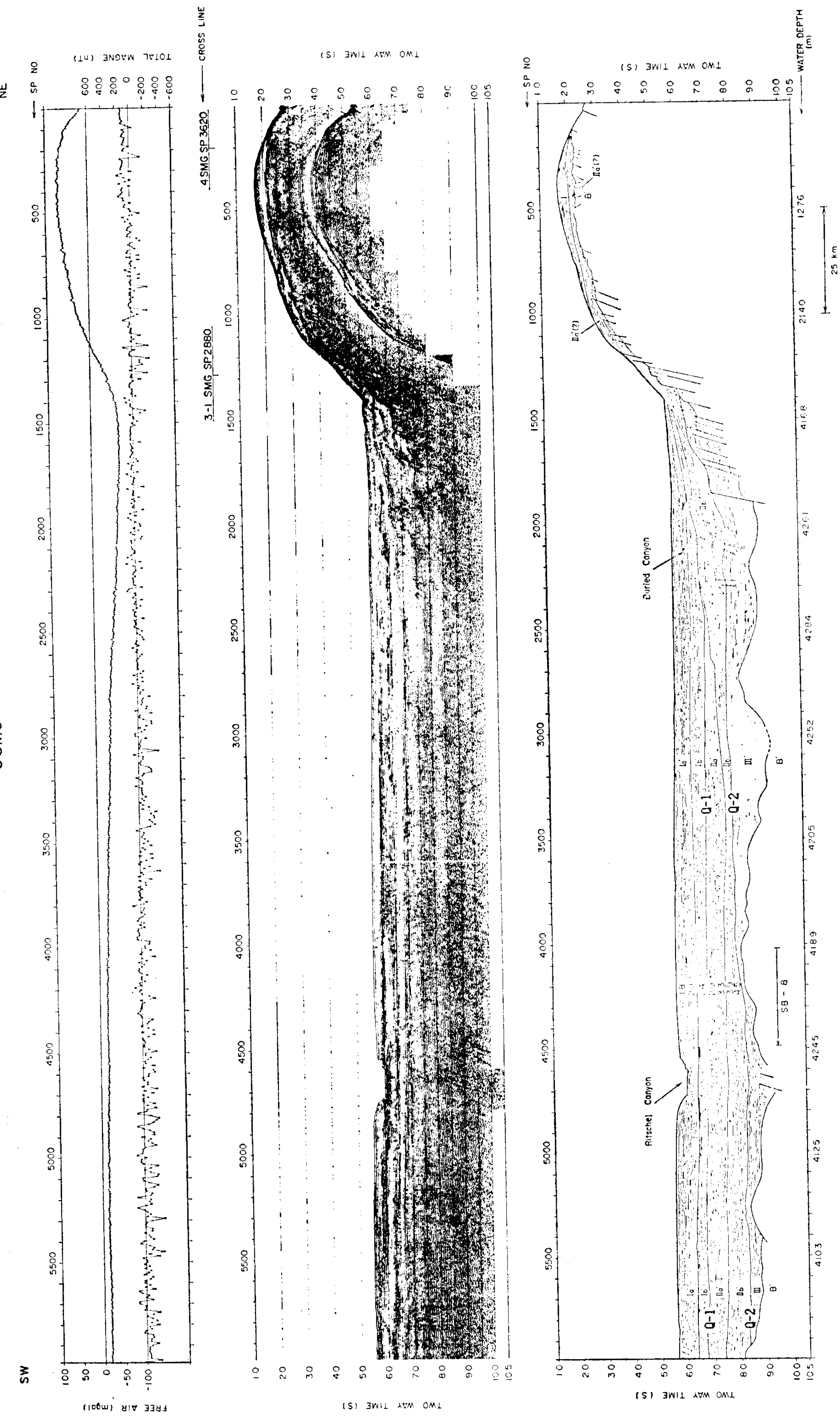

Fig. 12. *Conventionally stacked and interpreted section of Line 5-SMG with the profiles of the free-air gravity anomaly and total magnetic anomaly.*

7. Seismic Interpretation and General Feature of the Sedimentary Basin

The top of acoustic basement and two key horizons are defined as remarkable seismic boundaries in the survey area. These can extensively be traced in both areas of Lützow-Holm Bay and Riiser-Larsen Sea, and are approximately identified over the Ridge in terms of seismic reflection characteristics. The age of horizons is not identified due to unavailability of stratigraphic well data in or near the survey area.

The top of acoustic basement (Horizon B in this paper) is traced along the discordant boundary against upper sedimentary seismic facies, which is mainly indicated by geomorphic feature, piercement and envelope of diffractions.

The shallower key horizon in sediments named "Horizon Q-1" herein is traced along the base-discordant and its correlatively concordant boundaries showing rather strong and continuous reflection boundaries. Remarkable onlap is observed near the foot of Gunnerus Ridge (Fig. 10).

The deeper key horizon in sediments named "Horizon Q-2" is traced along apparent concordant boundaries as a whole, where seismic facies changes in a rather abrupt manner from "transparency" to "lamination" at many sites. This horizon terminates with "abut" to the acoustic basement shallowing toward the north as shown in Lines 2-1 and 2-2-SMG.

Based on these two key horizons, Units I, II, III and I′, II′, III′ are defined in areas of Lützow-Holm Bay and Riiser-Larsen Sea, respectively. Units I, II and I′, II′ are subdivided into Ia, Ib, IIa, IIb and Ia′, Ib′, IIa′, IIb′, respectively. Stratigraphic interpretation along the seismic lines is shown as in Figs. 8–12.

Acoustic basement in the survey areas is considered to be basically composed of continental basement in Gunnerus Ridge and oceanic basement in the deep sea area. The oceanic basement has a deeping trend with maximum depth over 9 s and forms a thickening sedimentary basin toward the foot of the continental slope with maximum thickness over 3.0 s, which are observed in the schematic maps of Figs. 13 and 14. Seismic character of Horizon B is observed to change from the abyssal plain to the upper continental rise in the manner of a stepwise succession as (1) high reliefs with strong diffractions, (2) gentle surface with weak diffractions and (3) discontinuous or weak reflection lineups. Such observation on the three types (1)–(3) is supposed to correspond to a stepwise difference of the age of the oceanic basement (Figs. 8 and 9).

The sequence named Unit III between Horizons B and Q-2 is observed above the older basement with seismic characteristics of type (3) mentioned above, where local basement reliefs are burried by filling up with sediments of irregular seismic facies. Laminated seismic facies with partial topset against Horizon Q-2 are observed near Antarctica and the west foot of Gunnerus Ridge, and gradually change to chaotic or reflection-free facies toward the distance. This lamination may suggest a shallow depositional environment near the continental basement. However, the "Weddell Sea unconformity" and the underlaid seaward dipping reflectors which deposited at an early stage of the breakup of Gondwanaland (Hinz and Krause, 1982) cannot be clearly recognized in this survey.

Unit II (II′) between Horizons Q-1 and Q-2 seems to be composed of laminated seismic facies except for the northern part of the area (Lines 2, 2-1-SMG) and areas

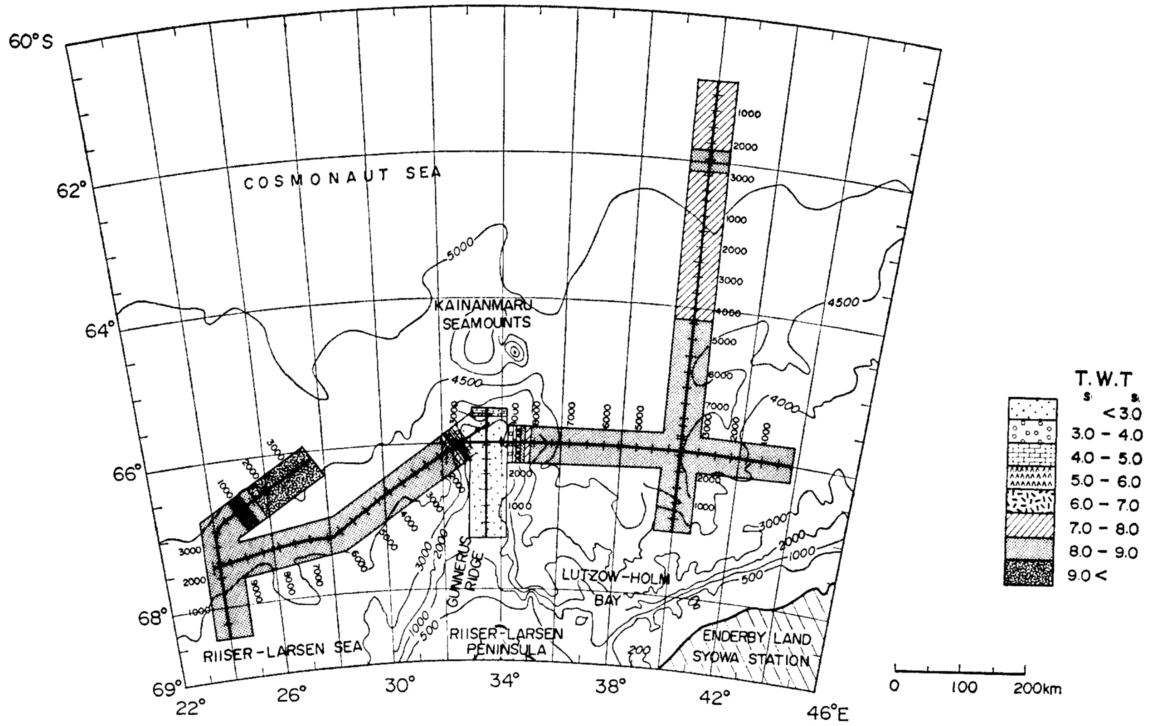

Fig. 13. Schematic acoustic basement map of two-way travel time(s) off Queen Maud Land.

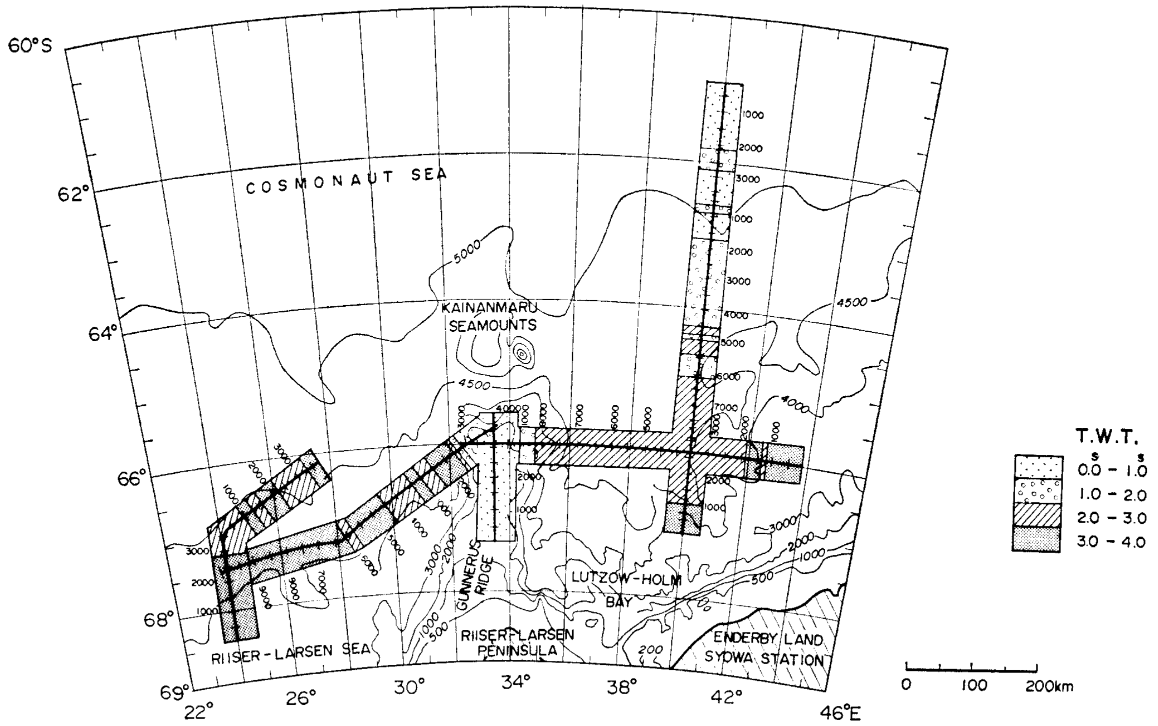

Fig. 14. Schematic isochron map of total sediments in seconds off Queen Maud Land.

near the Continent and the Ridge. In the former area, the lower part of this Unit (IIb, II'b) directly overlies the basement of types (1) and (2). Near the Ridge and the Continent, channel-like seismic configuration and irregular discontinuous reflection segments are remarkably observed.

Unit I (I′) between Horizon Q-1 and the sea bottom is extensively composed of laminated seismic facies. However, in contrast to the parallel-laminated seismic facies in the abyssal plain to the lower continental rise, active channels are developed in the central continental rise of Riiser-Larsen Sea block. In the upper continental rise, large scale channels having worked through the depositional period of Unit I and slumping configurations are clearly observed in Lützow-Holm Bay. On Gunnerus Ridge and its foot slopes, migrated wave patterns and arch-like irregular patterns which are possibly due to rather strong current working, are observed (Fig. 10).

8. Summary

Preliminary results of the TH-85 survey off Queen Maud Land, East Antarctica, which were carried out in the 1985–86 season by using R/V HAKUREI-MARU, are summarized as follows:

(1) The basement of Gunnerus Ridge is inferred to be continental crust by results of the dredging of the submarine exposed rocks, velocity estimates from sonobuoy data and nature of gravity and magnetic anomalies.

(2) The oceanic basement has a deepening trend with maximum depth over 9.0 s in two-way time from sea level and forms a thickening sedimentary basin toward the foot of the continental slope of Antarctica with maximum thickness over 3.0 s in two-way time below sea bottom. The deepening trend is correlatively observed in seismic sections and free-air gravity anomaly profiles.

(3) The sedimentary unit of the basin is divided into three major sequences, based on two key horizons (Horizons Q-1 and Q-2). Unit III overlies the older basement of type (3) with irregular seismic facies except near the Continent and the west foot of the Ridge where laminated facies is observed. Unit II (II′) is generally laminated seismic facies except channel-like facies near the Continent and the Ridge, and directly overlies the basement of types (1) and (2). Unit I (I′) is composed of laminated facies in the abyssal plain to the lower continental rise and higher energy depositional facies in the central to upper continental rise.

(4) The oceanic crust can visually be classified into three types in terms of seismic characteristics. It is suggested by chronostratigraphic consideration of overlaid sediments that such type difference may correspond to the age difference of basement.

(5) The average heat flow value of 52 mW/m^2 is recorded in the survey area. This value is slightly lower than a world ocean average value, and this may suggest that the age of the oceanic basement in this area is relatively old.

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