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PRELIMINARY REPORT OF THE TH97 GEOLOGICAL AND GEOPHYSICAL SURVEY RESULTS, NORTH OF THE ANTARCTIC PENINSULA

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Abstract: Geophysical and geological surveys of the Japan National Oil Corporation (JNOC) TH97 cruise on the R/V Hakurei-maru, in the Pacific margin of the northern part of the Antarctic Peninsula, were carried out in the 1997–98 austral summer season. The cruise was devoted to the western, northern and eastern continental margins of the northern part of the Antarctic Peninsula. The seismic data are interpreted together with the data which were collected in this area during JNOC TH80, 88, 96 and PetroBras and British Antarctic Survey cruises.

The area north of the Antarctic Peninsula is interpreted as the triple junction area among the Antarctic-Scotia-(former) Phoenix plates. The seismic data on the continental shelf of the northern part of the Antarctic Peninsula show distributed highly deformed sedimentary basins and volcanic features. Kr-Ar dating of fresh andesite recovered from a minor ridge south of Elephant Island gave a 7 to 8 Ma, Late Miocene age. It suggests the Late Miocene tectonic event which outlined the tectonic framework in the area. The deformation trend is interpreted to be controlled by the regional trend of sinistral transtensional movement between the Antarctic and Scotia plates.

key words: Pacific Margin of the Antarctic Peninsula, Bransfield Strait, marine geological and geophysical surveys, sedimentary sequences

1. Introduction

The Technology Research Center, Japan National Oil Corporation (JNOC) has been conducting marine geophysical and geological surveys of the Antarctic continental margins with the R/V HAKUREI-MARU since 1980. Some of the results of previous cruises have already been published (KIMURA, 1982; OKUDA *et al.*, 1983; SATO *et al.*, 1984; TSUMURAYA *et al.*, 1985; MIZUKOSHI *et al.*, 1986; SAKI *et al.*, 1987; YAMAGUCHI *et al.*, 1988; SHIMIZU *et al.*, 1989; ISHIHARA *et al.*, 1996; YUASA *et al.*, 1995; TANAHASHI *et al.*, 1994, 1997, 1998).

This paper reports the preliminary survey results for the northern margin of the Antarctic Peninsula, which was surveyed during the TH97 cruise.

The TH97 survey cruise was originally planned to survey the areas around the South Orkney Islands. The survey cruise started from Cape Town, South Africa on December 29, 1997. When the Hakurei-maru approached Bruise Rise at 60°S, 40°W, we found that the thick pack ice prevented the ship from surveying the South Orkney Islands area. The main target was shifted to a survey of the tectonic framework of the northern margin of the Antarctic Peninsula, which we surveyed preliminarily during the TH96 cruise. The geophysical survey lines were planned to complement the previous surveys of JNOC (TH87, 88 and TH96 cruises); PetroBras (GAMBOA and MALDONADO, 1990); British Antarctic Survey (LARTER and BARKER, 1991; KING *et al.*, 1997); Russian VNIIOKEANOLOGIYA (KAVOUN and VINNIKOVSKAYA, 1994); Spanish GEBRA (CANALS *et al.*, 1994; GRACIA *et al.*, 1996) and HESANT (ALDAYA and MALDONADO, 1996); and the Italian OGS (COREN *et al.*, 1997) cruises.

The tectonic setting of the TH97 survey area is shown in Fig. 1. A topographic map of the area is shown in Fig. 2.

The TH97 survey area lies in the junction area between the northern margin of the Antarctic Peninsula and the Scotia Sea. There are magnetic lineations, which were interpreted to be formed during the Oligocene, in the western Scotia Sea (BRITISH ANTARCTIC SURVEY, 1985). The northern margins of the Antarctic Peninsula and South Orkney micro-continent are believed to have been the forearc terrain of the Andean Arc during the Mesozoic (DALZIEL and ELLIOT, 1973), and were separated from the Andean Arc and each other with the spreading of the Scotia and Powell Basins during the Oligocene to Miocene, respectively (BARKER *et al.*, 1991; COREN *et al.*, 1997). There are several islands, Elephant, Gibbs, Aspland and O'Brien, on the continental shelf north of the Antarctic Peninsula. They are mainly composed of metamorphic sedimentary rocks which were interpreted to be formed under forearc conditions in the Mesozoic (BRITISH

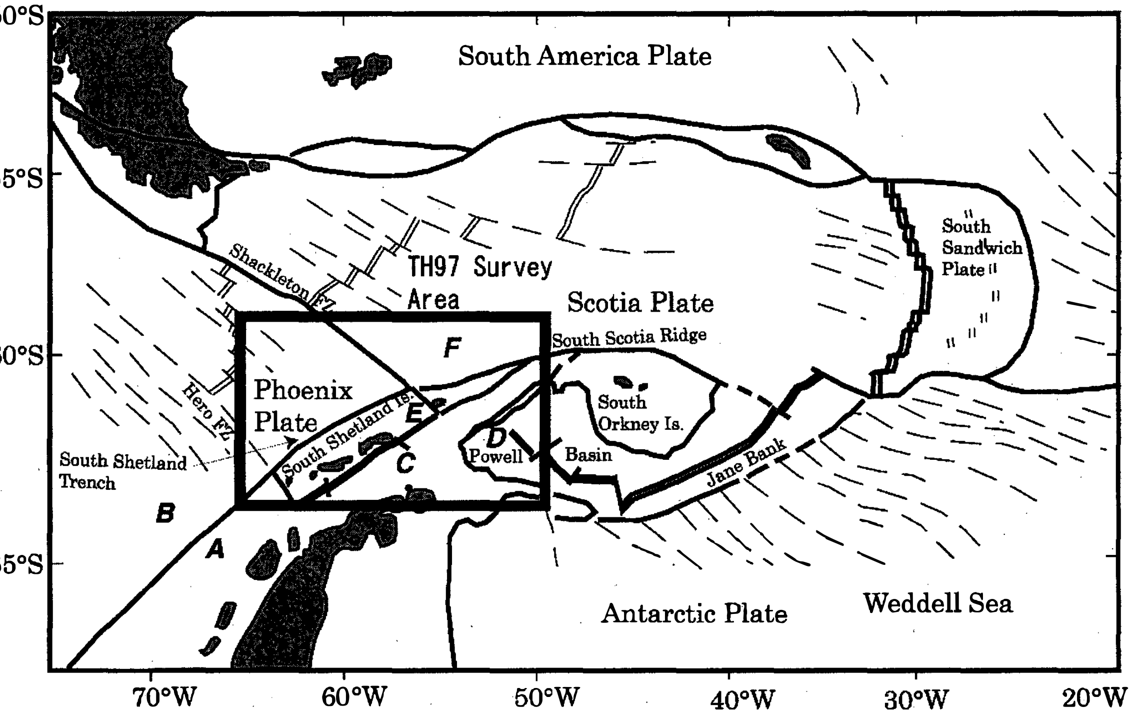

Fig. 1. Tectonic setting of the TH97 survey area of the northern margin of the Antarctic Peninsula. Modified from GALINDO-ZALDIVAR *et al. (1994). "FZ" means Fracture Zone. "C" to "F" show the area codes for seismic stratigraphical description in this paper according to* TANAHASHI *(1998).*

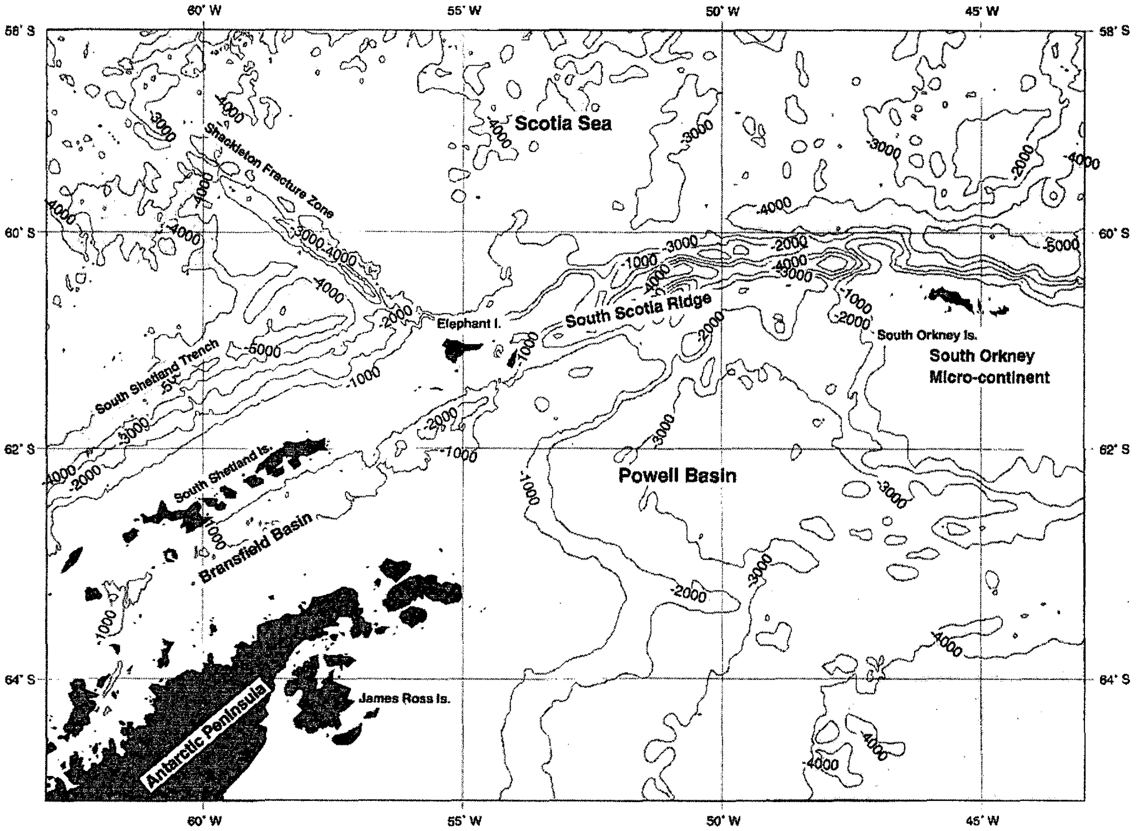

Fig. 2a. Topographic map in the northern margin of the Antarctic Peninsula, drawn by GMT (WESSEL and SMITH, 1991) using estimated topographic data file from the satellite altimetry by SANDWEL and SMITH (1992) with 1000 m contour interval.

ANTARCTIC SURVEY, 1985). Small exposure of Miocene mudstone in Seal Rocks off the northern coast of Elephant Island is the only reported sedimentary sequence in these islands (DALZIEL, 1989).

There was a triple junction among Antarctica, Scotia, and the former Phoenix plates until the cessation of spreading in the Aluk Ridge between the former Phoenix and Antarctic plates at about 4 Ma (LAWVER *et al.*, 1996). The boundaries of these plates are the South Scotia Ridge, the Shackleton Fracture Zone, and the South Shetland Island Arc system. The South Scotia Ridge is developed between the Scotia Sea and the Powell Basin on the Antarctic plate. It consists of northern and southern ridges and a deep valley between these ridges. The Shackleton Fracture Zone is interpreted as the structure between the Scotia Sea and the former Phoenix plate, which is part of the Antarctic plate at present (LAWVER *et al.*, 1996). The South Shetland Island Arc system is composed of the South Shetland Trench, the South Shetland Islands and the Bransfield Basin, between the former Phoenix plate and the Antarctic Peninsula on the Antarctic plate. The triple junction in this area has been transformed into a single plate boundary between the Scotia and Antarctic plates since 4 Ma. The extensional features in Bransfield Strait can be interpreted by a trench roll-back model (LAWVER *et al.*, 1996). The cooling slab under the trench sinks and pulls the fore-arc lithosphere. The extensional features in the South Scotia Ridge are interpreted through the trans-tensional tectonics caused by re-organiza-

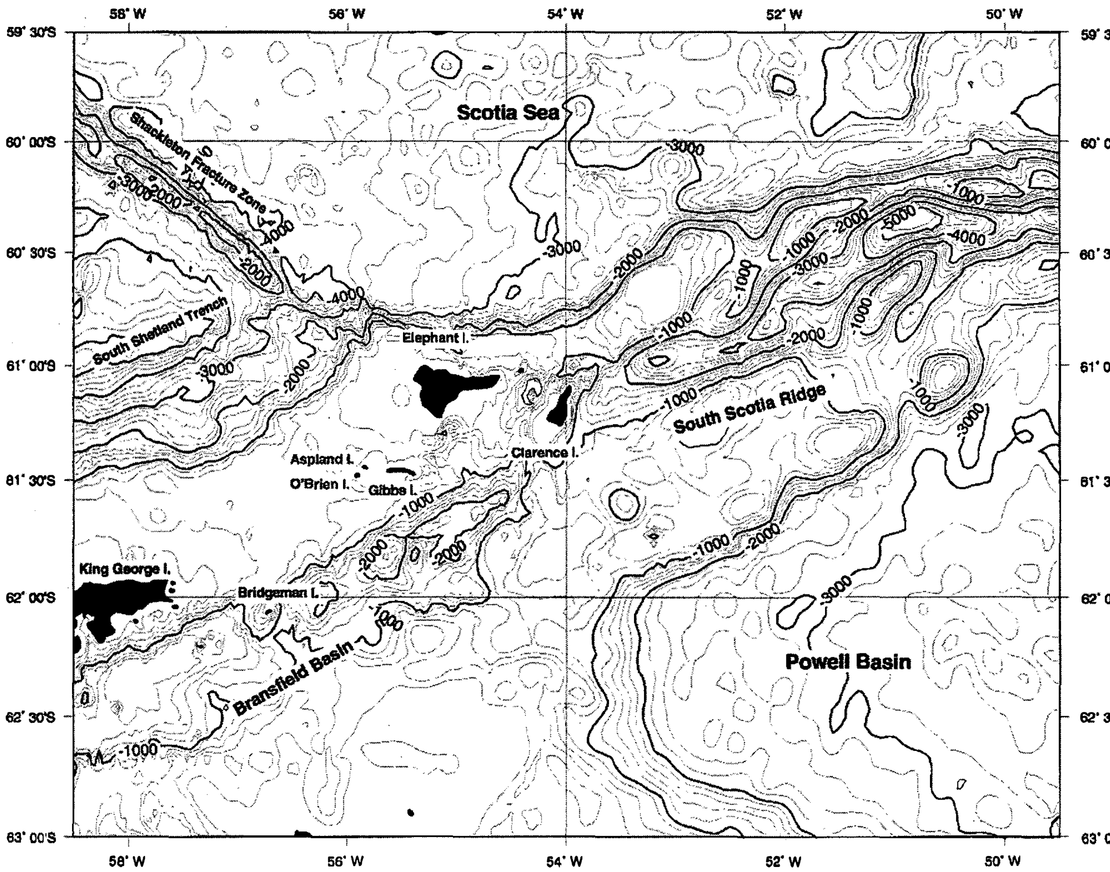

Fig. 2b. Detailed topographic map of TH97 survey area using same data with 200 m contour intervals.

tion of the plate boundary (LAWVER *et al.*, 1996; GALINDO-ZALDIVAR *et al.*, 1994).

2. Outline of Survey Methods

The marine geological and geophysical survey of the TH97 cruise was carried out from December 30, 1997 to January 31, 1998. The data and samples which were acquired during the TH97 cruise are listed in Table 1. A summary of TH97 survey methods with specifications of equipment and operating conditions is given in Table 2.

Seismic sources and the recording system were fully modified from those of previous cruises. The seismic source was towed by two cables equipped with two G-gun clusters each. Each cluster consisted of four 250 in^3 (16.3 *l*) G-guns. Three guns were set to generator and one to injector, respectively. The total air volume of the sound source was 3000 in^3 for the generator and 1000 in^3 for the injector. The shot timing was controlled to generate an impulsive seismic pulse by adjusting the shot delay time of injector guns. Single, 24 bit, 240 channel digital streamer cable and recording system were used. At the beginning of the cruise, the shot time interval was set to 12 s which corresponds to about a 25 m interval for the survey lines 4SMG and 5SMG. SMG means survey lines with seismic, magnetic and gravity surveys. The shot interval was shifted to 24 s (about 50 m) to avoid the risk of an air supply problem. The towing

Table 1. Summary of the TH97 cruise.

Survey period	32 days
Seismic reflection Survey	1788 km
Magnetic survey	5682 km
Gravity survey	12990 km
Dredge	6 sites
Gravity coring	6 sites

Table 2. Summary of survey equipment and operating conditions of TH97.

Survey	Instrument (specification) and operating conditions	
Multichannel seismic reflection (MCS)	Source:	4×SSI G-gun clusters in total. Each cluster consists of 4×250 in^3 (4×4.1 *l*) G-guns. (3000 in^3 generator+1000 in^3 injector, in total) air pressure is 2000 psi (13.8×10^6 Pa)
	Receiver:	SYNTRAK 480-24 24 bit digital streamer cable (12.5 m×6 ch/75 m/section×40 sections=240 ch 3000 m in total)
	Recorder:	SYNTRAK 480
	Sampling interval:	2 ms (resample to 4 ms for data processing)
	Record length:	9 s
	Shot interval:	*ca.* 25 m, 11 s (4SMG and 5SMG) and *ca.* 50 m, 22 s (rest of all) with 4.4 knot ship speed
	CMP coverage:	6000% (4SMG and 5SMG) and 3000% (other survey lines)
Gravity	Lacoste & Romberg SL-2 gravimeter	
Magnetics	Geometrics G-866 proton magnetometer	
	Tera Teknika three component shipboard magnetometer	
Bathymetry	12 kHz PDR system (Raytheon CESPIII with PTR and LSR1811)	
Subbottom profiling	3.5 kHz SBP system (Raytheon CESPIII with PTR and EPC)	
Bottom sampling	Gravity corer and chain bag dredge	

system's air supply hose was frequently broken and prevented completion of the long straight survey lines.

All the reflection and refraction seismic data were thoroughly processed by JAPEX/GeoScience Inc. after the cruise. A conventionally filtered CMP (Common Mid-Point) stack and time migration processes were applied. The time migration result was used as the standard data set for interpretation. In addition, all of the profiling data were used for further depth conversion processing. The plotting scales are unified in this report with a vertical exaggeration of 8.33.

3. Geological Sampling

A summary of sampling sites and samples is given in Table 3. Sampling sites for dredges (D) and gravity coring (GC) are shown in Fig. 3. Most gravity cores were intended to sample the young sedimentary strata in the basin area. Sampling of GC1803 was tried, to sample the old sedimentary sequence on the South Scotia Ridge, but failed. Dredges were also tried to obtain pre-Holocene sequences in the continental shelf area.

Table 3. Summary of bottom samplings.

Site	Lat. (S)	Lon. (W)	Depth (m)	Recovery	Remarks
GC1801	59°41'26"	38°54'27"	2131	2.96 m	Dark grayish yellow-greenish gray-gray siliceous silt (0-158 cm) with siliceous sandy silt (90-99 cm), and gray-dark grayish yellow siliceous sandy silt (158 cm +). Bioturbation is typical.
GC1802	59°00'05"	49°51'37"	3838	3.13 m	Gray siliceous sandy silt (0-39 cm) and gray-dark greenish gray silt (39 cm+). Diatomaceous (0-87 cm) and bioturbation are typical.
GC1803	60°34'09"	52°57'23"	582	0.63 m	Coarse sand with gravels (breccia, tuff, granite) and shell fragments. Foraminifera appear 28cm +.
GC1804	61°44'41"	50°15'36"	3269	4.03 m	Gray-yellowish gray silty clay with several black layers of fine sand (305-314 cm). Bioturbation is typical throughout the core.
GC1805	62°00'00"	52°00'10"	2834	2.98 m	Gray silt (0-57 cm), gray-yellowish gray (57-290) and dark greenish gray (290 cm +) sandy silt. Dark brown-gray fine sand layer (147-162 cm) with abundant planktonic foraminifera in upper part. Bioturbation is typical in the upper part which is very soft (73-99 cm).
GC1806	60°11'08"	55°30'27"	3531	4.74 m	Dark grayish yellow-dark greenish gray siliceous silty clay (0-203 cm) and gray-dark greenish gray silt (203 cm +). Sandy silt is intercalated (292 -350 cm). Several dark greenish gray and dark gray several mm layers are intercalated between 39 and 120 cm.
D1801	61°23'59" 61°24'58"	52°42'28" 52°42'28"	774 562	80 kg	Cobble to boulder size of gravel consist of granite, diorite, shale, hornfels, slate.
D1802	61°29'20" 61°29'10"	54°54'53" 54°54'32"	1138 1200	60 kg	Abundant pebble-boulder of gray-olive gray consolidated sandy siltstone. Granules to cobbles of gravel consist of schist and granite.
D1803	61°31'57" 61°31'43"	54°42'10" 54°42'33"	1230 1194	250 kg	Abundant pebble to boulder of gray-olive gray consolidated sandy siltstone and minor fine sandstone. Granules to cobbles of gravel consist of granite, diorite, schist, hornfels and slate.
D1804	61°37'20" 61°37'11"	53°31'50" 53°32'25"	668 566	50 kg	Abundant cobbles of gray-olive gray consolidated sandy siltstone. Cobbles of gravel consist of granite, hornfels, green tuff, sandstone, siltstone.
D1805	61°16'46" 61°16'19"	56°39'38" 56°40'10"	766 620	350 kg	Abundant cobble size of consolidated siltstone, sandstone and limestone. Bioturbation is typical of siltstone and sandstone. Abundant cobbles to boulders of gravels of granite, gabbro, hornfels, schist and slate. ome sedimentary rock and gravels are coated with thin (<1 mm) manganese oxide.
D1806	61°22'15" 61°22'11"	55°55'08" 55°54'46"	263 284	120 kg	Abundant cobbles to boulder of light gray volcanic rock gravels are interpreted to be closed to the vent site from their uniform and fresh appearance.

Locations and depths of dredges are listed for the first (upper) and last (lower) touches. Recovery: recovered core length and dredge sample weight.

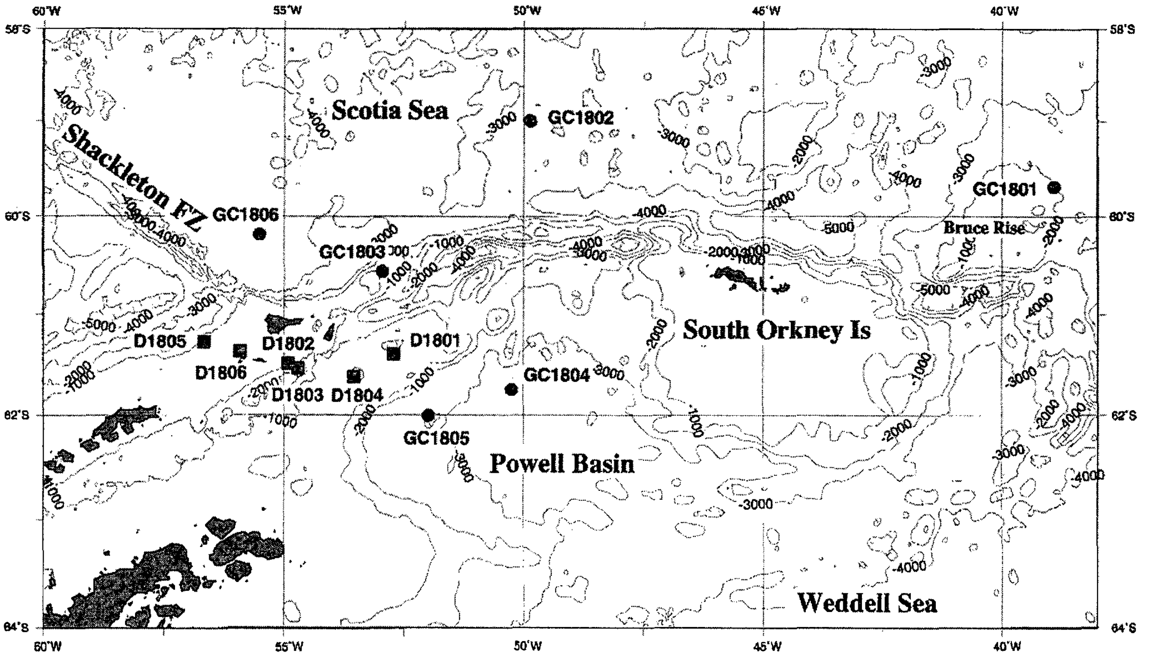

Fig. 3. Sampling sites of the TH97 survey area in the northern margin of the Antarctic Peninsula. Solid circles show the gravity coring sites and solid squares show dredge sites of the TH97 cruise.

Considerably consolidated siltstone and sandy siltstone were recovered from the sites of D1802, D1803, D1804 and D1805. A large amount of fresh volcanic rock was sampled from D1806.

Core samples of GC1801, GC1802, GC1804, GC1805, GC1806 and D1802 yield mostly latest Pleistocene radiolarian assemblage which is correlated to the *Antarctissa denticulata* Zone; and the sampled sediments are dated as to their ages of deposition. Samples from D1803 and D1804 yielded a small amount of radiolaria which are probably correlated to the Early Pliocene *Helotholus vema* Zone.

Planktonic foraminifera were recovered from the core samples of GC1803 (28–47 cm) and GC1805 (107–165 cm). *Neogloboquadrina pachyderma* (Ehrenberg) is a dominant species and minor *Globigerina* cf. *quinqueloba* Natland appears. This suggests the sediment which yielded this assemblage was deposited during the Pliocene or later. Five benthic foraminiferal assemblages were identified from the cored sediments;

a) The *Globocassidulina* spp. —*Cibicides* spp. assemblage is characterized by the dominant calcareous species and represents Antarctic bottom water.

b) The *Epistominella exigua* assemblage represents a mixture of Antarctic bottom water and Antarctic surface water.

c) *Martinottiella antarctica* and d) *Trochammina* spp. assemblages are arenaceous assemblages and represent the upper layer of Antarctic bottom water.

e) The *Cyclammina* spp. assemblage represents lower layer of Antarctic bottom water.

All six cores which were sampled during the TH97 cruise yielded abundant *Nitzschia kerguelensis*, mostly correlated to the youngest diatom assemblage zone, the

Nitzschia kerguelensis Zone (0–0.2 Ma). The upper part of this zone is characterized by the abundant *Rhizosolenia* cf. styliformis and spores of *Chaetoceros.* Core samples of GC1801 show two more diatom zones, *i.e.*, the *Hemidiscus karstenii* Zone (0.2–0.35 Ma) and the *Rouxia isopolica* Zone (0.35–0.62 Ma). Samples of D1802 includes two types of sedimentary rocks which yield diatoms of the *Rouxia isopolica* Zone and the *Nitzschia kerguelensis* Zone. Although most samples of D1803 are poor in diatoms, one sample yields diatoms of the *Rouxia isopolica* Zone. Samples of D1805 yield a large quantity of diatoms but they are poorly preserved. Two possible older diatom zones are recognized for the samples from D1805; the *Nitzschia interfrigidaria* Zone (3.1–3.6 Ma) and the *Thalassiosira inura* Zone (lower Pliocene).

Abundant fresh volcanic rocks were sampled from D1806 at a small peak in the core of the small anticline, 7 km NNE of Aspland Island and 35 km SW of Elephant Island (Fig. 14). Major element chemistry suggests that the rock is andesite, which belongs to the calc-alkaline rock series. Whole-rock K-Ar isotope age determination analysis, carried out by Teledyne Isotopes, gave the results as 8.3±0.4 and 7.2±0.4 Ma, Late Miocene ages, for the andesite.

Micropaleontological analysis shows that most of the core samples from the Scotia and Powell Basins are interpreted to have been deposited during the latest Pleistocene, and that dredged samples from southeast and west of Elephant Island are consolidated siltstone and sandy siltstone which are interpreted as being of Early Pliocene age. The age data of the dredged andesite from the core part of the anticline suggests that the tectonism which was accomplished with many folds in this area occurred during the Late Miocene.

4. Gravity and Magnetic Surveys

Gravity anomaly data which were obtained during the TH97 cruise are plotted with the data of previous JNOC cruises TH87, 88 and 96 in Fig. 4. Most of the gravity anomaly pattern is well correlated with the topography. A prominent feature is the very low gravity anomaly area developed over the continental slope along the South Shetland Trench. This low extends to the junction area of the Shackleton Fracture Zone and the basement of the Antarctic Peninsula. In contrast, there is no low area observed along the northern slope of the South Scotia Ridge.

Magnetic anomaly data which were obtained during the TH97 cruise are plotted with the data of previous JNOC cruises of TH87, 88 and 96 in Fig. 5. There are high amplitude magnetic anomalies along the Bransfield Basin in the west, and along the southern ridge of the South Scotia Ridge in the east. The former and latter anomalies correspond to the rifting activity and the possible volcanic intrusion along the ridge, respectively. The northern ridge of South Scotia Ridge is magnetically very quiet, in contrast. There is an intense broad positive anomaly 40 km west of Aspland and O'Brien Islands. A small scale and short wavelength anomaly, which suggests volcanic intrusion, is observed over the topographic high of the D1806 dredge site northwest of Aspland and O'Brien Islands.

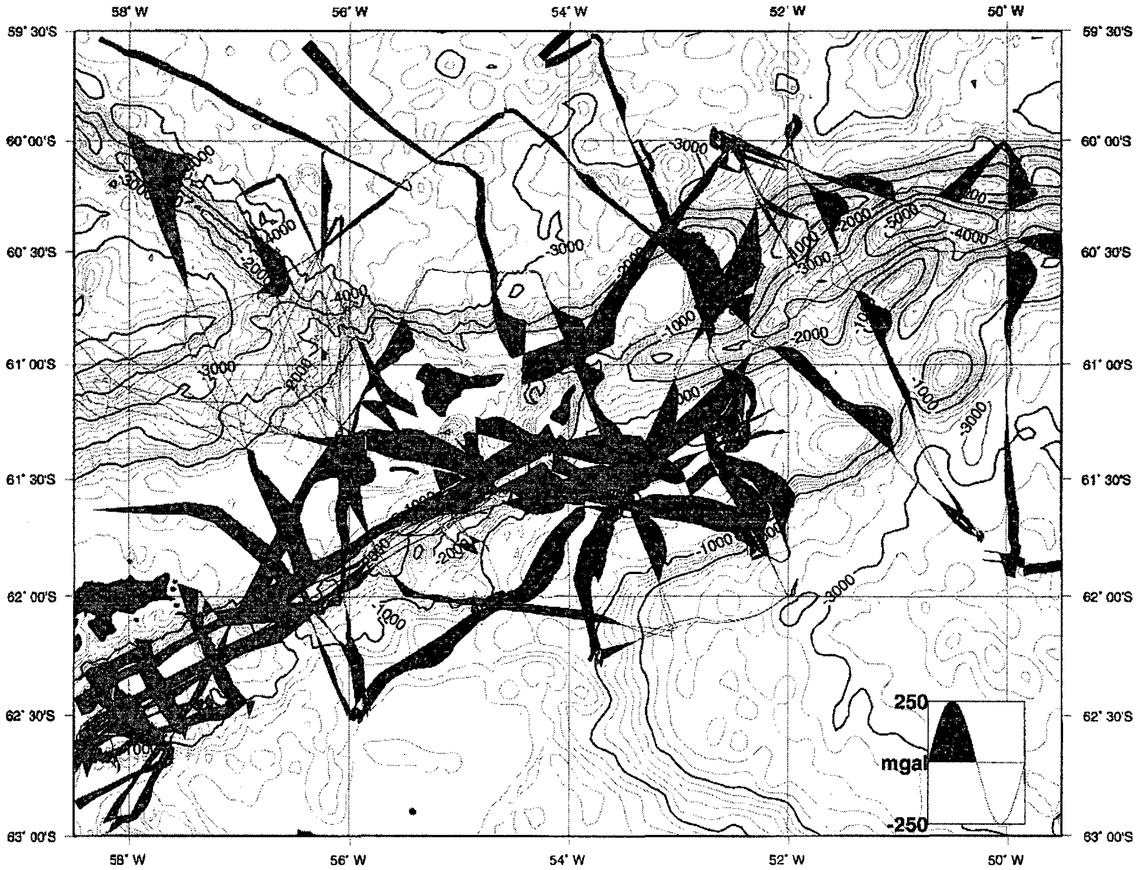

Fig. 4. Free-air gravity anomaly profiles along the ship's track during the TH97 cruise in the northern margin of the Antarctic Peninsula. Gray profiles show previous JNOC cruise data during TH87, TH88 and TH96.

5. Preliminary Interpretation of Seismic Survey Results

Seismic survey lines of the TH97 cruise are shown in Fig. 6.

Although fairly extensive previous survey cruises have been carried out by many organizations in and near the TH97 survey area (ANDERSON, 1991; BARKER and AUSTIN, 1994, 1998; BOCHU *et al.*, 1995; CAMERLENGHI *et al.*, 1994; CUNNINGHAM *et al.*, 1995; GAMBOA and MALDONADO, 1990; GRACIA *et al.*, 1996; GRAPE TEAM, 1990; JIN *et al.*, 1996; KIM *et al.*, 1995; LARTER and BARKER *et al.*, 1991; LAWVER *et al.*, 1994, 1996; LODOLO *et al.*, 1993; TANAHASHI *et al.*, 1998), subsurface geological information is very much limited and most authors interpret the subsurface geology by correlation to the land geology (DALZIEL, 1989) and distant DSDP and ODP drilling results on the ocean floor. Because of the lack of offshore geological information, the seismic interpretation in this paper is highly preliminary.

Seismic reflection profiles of the typical survey lines, 4SMG, 5SMG, 6SMG, 9SMG and 11SMG in Fig. 6 are shown in Figs. 7 to 11, respectively. Some parts of the seismic profiles are shown as, color coded images to indicate detailed seismic features, in Figs. 12 to 16. Figures. 12 (5SMG) and 13 (14SMG) show the eastern and western parts of eastern Bransfield Basin, respectively. Figure 14 (5SMG) shows dredge site D1806,

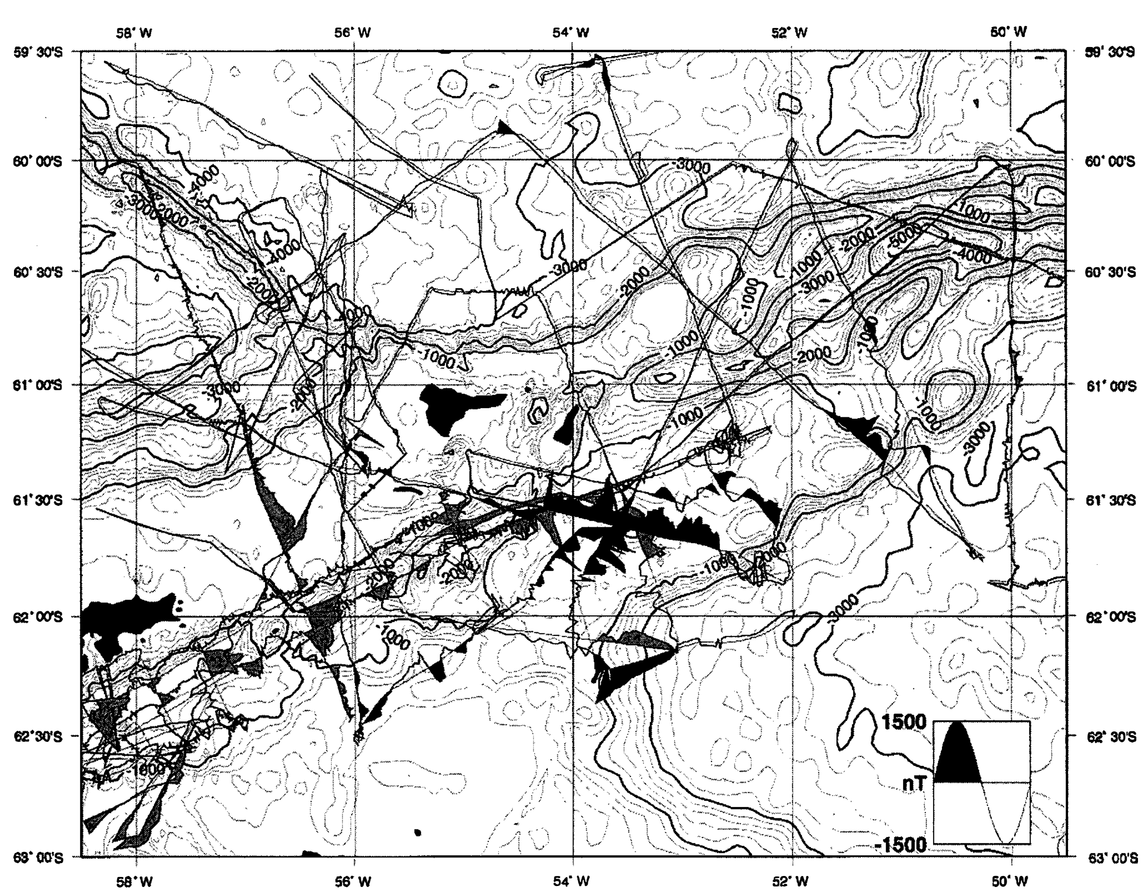

Fig. 5. Total magnetic anomaly profiles along the ship's track during the TH97 cruise at the northern margin of the Antarctic Peninsula. Gray profiles show previous JNOC cruise data during TH87, TH88 and TH96.

southwest of Elephant Island. Figures 15 (5SMG) and 16 (6SMG) show the bottom simulating features over the South Shetland Trench slope and in the Scotia Basin, respectively.

The seismic sequences cannot be traced and correlated in the whole area because of the complex and variable tectonic environment. Thus, the TH97 survey area was divided into four sub-areas, *i.e.*, the Bransfield Strait area (C), Powell Basin and South Scotia Ridge area (D), Northern deep ocean (former Phoenix plate) area (E), and Scotia Basin area (F), as the TH96 report (TANAHASHI *et al.*, 1998) for the convenience of the interpretation. As there are no stratigraphic control bore holes in this area, we infer the age of stratigraphic events after the estimated basement formation age. A preliminary stratigraphic correlation table of these areas in the TH97 survey area is given in Table 4. Interpreted seismic sequences are shown on the profiles. The depth and layer thickness along the seismic section are given with the two way travel time (TWT) in seconds. Positions along the survey lines are given as SP (Shot Point) numbers.

5.1. *Bransfield Strait area (C)*

Lines 5SMG (Fig. 12) and 14SMG (Fig. 13) cross the Bransfield Basin, in the northeastern end and the center of the eastern basin, respectively. There is a distinct unconfor-

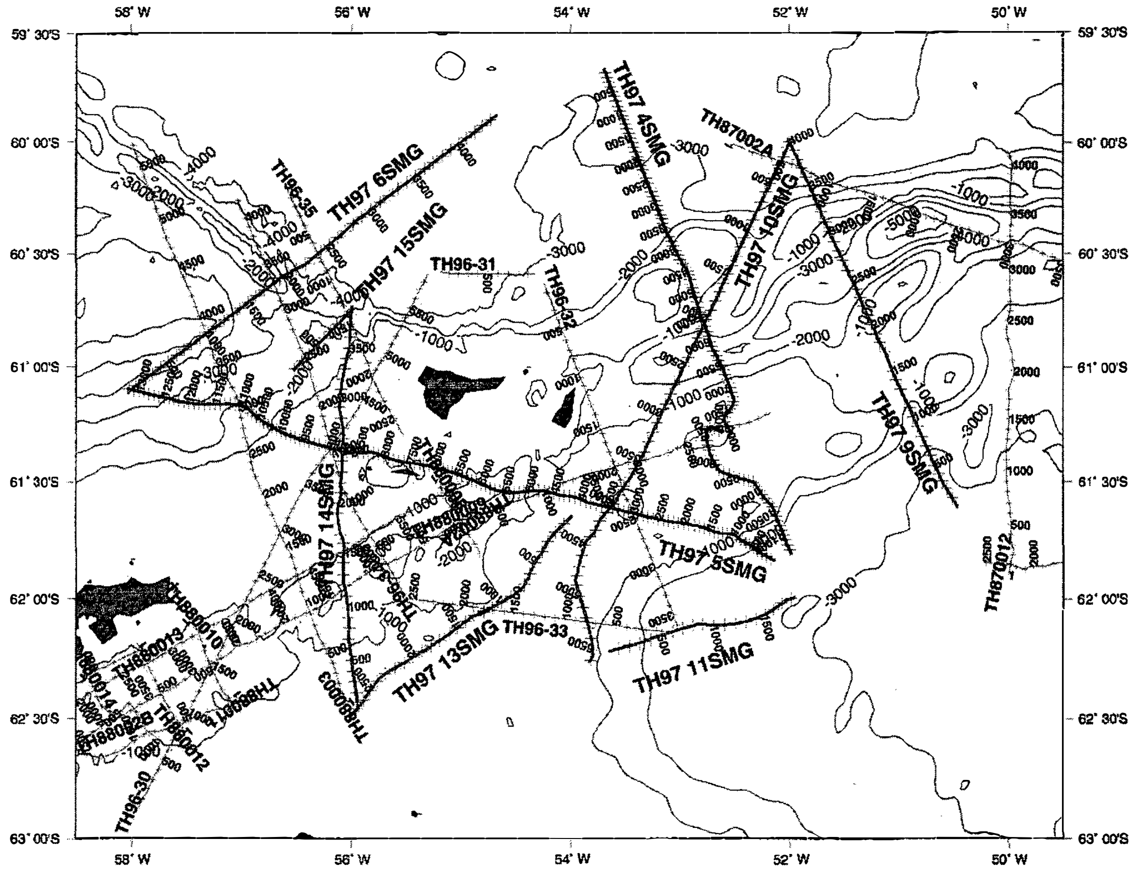

Fig. 6. Multichannel seismic reflection survey lines during the TH97 cruise. Thin lines are the TH87, TH88 and TH96 survey lines. The numbers along the survey lines are SP (Shot Point) numbers.

mity between the uppermost less deformed clearly stratified sequence (*e.g.*, sequence C1 in Fig. 13) and the lower highly deformed possible synrift sequence (*e.g.*, sequence C2 in Fig. 13) on the southeastern margin of Bransfield Basin. The upper sequence is probably correlated to the topset sequence overlying the seaward inclined foreset like sequence on the Antarctic Peninsula shelf.

The 50 km wide easterly tilted basin is developed at the northeastern end of the eastern Bransfield Basin along 5SMG (Figs. 8b and 12). Three second-order easterly tilted basins are developed on the western slope of the first order tilted basin. Each second order basin has a tectonic high with anticlinal fold possibly with the basement intrusion at the eastern end. The geometry shows a typical extensional rifting structure. Dredge samples at D1802 and D1803 show that the bottom sediment at the slope of the rifted anticlinal highs is mostly of Early Pliocene age. It is interpreted that the rifting began in the Pliocene or later. This coincide the estimation by LAWVER *et al.* (1996) as 4 Ma for the extension commenced in this area caused by the cessation of the Antarctic-Phoenix spreading center activity. Late Miocene andesite (D1806, Fig. 14) forms an intrusive body which is the core of an anticline. This suggests that the major tectonic activity, which made the folds around Elephant Island, occurred in this age. Even the folding trend is not valid because of the low density of seismic lines. It is probably in

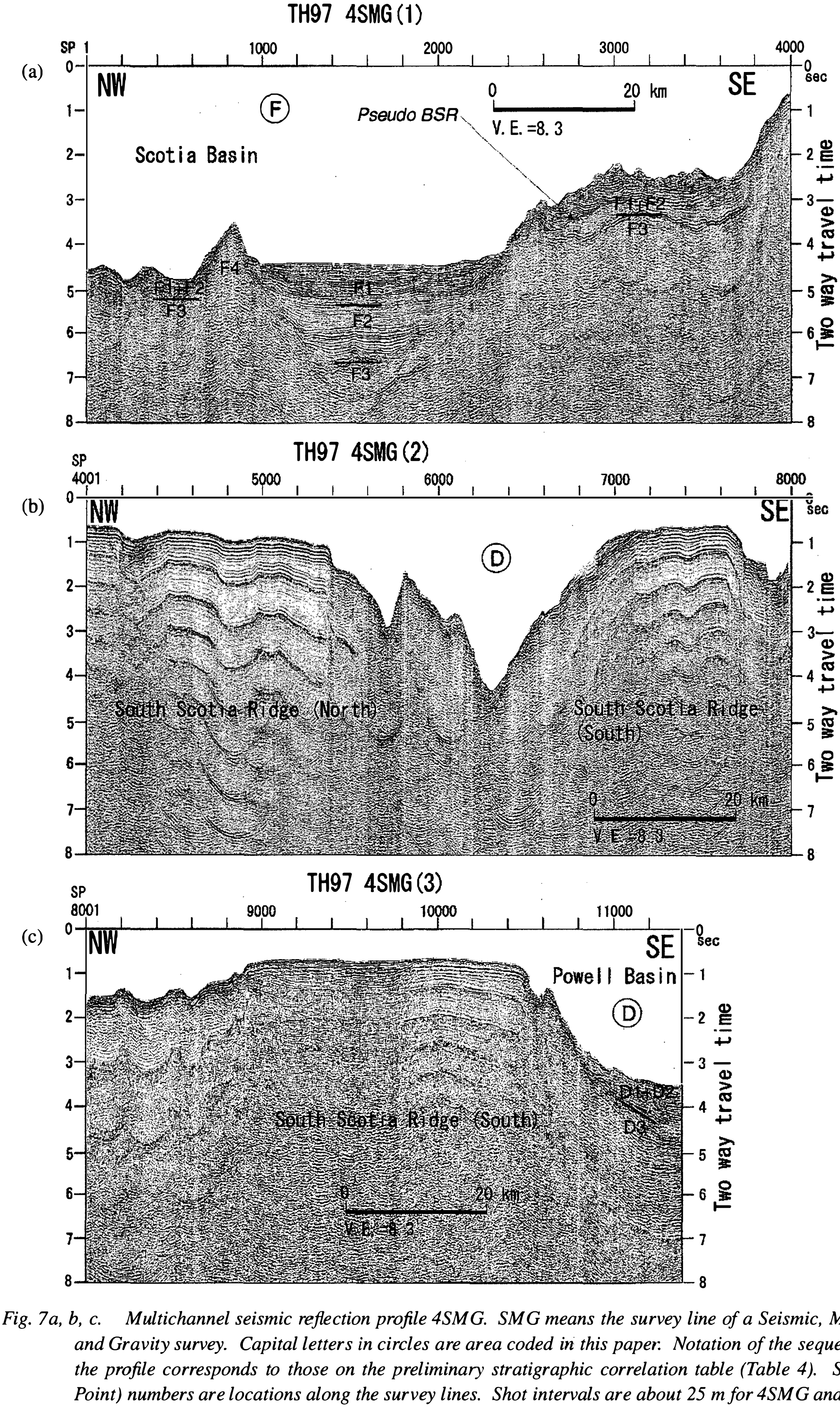

Fig. 7a, b, c. Multichannel seismic reflection profile 4SMG. SMG means the survey line of a Seismic, Magnetic and Gravity survey. Capital letters in circles are area coded in this paper. Notation of the sequences on the profile corresponds to those on the preliminary stratigraphic correlation table (Table 4). SP (Shot Point) numbers are locations along the survey lines. Shot intervals are about 25 m for 4SMG and 5SMG, and about 50 m for other survey lines during TH97. "V.E." means Vertical Exaggeration.

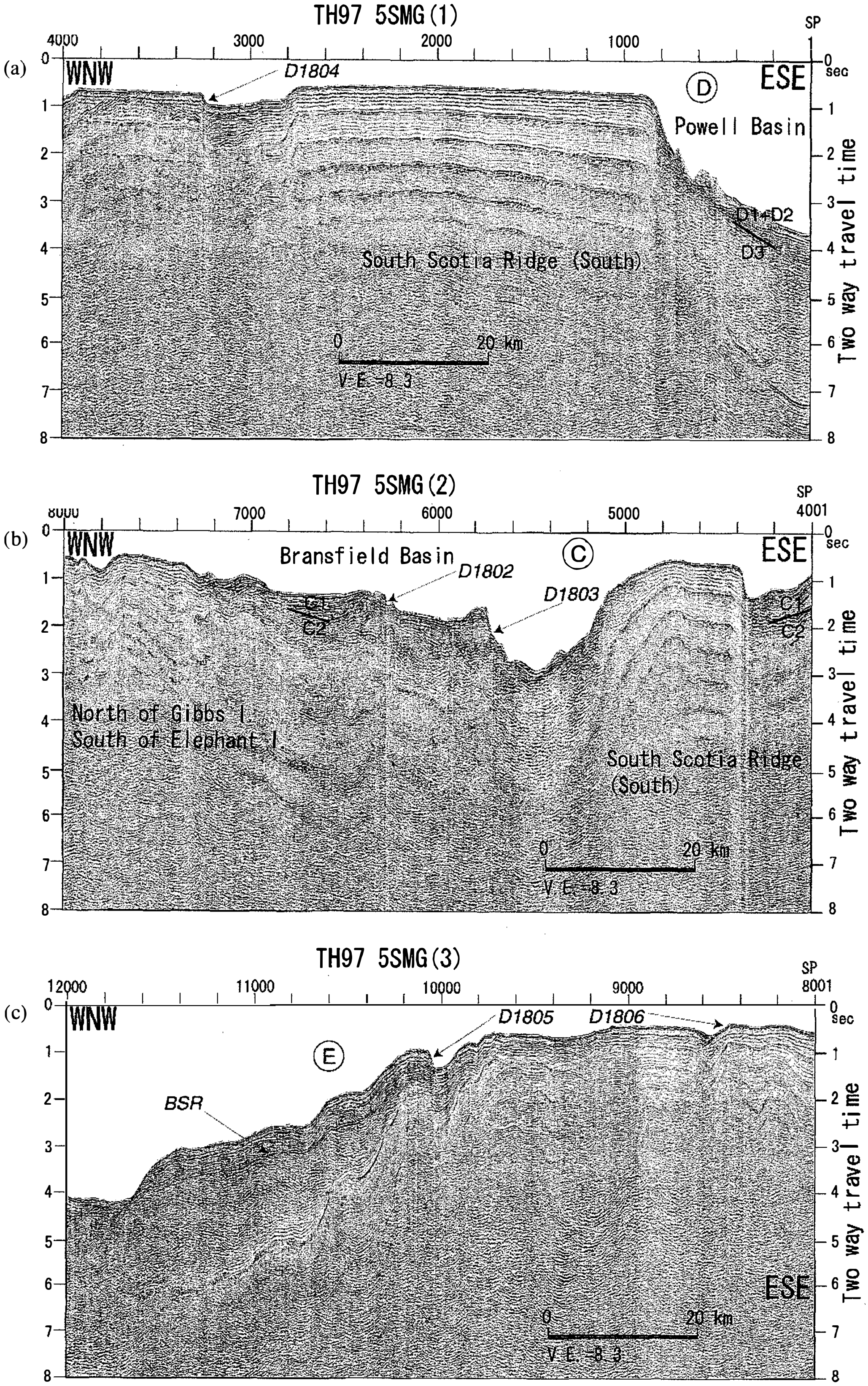

Fig. 8a, b, c. Multichannel seismic reflection profile 5SMG. Capital letters in circles are area codes in this paper.

(d)

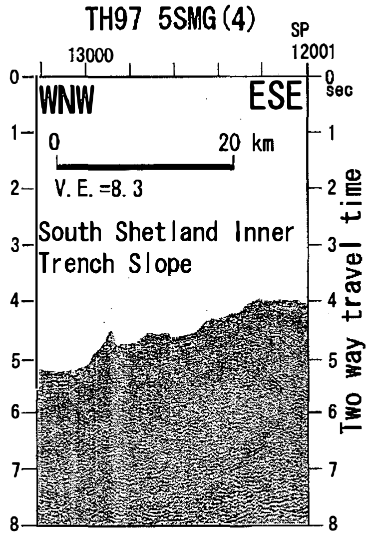

Fig. 8d (continued).

northwest to southeast direction.

5.2. Powell Basin and South Scotia Ridge area (D)

Seismic profiles 4SMG (Fig. 7c), 5SMG (Fig. 8a) and 11SMG (Fig. 11) cross the western margin of Powell Basin. There is a distinct unconformity which corresponds to the boundary between the lower deformed sequence and the upper well stratified sequence in the marginal area. The unconformity is probably correlated to the base of the basin fill sequence. The lower sequence in the margin is interpreted as the sediment which was deposited during the rifting stage prior to the spreading of Powell Basin.

Lines 4SMG (Fig. 7b) and 9SMG (Figs. 10a and 10b) cross the South Scotia Ridge, which has northern and southern ridges and a deep V-shaped mid-valley between them. The morphology shows a typical tectonic feature characterized by the several graben structures. The northern ridge has a partly reflection-free possible old hard basement. There is a northerly inclined slope sequence on the northern part of the northern ridge (9SMG, Fig. 10b) and graben-like depressions which were partly filled with stratified sediments (4SMG, Fig. 7b). The south mid-valley slope is composed of inclined sedimentary sequences more than 1 s in thickness. The relationship of top-lapped lower and down-lapping upper foreset sequences is developed on the outer continental shelf of the southern South Scotia Ridge at SP6900 to 7050 of 4SMG. The relationship is widely developed in the outer continental shelf margin in the western continental shelf of the Antarctic Peninsula. It is interpreted that the relationship of the sequences is formed by the eustatic sea-level change which is mainly controlled by the variation of glacial development.

Southern Scotia Ridge is mostly reflection free along 4SMG (Figs. 7b and 7c) and 5SMG (Figs. 8a and 8b), and is interpreted as an old hard basement. In contrast, the ridge on 9SMG (Fig. 10a) consists of 2 s thick sedimentary sequences which is intensely deformed, specially with the southeasterly facing normal faults and northwesterly tilting deformation. This part of the South Scotia Ridge may be uplifted from the deeper sedimentary basin with a possible igneous intrusion along the ridge. It is supported by

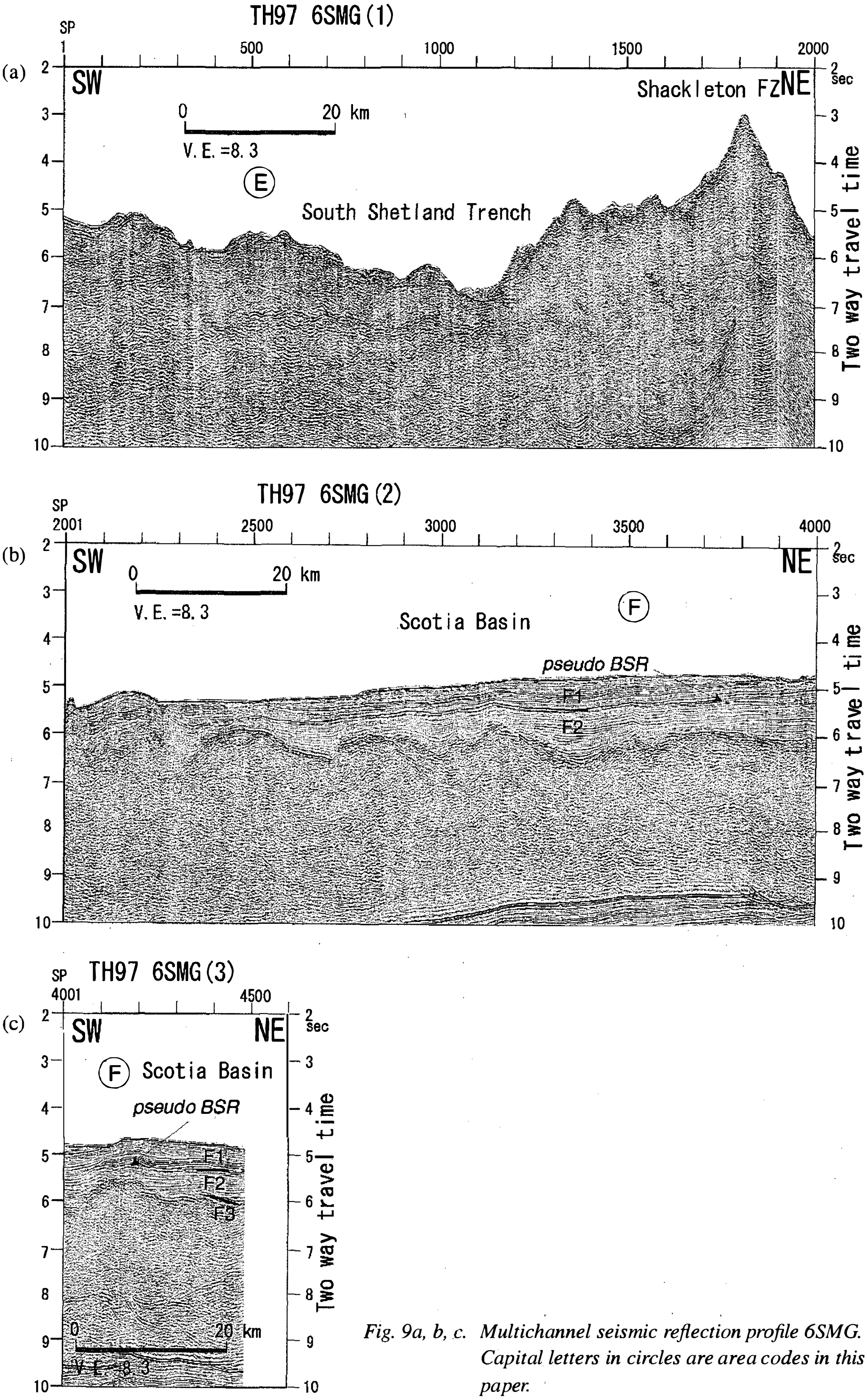

Fig. 9a, b, c. Multichannel seismic reflection profile 6SMG. Capital letters in circles are area codes in this paper.

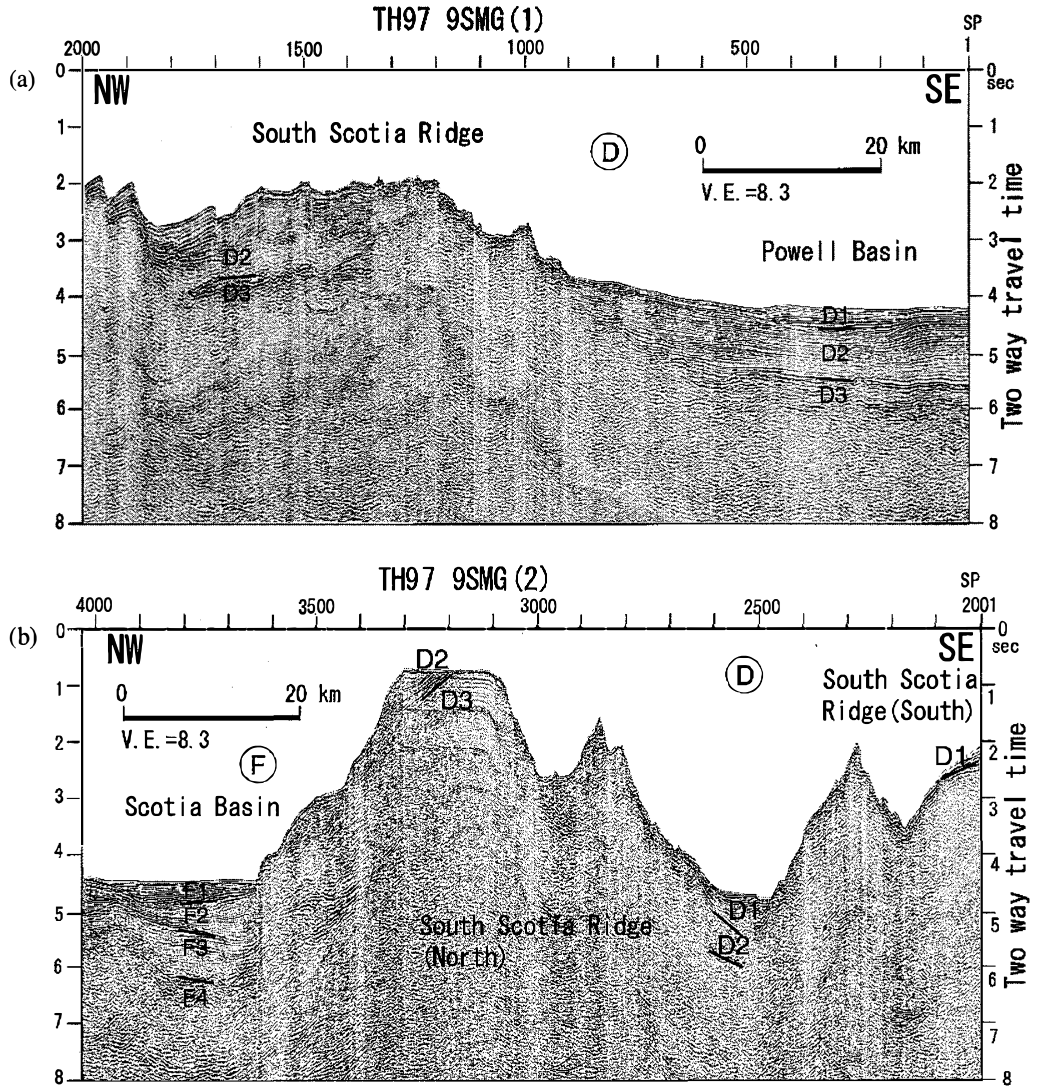

Fig. 10a, b. Multichannel seismic reflection profile 9SMG. Capital letters in circles are area codes in this paper.

the topographic highs nearby SP1000–1300 of 9SMG (Fig. 6).

5.3. Northern shelf and deep ocean area (E)

This area includes the former Phoenix Plate area and the continental shelf west of the Bransfield Basin. There is a severely deformed thick sedimentary basin area in the shelf southwest of Elephant Island. The distribution of the sedimentary sequences is not clear because it is variable and the survey lines are too sparse.

The continental slope on the profile 5SMG (Fig. 8c) shows anticlines and synclines which are concordant with the topography. There is a prominent BSR (Bottom Simulating Reflector) on the middle slope (Fig. 15; 1300–2600 m in water depth). The lower slope is so intensely deformed that the stratification is not obvious. There is a clear reflection from the decollemant or basement of the subducting slab under the trench wedge along 6SMG (Fig. 9a). The Shackleton Fracture Zone on 6SMG show a rough

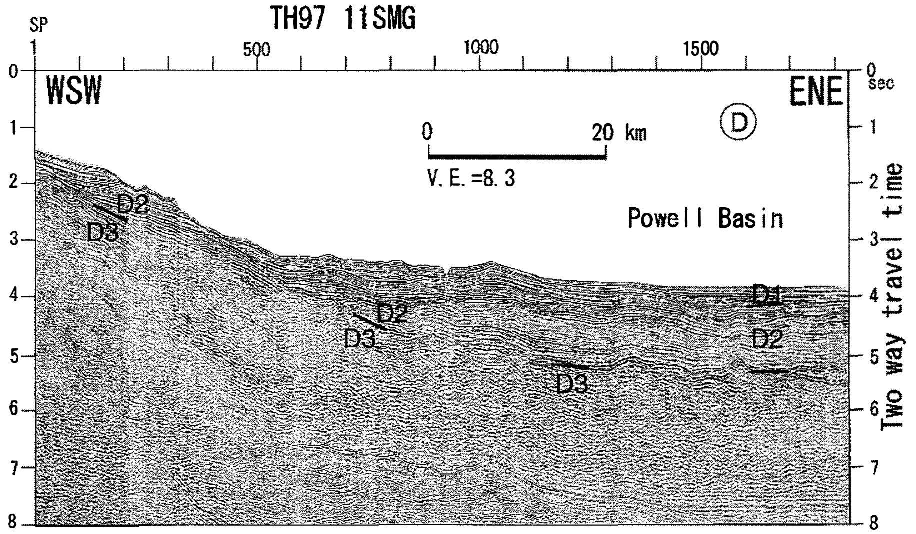

Fig. 11. Multichannel seismic reflection profile 11SMG from the northern offshore shelf of the northernmost Antarctic Peninsula to the Powell Basin. Capital letters in circles are area codes in this paper.

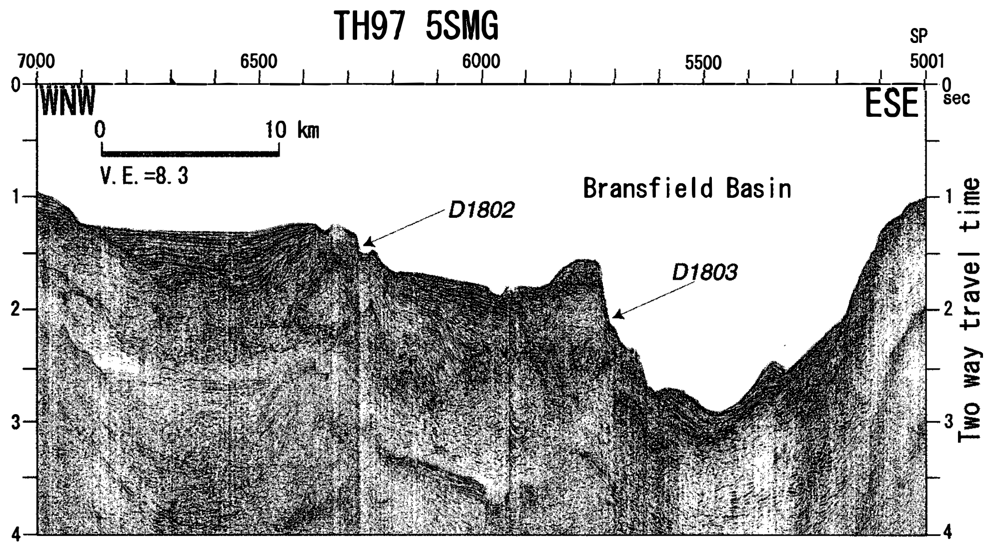

Fig. 12. Detailed color coded multichannel seismic reflection profile of 5SMG at the eastern part of eastern Bransfield Basin.

plateau on the southwest and a peak on the northeast (Fig. 9a).

5.4. Scotia Basin area (F)

The Scotia Basin has a 1.0 to 1.5 s thick, well stratified, little deformed sedimentary sequence on the clear oceanic basement (Figs. 9b and 9c). The basin margin contiguous to the Shackleton Fracture Zone is a 10 km wide gentle anticline which deforms the sedimentary sequence just below the seafloor. This suggests that some compressive stress acts between the Scotia Sea crust and the Shackleton Fracture Zone. Sedimentary

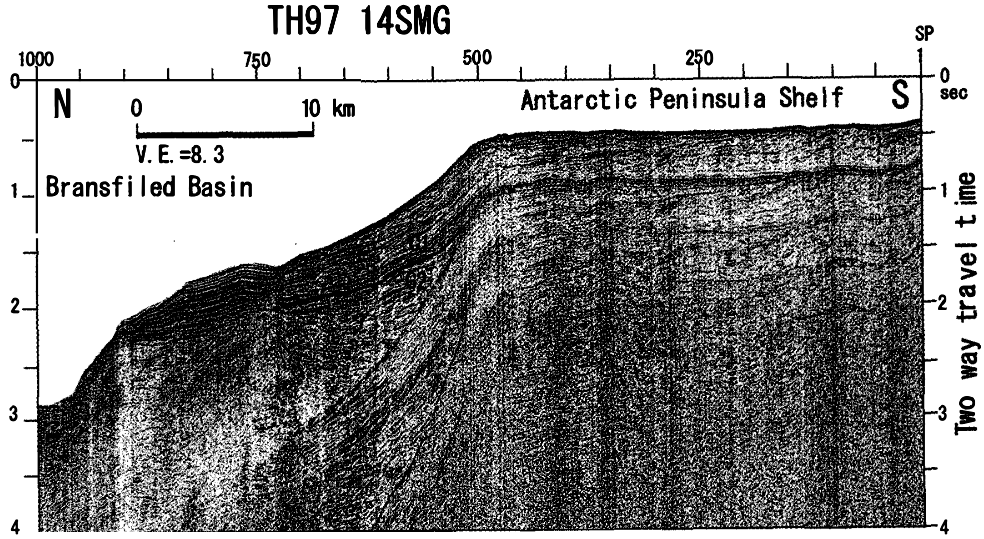

Fig. 13. Detailed color coded multichannel seismic reflection profile of 14SMG at the western part of eastern Bransfield Basin.

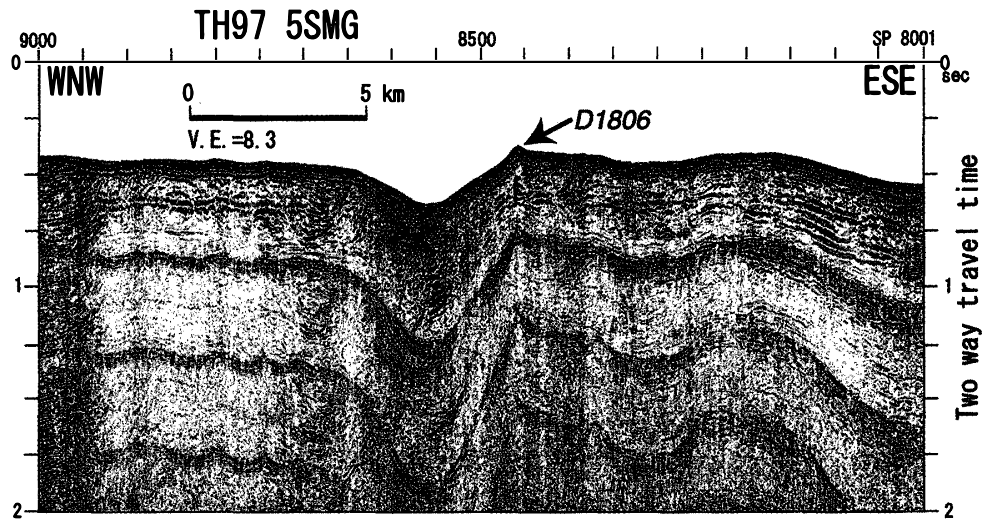

Fig. 14. Detailed color coded multichannel seismic reflection profile of 5SMG at the D1806 dredge site, southwest of Elephant Island.

sections along 6SMG and the basin margin of 4SMG show the characteristic BSR-like feature, *i.e.* the lower boundary of the high reflectivity zone traces sub-parallel to the bottom geometry. Common BSR is an intense reflection and is interepreted as a boundary between the gas hydrate and free gas layers as in the case of the South Shetland Trench (TINIVELLA *et al.*, 1998). As the boundary on the TH97 profiles in the Scotia Basin is not a reflector, we call it a pseudo-BSR (Fig. 16). This feature cannot be explained by the upper gas hydrate layer-lower free gas charged layer model, because the upper surface of the free gas layer makes a distinct reflection. The pseudo-BSR may reflect the diagenetic feature of silica minerals.

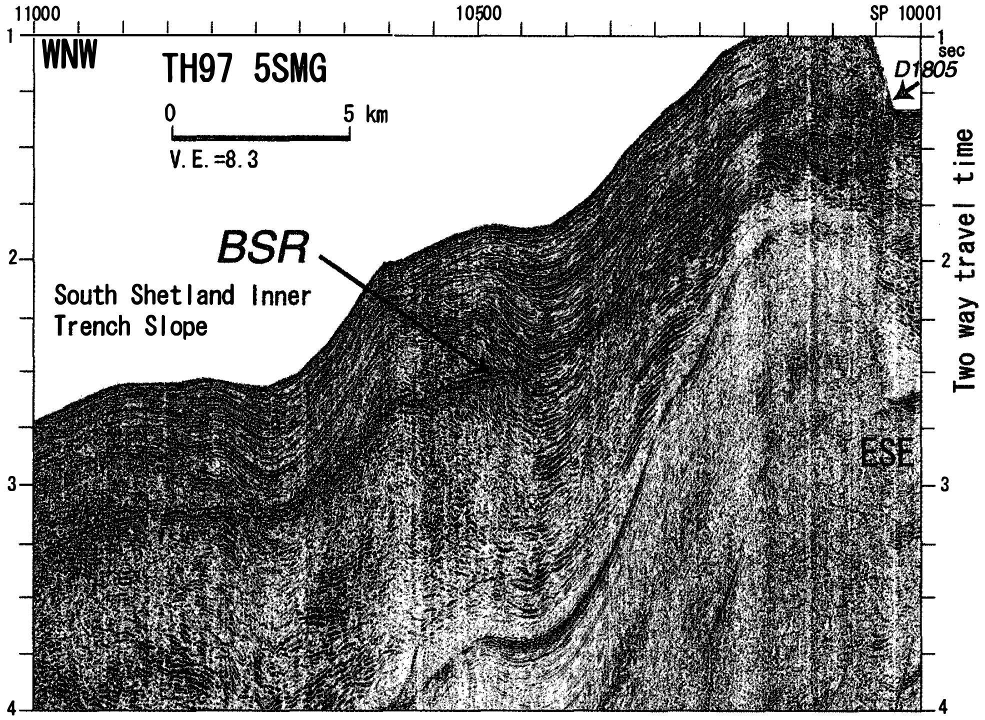

Fig. 15. Detailed color coded multichannel seismic reflection profile of 5SMG at the continental slope. Note the distinct BSR (Bottom Simulating Reflector).

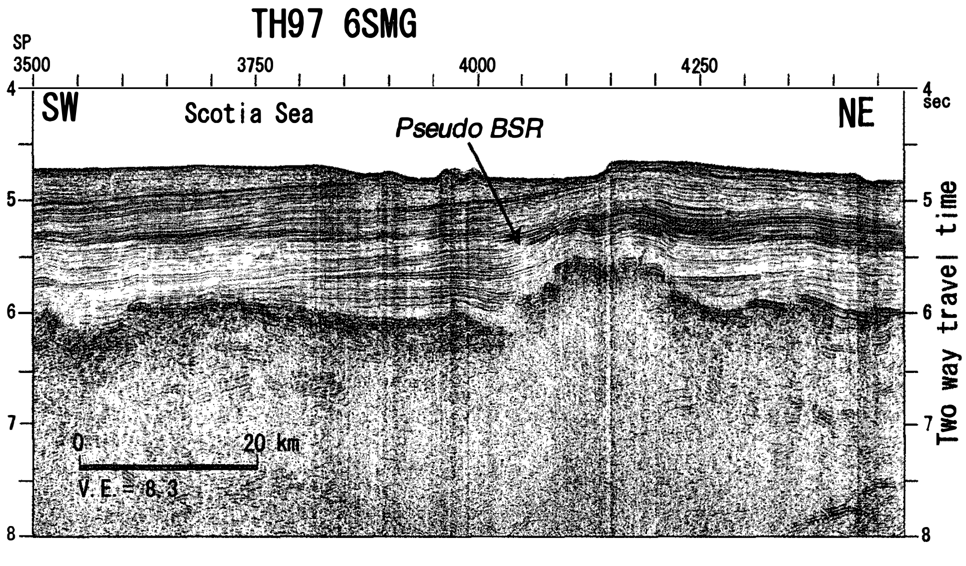

Fig. 16. Detailed color coded multichannel seismic reflection profile of 6SMG at Scotia Basin. Note the pseudo-BSR (Bottom Simulating Reflector).

There is an anticlinally deformed mound, in which a prominent unconformity reflector and pseudo-BSR are developed in 2 s thick sediments, at the foot of the northern slope of South Scotia Ridge at SP2400 to 3700 of 4SMG (Fig. 7a.). The anticline was formed in the uppermost formation; this suggests that the compressional tectonics is

Table 4. Preliminary correlation table of sedimentary sequences of offshore northern margin of the Antarctic Peninsula (modified from TANAHASHI *et al., 1998)*

Age \ Area			Bransfield Strait	Powell Basin and South Scotia Ridge	Northern Shelf and Deep Ocean	Scotia Basin
			C	D	E	F
Quaternary						
Neogene	Pliocene					F1+F2
	Miocene	Late				
		Middle	C1+C2	D1+D2	E1+E2	
						F3
		Early				
Paleogene	Oligocene					F4
	Eocene		C3	D3+D4	E3	
	Paleocene			D5		
Cretaceous			C4		E4	

active across the boundary between Scotia Sea crust and the South Scotia Ridge. The upper sequence shows the highly irregular bedform structure, which suggests strong bottom current activity along the foot of the slope. Lower sequences of the mound show the more gentle and continuous sedimentary structures.

Thick (3.2 s in max.) sediments filled the 30 km wide depression to the northwest of the mound, SP 1000 to 2300 of 4SMG (Fig. 7a). Sedimentary sequences generally fill the V-shaped basin basement. The upper sequence shows good stratification and fills the depression in the gently deformed lower sediments. The middle sequence shows a less deformed weakly stratified nature. The lower sequence shows the shape that intrudes into the middle sequence.

The pair of anticlinal mounds on the foot of South Scotia Ridge, and the thick sedimentary basin north of it, is also observed at SP3400 to 4000 of 9SMG (Fig. 10b) and TH96 30SMG (TANAHASHI *et al.*, 1998). The structure suggests that the compressive movement across the northern slope of South Scotia Ridge is active some extent.

6. Discussion and Summary of Geological History of the TH97 Survey Area

1) Rifting prior to the spreading of the Scotia and Powell Basins in the northern margin of the Antarctic Peninsula continental shelf occurred until the Late Oligocene. The deformed sequence in the shelf and chaotic sequence in the transitional area between the slope and the floor of the Powell Basin, under the possible breakup unconformity (boundary between D2 and D3 of 11SMG; Fig. 11), suggest rifting activity. The basement, which is now distributed in the South Orkney Islands area and Elephant Island area, consists of Mesozoic or older fore-arc sequences of the Andean Arc (DALZIEL and ELLIOT, 1973).

2) The maximum sedimentary thickness in Powell Basin is about 1.8 s along 9SMG (Fig. 10a). Characteristic bedforms with cross bedding are developed in the junction between the slope and flat basin bottom (Figs. 10a and 11). This sedimentary structure is interpreted to have been formed as the contourites by LAWVER *et al.* (1994).

Powell Basin spread as a pull apart oceanic basin from the Late Oligocene to the Early Miocene (27–18 Ma, drift phase; COREN *et al.*, 1997). Scotia Basin spread in the same age (BRITISH ANTARCTIC SURVEY, 1985). Older basements which were developed in the Elephant Island area, northern and southern South Scotia Ridge were rifted and separated. Some sedimentary basins were probably devloped south and west of Elephant Island.

3) Anticlinal and synclinal folding with andesitic volcanism occurred in the south and west of Elephant Island during the Late Miocene. Igneous intrusion and basement uplift at the eastern part of the southern ridge of South Scotia Ridge probably occurred. It may have been related to the conversion of the stress regime in the period of the cessation of spreading in the Scotia and Powell Basins. COREN *et al.* (1997) interpreted the Powell Basin formation to have been completed by the Early Pliocene. Possible active compressive movement east of the present end of the South Shetland Trench, i.e. the junction with the Shackleton Fracture Zone, is suggested by deformation of the uppermost sequences along the southern margin of Scotia Basin.

4) Bransfield Basin is an active extensional basin located at the back-arc basin position of the so-called island arc-trench system. But the island arc volcanism stopped about 4Ma or before and it lacks active island arc tectonic features, such as island arc volcanic activity and a deep inclined seismic zone (LAWVER *et al.*, 1996). The driving force to extend the basin is interpreted by the trench roll back model after the end of the oceanic spreading activity of the Antarctic-Phoenix spreading center at 4 Ma (LAWVER *et al.*, 1996). The basin was developed with rift propagation from northeast to southwest (BARKER *et al.*, 1998). The southern margin of the basin shows a typical passive rifted continental margin structure with prograding sequences at the top (Fig. 13). The northern margin shows the rifted and extended structure with the tilted blocks (Fig. 12).

5) Two types of bottom simulating seismic phenomena are well developed in this area. One is developed along the South Shetland inner trench slope (Fig. 15). The BSR in the area has been analyzed in detail by LODOLO *et al.* (1993) and TINIVELLA *et al.* (1998) and is interpreted as the boundary between the upper gas hydrate cemented layer and lower hydrate free layer whose top has a thin free gas layer. The other is developed in the southwestern part of the Scotia Basin (Fig. 16). It is not a reflection but a boundary where the reflection energy changes abruptly. It may be correlated to the phase boundaries of silica minerals.

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