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Preliminary report on geological and geophysical survey results in the Princess Elizabeth Trough and its vicinity by R/V Hakurei-maru

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Abstract: Geophysical and geological surveys in and around the Princess Elizabeth Trough, East Antarctica, were carried out in the 1998-99 austral summer season. The survey area covers the Princess Elizabeth Trough, the southern margin of the Kerguelen Plateau, and the Bruce Plateau. Magnetic lineations, which were tentatively identified as anomalies M12 to M10, were recognized on the abyssal plain in the Princess Elizabeth Trough. Six seismic sequences (A to F) are recognized in the Princess Elizabeth Trough and north of the Bruce Plateau. On the southern Kerguelen Plateau, five seismic sequences (KP1 to KP5) are recognized.

The geological time of the seismic sequences was estimated based on correlation with lithostratigraphic results of ODP Site 738 and relationship to tectonic history in this area. The geological times of the sequences are as follows. Sequence F on the continental rise is a pre-rift sequence that was deposited in late Jurassic or older time. On the abyssal plain in the Princess Elizabeth Trough, where magnetic lineations are observed, sequence F consists of oceanic crusts and was formed in the Early Cretaceous. Sequence E is a syn-rift sediment formed during late Jurassic to Early Cretaceous time. Sequence D is a post-rift sediments formed in the Early Cretaceous. Sequence C was deposited with marine transgression, which occurred with regional crustal subsidence accompanying the subsidence of the southern Kerguelen Plateau after approximately 90 Ma. Sequences C and B are correlated with sediments formed during Late Cretaceous to middle Eocene time and sediments formed after the middle Eocene, respectively. Sequence A is sediments formed during early Miocene to Quaternary time.

key words: Princess Elizabeth Trough, marine geophysical and geological surveys, seismic sequence

1. Introduction

The Technology Research Center, Japan National Oil Corporation, has been conducting marine geophysical and geological surveys of the Antarctic continental margins with R/V Hakurei-maru since 1980. Some of the results of previous cruises have already been

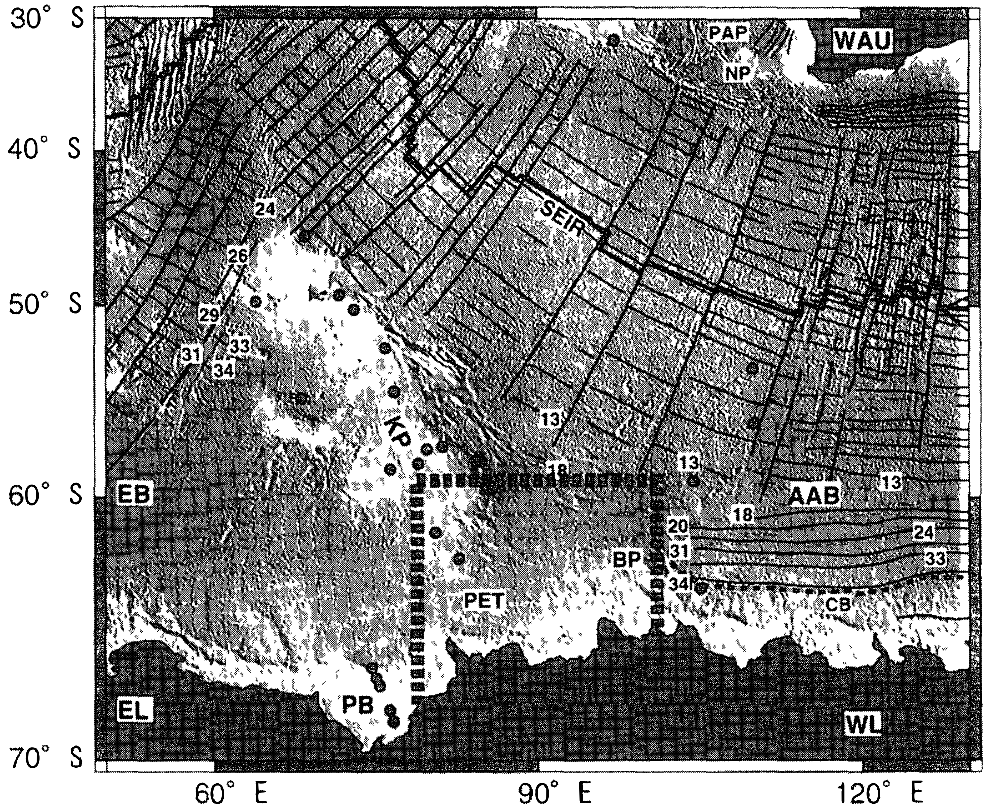

Fig 1 Tectonic setting of the TH98 survey area The box of thick broken lines shows the TH98 survey area Thin lines show the magnetic lineations and fracture zones, which are drawn using data of the NOAA National Geophysical Data Center (NGDC) Global Relief The topographic relief is drawn using the satellite altimetry by Smith and Sandwell (1992) Solid circles are the locations of drilling sites of ODP and DSDP AAB Australian-Antarctic Basin, BP Bruce Plateau, CB Continent-Ocean Boundary, EB Enderby Basin, EL Enderby Land, KP Kerguelen Plateau, NP Naturaliste Plateau, PAP Perth Abyssal Plain, PB Prytz Bay, PET Princess Elizabeth Trough, SEIR Southeast Indian Ridge, WAU Western Australia, WL Wilkes Land Numerals show anomaly numbers of magnetic lineation Many figures including this map were drawn with the Generic Mapping Tools (GMT) by Wessel and Smith (1991)

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, Tanahashi *et al* , 1997, 1998, 1999)

Figures 1 and 2 show a tectonic map and a topographic map of the survey area, respectively The survey area is located between the Australian-Antarctic Basin and the Enderby Basin The Kerguelen Plateau extends approximately 2500 km between 46°S and 64°S in the northwest-southwest direction as a basement anomaly on the Antarctic plate The Princess Elizabeth Trough extends between the Kerguelen Plateau and Antarctica The Bruce Plateau (Sproll and Dietz, 1969), which is located at the eastern part of the survey area, consists of folded sequences formed from Late Cretaceous to pre-Cretaceous time (Ishihara *et al* , 1996)

Powell *et al* (1988) discussed pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean According to their recon-

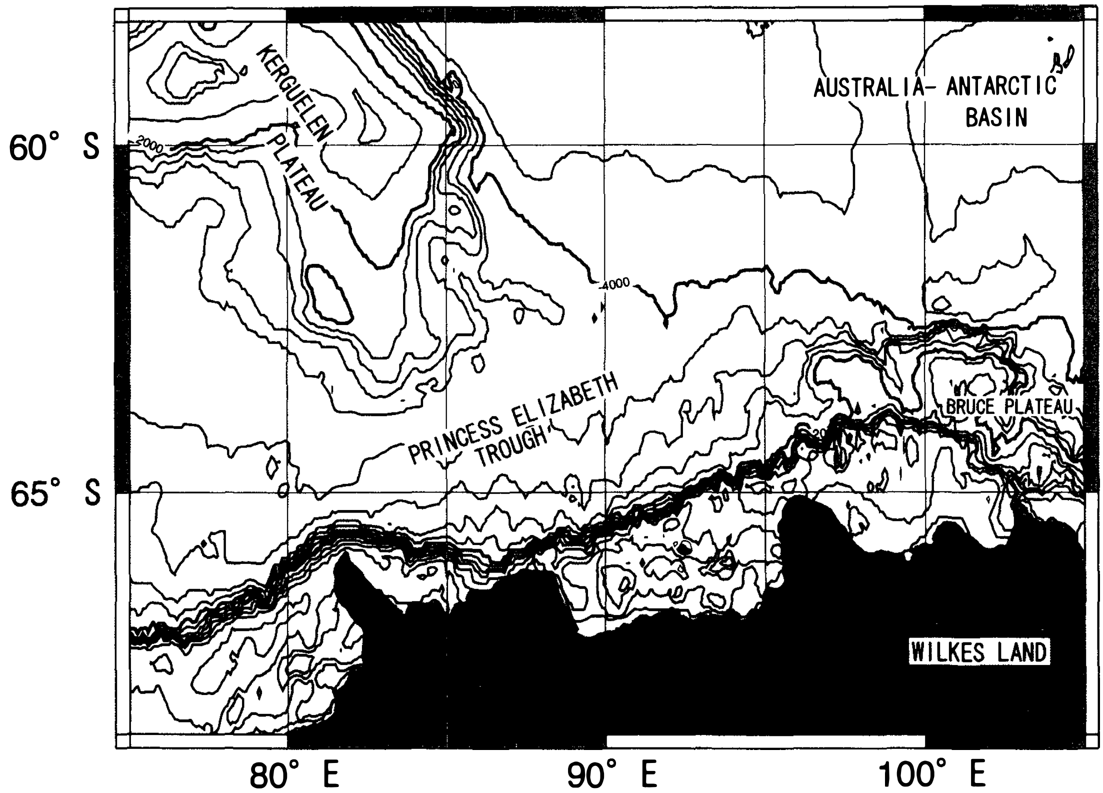

Fig 2 Topographic map of the TH98 survey area drawn using NOAA/NGDC ETOPO5 data. Contour interval is 400 m

struction maps, a triple junction of Australia-Antarctica-India existed in Late Jurassic time (about 160 Ma) The western to southwestern margin of Australia, associated with the triple junction, has been well studied by geophysical and geological methods It has been indicated that seafloor spreading between the western margin of Australia and India started at anomaly M 11 time (Leg 123 shipboard scientific party, 1989) The breakup between Australia and Antarctica occurred some time between 110 and 90 Ma (Cande and Mutter, 1982) On the Antarctic side, seismic reflection surveys have been carried out in Prytz Bay, Enderby Basin, and the western margin of Wilkes Land (Stagg, 1985, Mizukoshi *et al*, 1986, Tsumuraya *et al*, 1985, Ishihara *et al*, 1996) The former reconstruction map of East Gondwana showed that the Antarctic continental margin at around 100°E in longitude was close to the triple junction of Australia-Antarctica-India

In this area, structural and stratigraphic surveys with seismic reflection and refraction methods have not been carried out We surveyed this area using the geological and geophysical method to investigate the structure of sedimentary basins in the continental margin around 90°E in longitude, however, the survey was limited to the area of continental rise and abyssal plain because of obstruction by pack ice First, the preliminary results of this cruise are reported in this paper Second, we describe the seismic stratigraphy in Princess Elizabeth Trough and its vicinity, and discuss the geological times of seismic sequences

Table 1 Summary of the TH98 cruise

Survey period	35 days
Multichannel seismic reflection survey	2490 km
Seismic refraction survey	2 sites
Magnetic and gravity survey	19214 km
Heat flow measurement	6 sites
Gravity coring	7 sites
Dredging	1 site

Table 2 Summary of survey equipment and operating conditions

Survey	Instruments and specification
Multichannel seismic reflection	Source 16×S S I G-Guns (240 cu in each, total=4000 cu in)
	Receiver SYNTRACK 480-24 bit digital streamer cable 12 5×240 ch, cable length=3000 m 16 hydrophones in each section
Seismic refraction	Source 16×G-Guns (Concurrent with MCS)
	Receiver DTC-6030 digital Ocean Bottom Seismometer (three geophones with a hydrophone)
Gravity	Lacoste & Romberg SL-2 gravimeter
Magnetic	Geometrics G-866 proton magnetometer
	Tera Teknika three components shipboard magnetometer
Bottom sampling	Gravity corer and dredger
Heat flow measurement	Nichiyu Giken GS-type, six channels
	Thermal conductivity Kyoto Denshi QTM-D3 type

2. Outline of cruise and survey method

The marine geological and geophysical survey of the TH98 cruise was carried out from December 18, 1998 to December 31 and from January 20, 1999 to February 9 Data acquired during this cruise are summarized in Table 1 A summary of survey methods in TH98 cruise is outlined in Table 2

19214 km of gravity and magnetic data were obtained, and 2490 km of multi-channel seismic reflection data were recorded with 4000 in^3 G-guns and a 3000 m (240 channel) digital streamer cable An even shot interval of 24 s was used during the seismic survey Ship speed was maintained at about 4 4 knots, corresponding to about 50 m in the 24-s shot interval Three ocean bottom seismometers were laid on the seafloor along the 17SMG line OBS-1 and OBS-3 were recovered after the refraction seismic survey

All the reflection and refraction seismic data were processed by JAPEX/GeoScience Inc after the cruise Coverage of common depth point (CDP) in the reflection seismic processing was 3000%

3. Geological sampling and terrestrial heat flow measurements

3.1 Sea bottom samplings

Unconsolidated sediments were obtained by a gravity corer at seven sites (Fig 3) A dredger was used to collect rocks at the east slope of the southern Kerguelen Plateau The results of bottom samplings are summarized in Table 3 A micropaleontological study of the obtained samples was carried out.

3 1 1. Foraminiferal fossils

Planktonic foraminiferals are abundant in eighteen samples from GC1902, 1904, 1905 and 1906 The assemblages are monospecific of *Neogloboquadrina pachyderma*, which ranges in age from Pliocene to Holocene Two benthonic foraminiferal assemblages are recognized, *i.e*, 1) calcareous *Nuttallides umbonifer*, and 2) arenaceous *Martinottiella Antarctica-Cyclammina* spp

3 1 2 Diatom fossils

Diatom fossils are contained in all samples from seven cores obtained on this cruise Diatom fossils can be divided into three zones of assemblages based on the diatomaceous zonation of Akiba (1982), *i.e*, 1) *Nitzschia kerguelensis* Zone—Holocene to late Pleistocene (0 to 0 2 Ma), 2) *Hemidiscus karstenii* Zone—late Pleistocene (0 2 to 0 35 Ma), 3) *Rouxia isopolica* Zone—late Pleistocene (0 35 to 0 62 Ma) The assemblages of diatom fossils corresponding to all of the three zones are included in cores GC1902, 1903, 1904, 1905 and 1907, while core GC1906 contains only the upper two zones *Hemidiscus karstenii* is missing from core GC1901

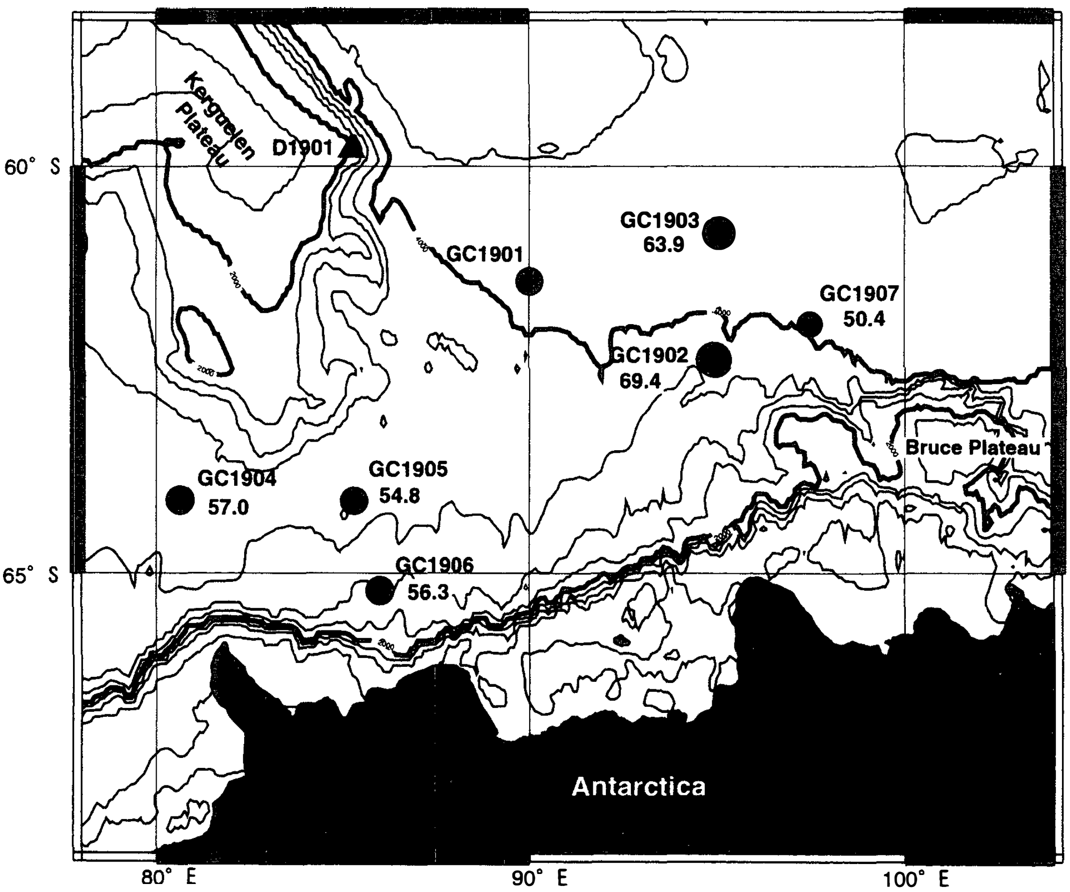

Fig 3 Locations of sea bottom samplings GC gravity core, D dredge, Numbers below GC core numbers show terrestrial heat flow values

Table 3 Summary of bottom sampling and heat flow measurements

Site	Lat (S)	Long (E)	Depth (m)	Recovery	Description	T C	H F
D1901	59°46′18″	85°13′48″	3193		Aplite, basalt, granite, diorite and gneiss		
	59°46′21″	85°07′08″	2480				
GC1901	61°29′38″	90°00′33″	4062	3 76	Siliceous clay intercalated with silty clay layers	0 845	
GC1902	62°28′36″	94°56′54″	3661	3 77	Siliceous clay scattered granule	0 904	69 38
GC1903	60°52′27″	95°04′54″	4281	2 85	Siliceous clay to siliceous ooze intercalated with silt to very fine sand layers	0 857	63 90
GC1904	64°09′41″	80°38′19″	3638	1 89	Clay intercalated sity clay layers to siliceous silty clay	1 087	57 04
GC1905	64°10′12″	85°18′22″	3655	3 82	Clay intercalated with very fine sandy silt to silt layers in the upper Siliceous silty clay in the lower	0 989	54 76
GC1906	65°11′54″	85°59′59″	2981	5 04	Clay with diatoms and radiolarians in the top and foraminifers in the bottom	1 034	56 28
GC1907	62°01′56″	97°29′16″	4105	4 49	Siliceous ooze in the upper and the lower Siliceous clay intercalated with coarse sand and sandy silt layers in the middle	0 903	50 41

Recovery Recovery length (m), T C Thermal conductivity (W/mk), H F Heat flow (mW/m²)

3 1 3 Radiolarian fossils

Seven cores from GC1901 to GC1907 contain similar Radiolarian assemblages, which are correlated to the *Antarctica denticulate* Zone This suggests that these cores range in age from the latest Pleistocene to Recent

3 2 Terrestrial heat flow measurements

Terrestrial heat flow data were obtained from the product of the geothermal gradient and the thermal conductivity of the sediments at six sampling sites from GC1902 to GC1907 by the gravity corer The geothermal gradient was measured during the sampling operation by six sensors installed at 80 cm intervals on the corer, while the thermal conductivity of the collected sediment samples was measured on board after the sampling operation

Heat flow values of 50 to 70 mW/m^2 were obtained (Fig 3) They are approximately equal to the world average value

4. Gravity and magnetic surveys

The relative gravity value measured by the onboard gravimeter was connected with the absolute gravity value at the port of Fremantle before and after the cruise Absolute gravity values on the sea were obtained after drift and Eotvos corrections Free-air gravity anomalies were calculated by subtracting normal gravity values based on IAG1967 from

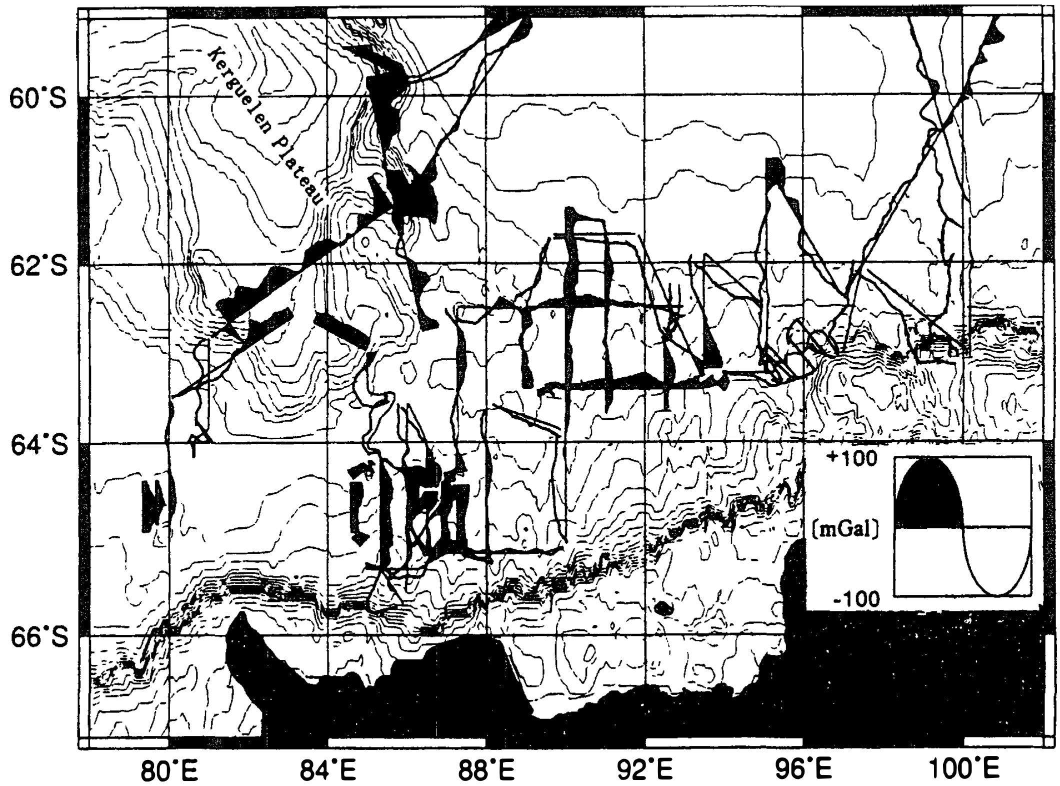

Fig 4 Free-air gravity anomaly profiles along the ship's track

the absolute values Profiles of Free-air gravity anomaly data along the track lines are shown in Fig 4 Relatively large positive anomalies correspond to the Kerguelen Plateau Positive anomalies are observed on the continental rise and the abyssal plain of the Princess Elizabeth Trough Negative anomalies are observed at the foot of the Kerguelen Plateau and in the basin around the Bruce Plateau

The magnetic anomaly value was obtained by subtracting the IGRF1995 reference field (IAGA Division V, Working Group 8, 1995) from the measured total magnetic field No correction was made for magnetic storms Figure 5 shows profiles of magnetic anomalies along the track lines Magnetic anomalies with large amplitude are observed on the Kerguelen Plateau Using magnetic anomaly data observed on this cruise and older available data, Ishihara *et al* (1999) recognized eastward or east-northeastward trending magnetic lineations on the abyssal plain in the Princess Elizabeth Trough They tentatively identified as anomalies M12 to M10 in the Mesozoic magnetic anomaly sequence

5. Seismic survey

5.1. Seismic refraction survey

A seismic refraction survey was carried out using ocean bottom seismometers (OBS) deployed at three sites along the seismic reflection survey line (17SMG) as shown in Fig 6 Two of the three OBS units, OBS1 and OBS3, were recovered Three components of seismometer and hydrophone data were recorded The hydrophone record section for

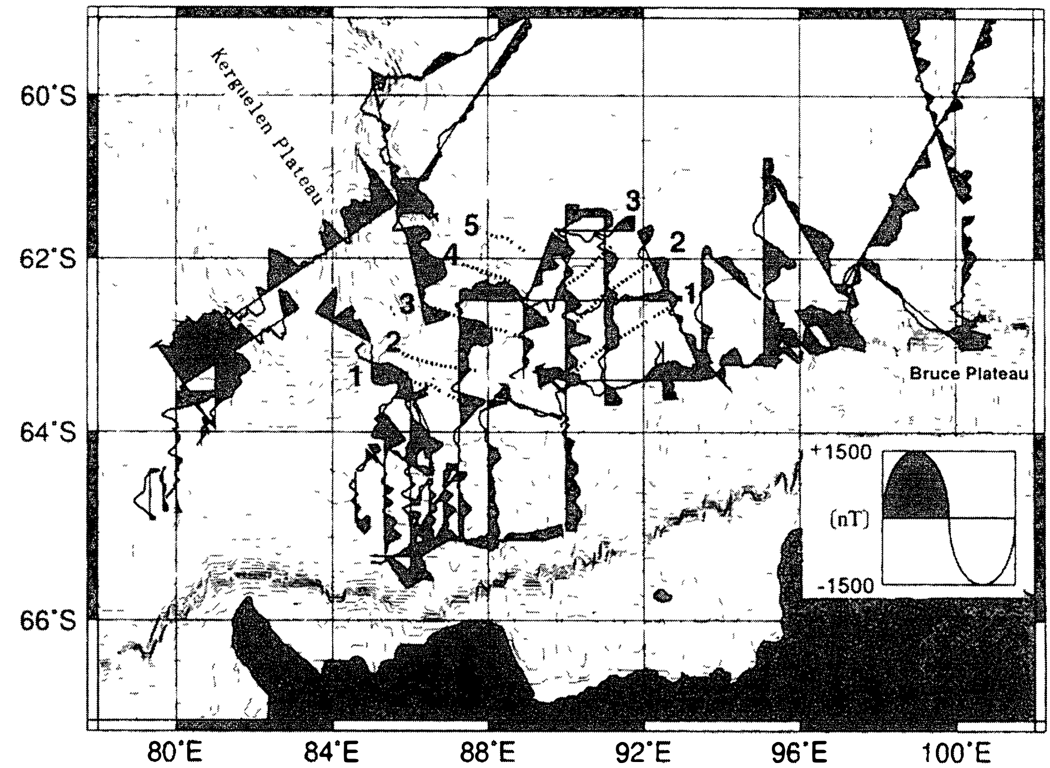

Fig 5 Magnetic anomaly profiles along the ship's track Dotted lines correspond to the location of magnetic lineations identified as magnetic anomalies M12 to M10 by Ishihara et al (1999) 1 M12, 2 M11A, 3 M11, 4 M10N, 5 M10

OBS3 is shown in Fig 7 as an example Velocities and layer thicknesses at the OBS1 and OBS3 sites were calculated from least square fits to the travel time data, assuming horizontal layering Velocity structures derived from the analysis are illustrated on the migrated depth section of reflection seismic profile 17SMG (Fig 8)

The velocity structure at the OBS-3 site is divided into four layers The layers with 1 63 to 4 64 km/s in velocity approximately correspond to the sequences A to E in the seismic reflection profile 17SMG described in Section 5 2 The lowest layer with velocity 5 65 km/s corresponds to an acoustic basement (sequence F) in the seismic reflection profile The velocity structure is different from it at the OBS site on the oceanic crust off western Wilkes Land (Ishihara *et al* , 1996) The velocity structure is similar to that in the magnetic quiet zone off southern Australia (Talwani *et al* , 1979, Finlayson *et al* , 1998)

5.2 Seismic reflection survey

Seismic reflection data were collected along 14 lines (Fig 6) They were processed according to a conventional seismic data processing flow Basic parameters and the processing sequence are shown in Table 4 In addition to conventional processing, time migration and depth conversion processing were carried out

5 2 1 Seismic sequences

We divided seismic sequences based on the existence of unconformity and difference of acoustic patterns Six seismic sequences, A, B, C, D, E, and F (acoustic basement), are

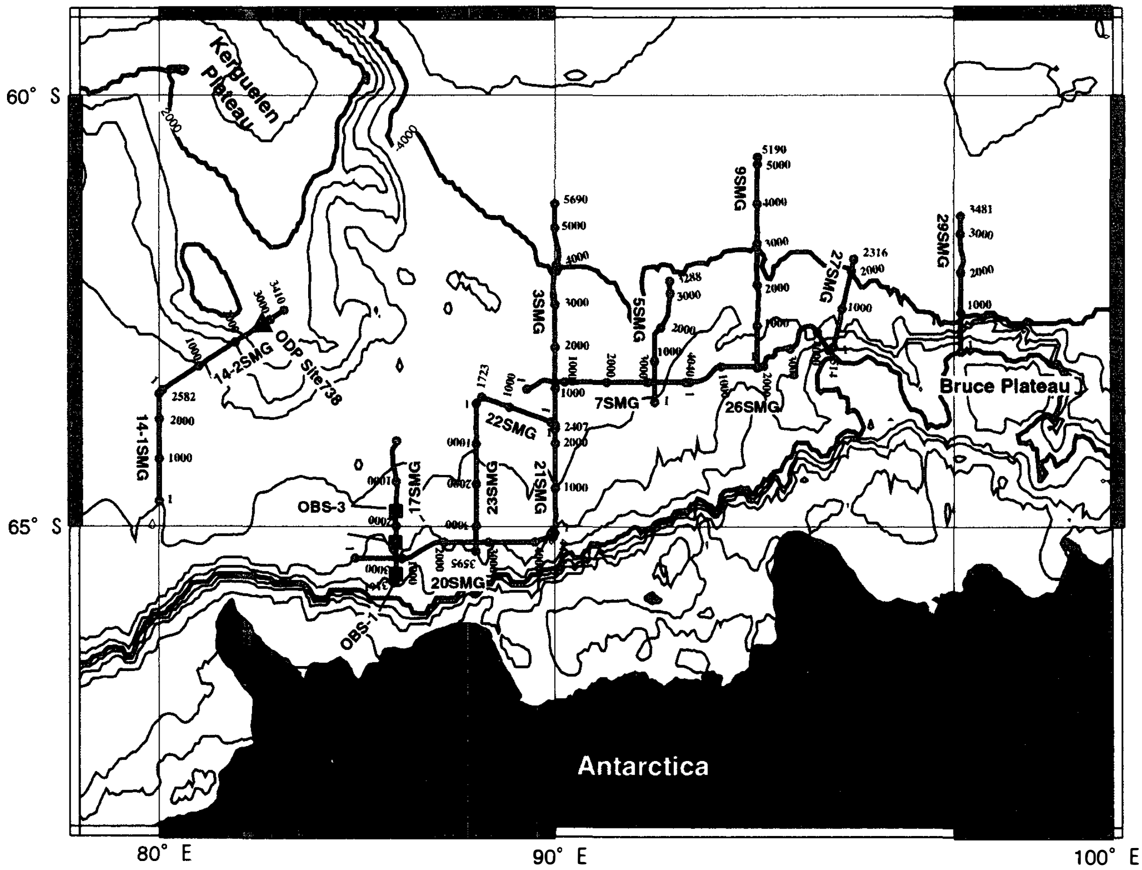

Fig 6 Lines of multichannel seismic reflection survey Solid squares show OBS sites

recognized from the top downward in Princess Elizabeth Trough and the northern basin of Bruce Plateau (Figs. 9a–h). On the Kerguelen Plateau, five seismic sequences, KP1, KP2, KP3, KP4 and KP5 (acoustic basement), are recognized (Fig 11) Seismic reflection patterns of the seismic sequences are summarized as follows The description of configuration patterns of reflectors in the seismic sequences is based on Mitchum *et al* (1977)

Sequence A is characterized by high amplitude reflectors with good continuity The sequence is well stratified and has parallel to subparallel configuration patterns on the lower continental rise and the abyssal plain (Fig 9a) The patterns suggest uniform rates of deposition on a stable basin plain (Mitchum *et al* , 1977) We interpret this to mean that sequence A mainly consists of turbidites and ice rafting sediments In contrast, the sequence has a complicated structure on the upper continental rise, where wavy, chaotic, and contorted patterns are recognized (Figs 9b and 9c) On the 20SMG profile, the reflectors are truncated in some places It is considered that the truncation occurred by erosion with development of submarine canyons, which are topographically recognized on the continental rise Some of the submarine canyons extend to the abyssal plain On the 17SMG profile, sediment mounds with a chaotic reflector pattern probably consist of slump sediments

Sequence B has subparallel to parallel configuration patterns with good to fair continuity and medium to low amplitude (Fig 9a) The low amplitude suggests that

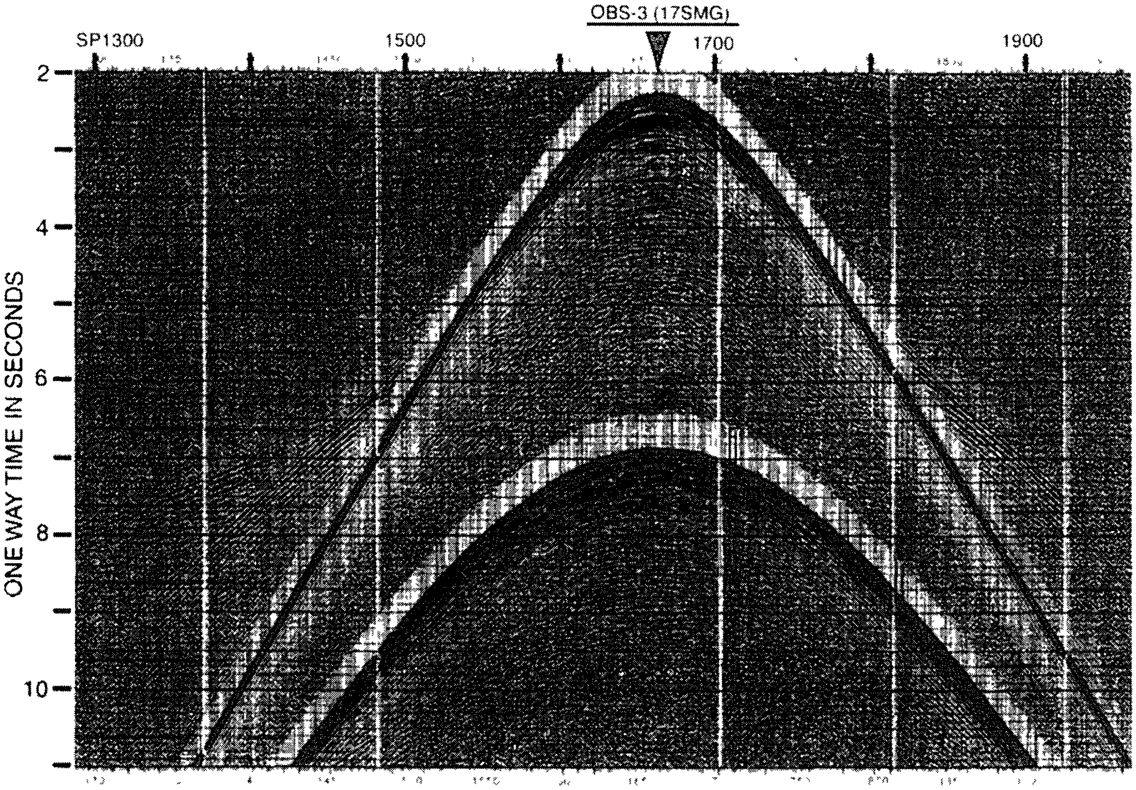

Fıg 7 Hydrophone record sectıon of OBS-3 on MCS lıne 17SMG

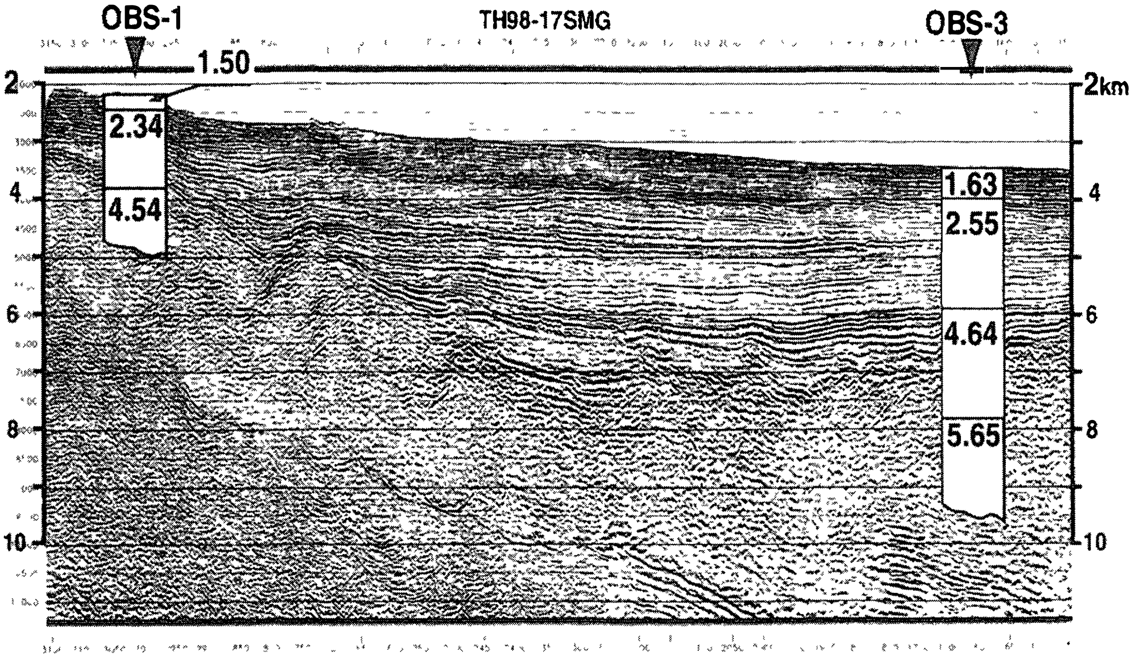

Fıg 8 Velocıty depth solutıons of seısmıc refractıon surveys, OBS-1 and OBS-3 along MCS lıne 17SMG The seısmıc reflectıon profile ıs a depth mıgratıon sectıon of 17SMG

Table 4 Basic parameters and sequence in processing of seismic reflection data

(1) Basic parameters in data processing	
Sampling rate	4 ms
Record length	9 5 s
Receiver channels	240 ch
Stacking folds	30
CDP interval	12 5 m
(2) Processing sequence	
1 Format conversion (SEG D to SEG Y)	
2 Trace edit	
3 CDP sort	
4 Prestack band-pass filter	
5 Minimum phase conversion	
6 First break suppression	
7 Amplitude recovery	
8 Prestack deconvolution	
9 Velocity analysis	
10 Normal moveout correction	
11 Mute	
12 CDP stack	
13 Poststack band-pass filter	
14 Datum correction	
15 Trace scaling	

sequence B consists of more homogeneous sediments than sequence A The unconformity between sequences A and B is well recognized on the continental rise (Figs 9b and 9c)

Sequence C has a subparallel configuration pattern with medium to fair continuity and medium amplitude (Fig 9a) Normal faults, which cut the acoustic basement, extend into sequence C on the abyssal plain (Fig. 9e) Sequence C onlaps sequence E (shown by an arrow in Fig 9f) to the south and the thickness increases to the north

A boundary reflector between sequences C and D is high amplitude and has good continuity Reflectors in sequence D have fair continuity and low amplitude (Fig 9g) Sequence D fills the lower sequences (E or F) unconformably The sequence is absent to the north, where it onlaps the lower sequence (Fig 9h), and to the south where it is obliterated by erosion

Sequence E has discontinuous reflectors with low amplitude The boundary reflector between the upper sequence and E has high amplitude and good continuity. The sequence unconformably fills faulted sequence F (Figs 9b, 9c, and 9f) The thickness of sequence E decreases to the north (Fig 9c) and is absent at approximately the foot of the continental rise (Figs 9f and 9g)

Sequence F is the acoustic basement and the top reflector has very high amplitude The bottom boundary of sequence F is not recognized Diffraction is observed in the upper part of sequence F (Figs 9a and 9b), suggesting that the surface of sequence F is irregular The sequence is highly cut by normal faults with northward dipping (Figs 9c and 9f) We estimated the pre-faulted topography of sequence F by shifting the fault blocks of F strata along the faults scarp (Fig 10) The estimated topography of sequence

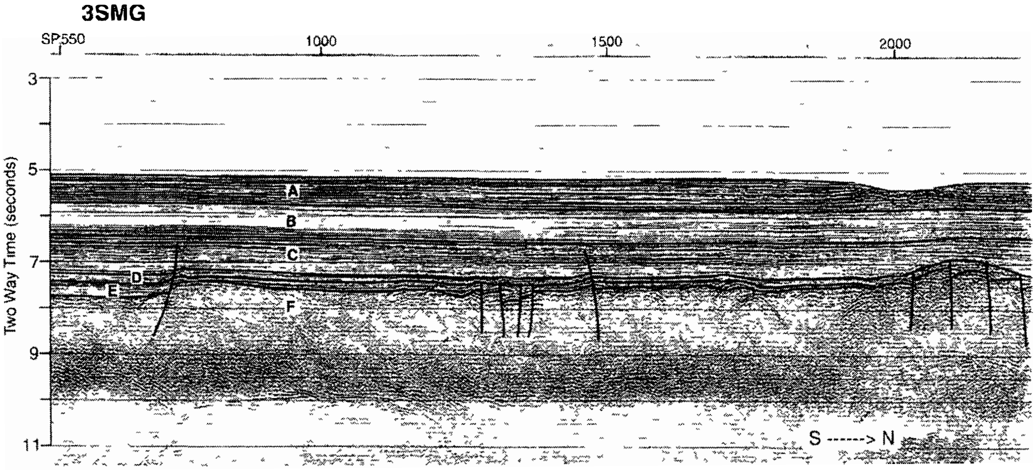

Fıg 9a Multıchannel seısmıc reflectıon profile wıth the ınterpretatıon of the southern part of lıne 3SMG (SP number 535 to 2230)

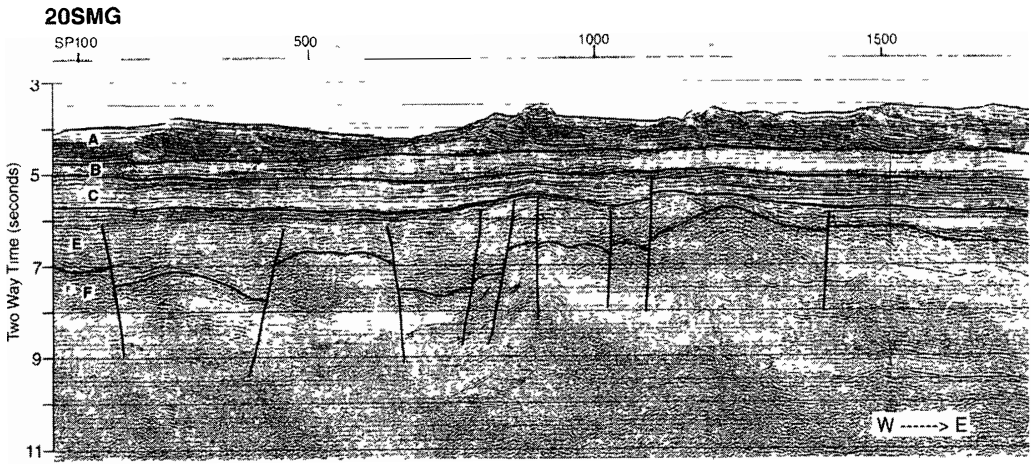

Fıg 9b Same as Fıg 9a except the western part of lıne 20SMG (SP number 60 to 1750)

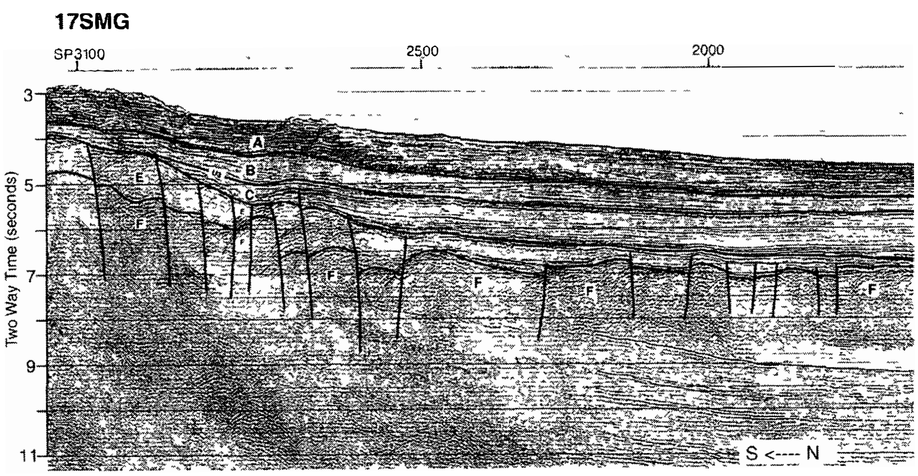

Fıg 9c Same as Fıg 9a except the southern part of lıne 17SMG (SP number 1650 to 3150)

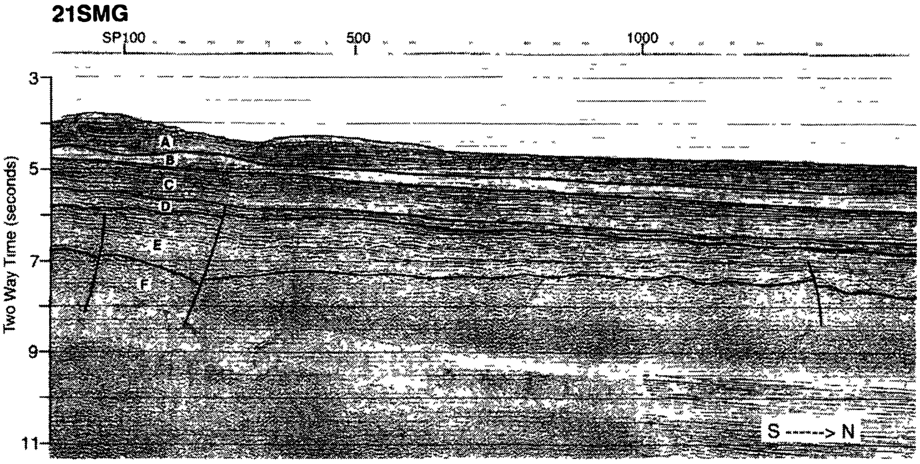

Fig 9d Same as Fig 9a except the southern part of line 21SMG (SP number 1 to 1470)

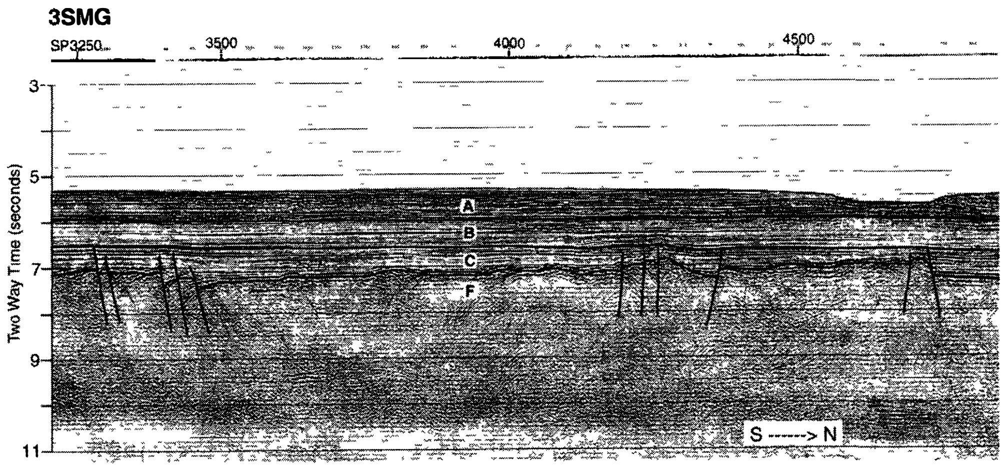

Fig 9e Same as Fig 9a except the northern part of line 3SMG (SP number 3210 to 4850)

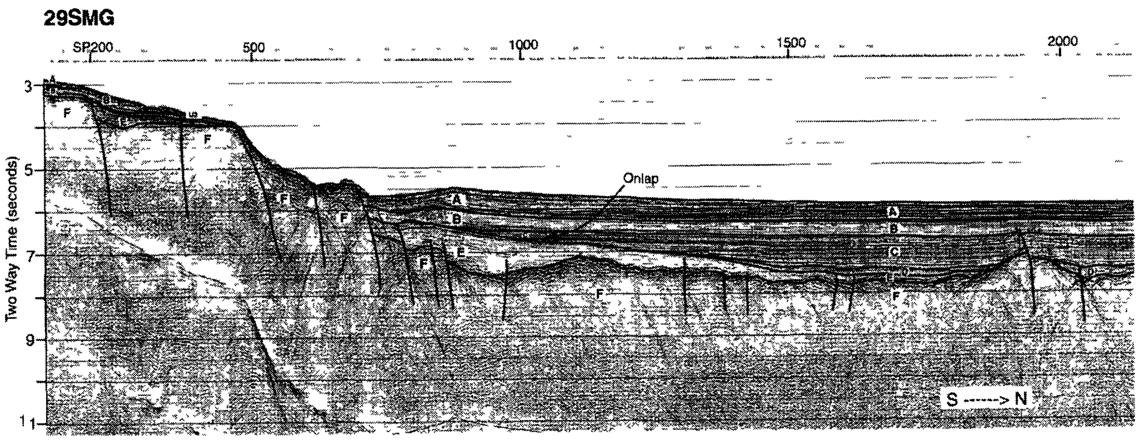

Fig 9f Same as Fig 9a except the southern part of line 29SMG (SP number 120 to 2130)

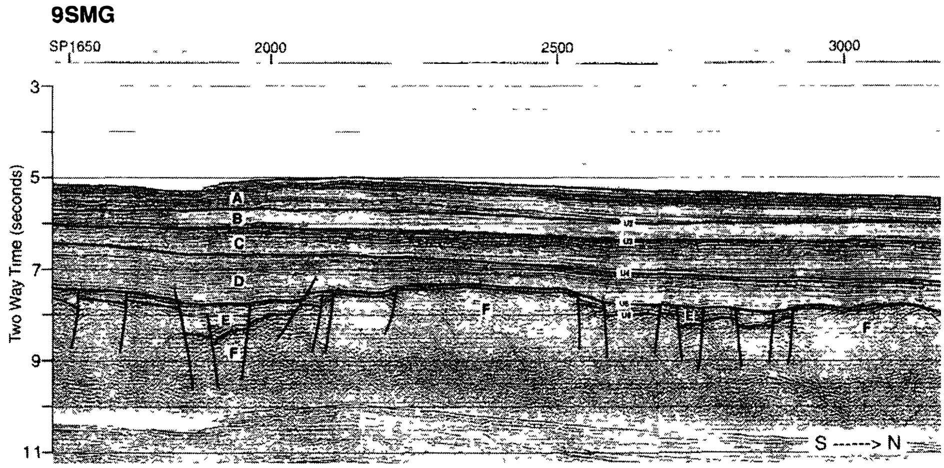

Fig 9g Same as Fig 9a except the central part of line 9SMG (SP number 1630 to 3170)

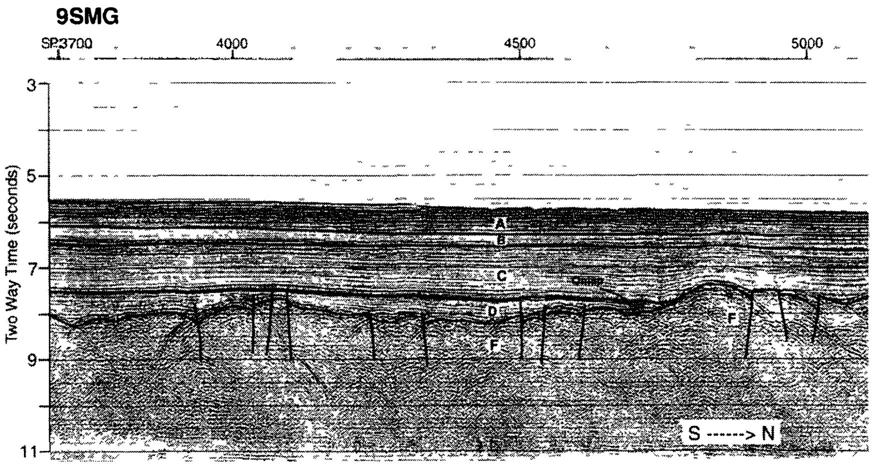

Fig 9h Same as Fig 9a except the northern part of line 9SMG (SP number 3690 to 5110)

F is rich in undulation

Five seismic sequences, KP1, KP2, KP3, KP4 and KP5 (acoustic basement), can be traced from the top downward on the southern Kerguelen Plateau (Fig 11) KP1 is very thin The reflectors in sequence KP2 have very low amplitude and the configuration pattern is similar to that of sequence B Sequence KP3 is thin, and the reflectors have high amplitude Sequence KP4 unconformably fills the faulted acoustic basement (KP5) Sequence KP5 undulates and is highly cut by faults, which extend into KP4

5 2 2 Distribution of seismic sequences

An isopack map of total thickness of sediments above the acoustic basement (sequence F) is shown in Fig 12 The thickness is less than 1 s on the Kerguelen Plateau and the Bruce Plateau The area of 2 to 3 s in thickness of sediments covers most of the southern part of Princess Elizabeth Trough

Sequences A and B are widely distributed in the surveyed area They are only absent, due to erosion, on the northern slope of the Bruce Plateau Sequence C is absent on the Bruce Plateau and in the shallowest area of seismic profile 17SMG It seems to be missing

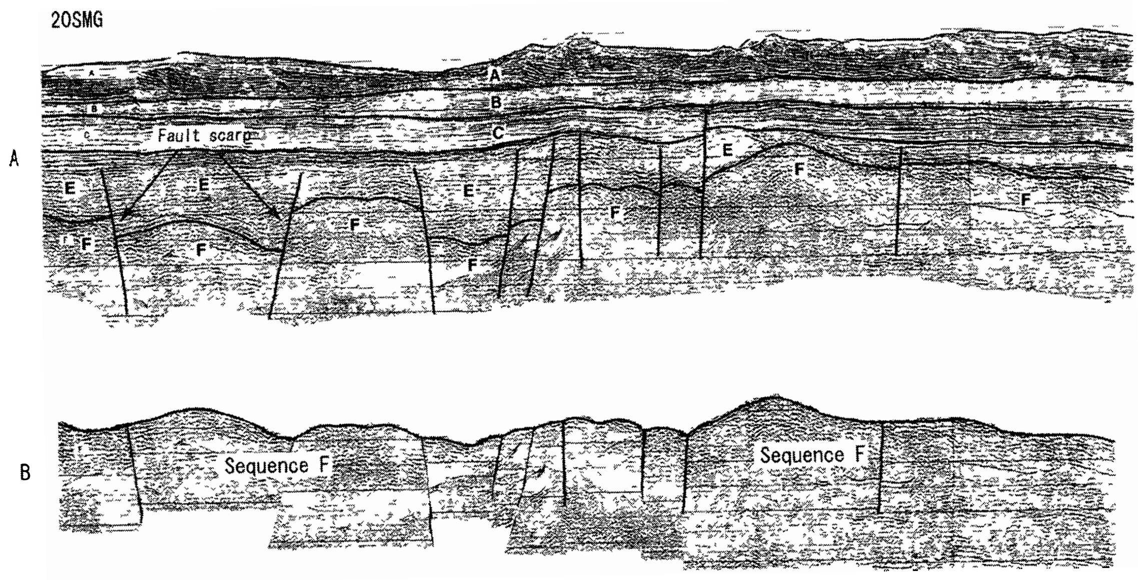

Fig 10a

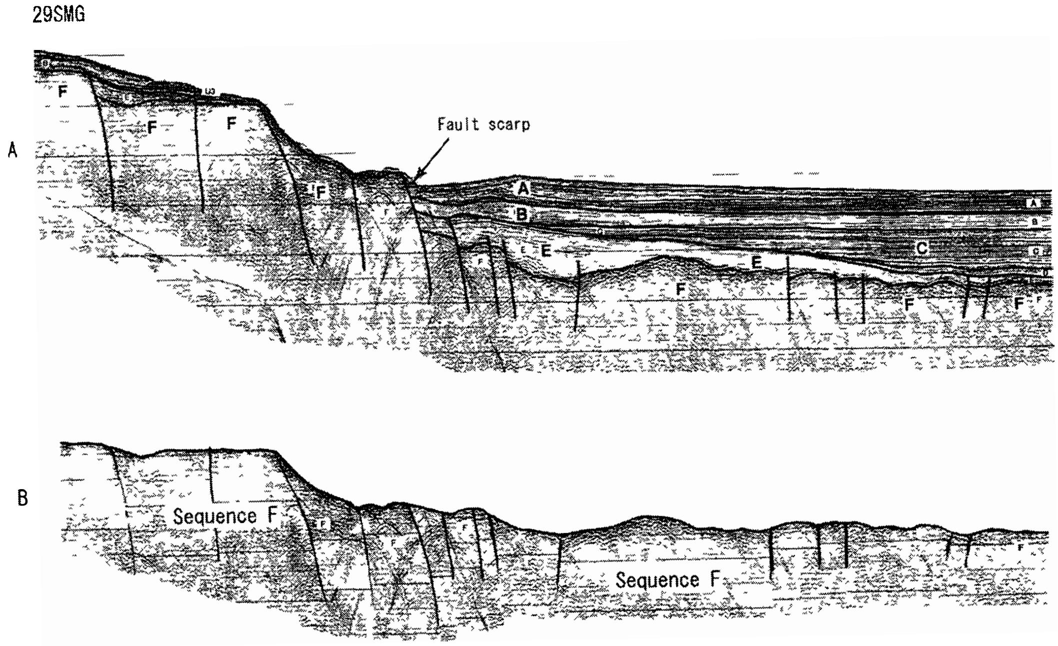

Fig 10b

Fig 10 Estimated reconstruction section of the topography of top of sequence F before rifting a reconstruction section along 20SMG, b reconstruction section along 29SMG In both sections, A is the present structure and B is the reconstruction section

in an area shallower than the continental slope The depositional and distributional features of sequence C suggest that the sequence was deposited during marine transgression The thickness of D is generally less than 0 4 s, but it exceeds 1 0 s in the area along 9SMG The area is probably the depositional center of the sequence The distributed area of sequences D and E is shown in Fig 13

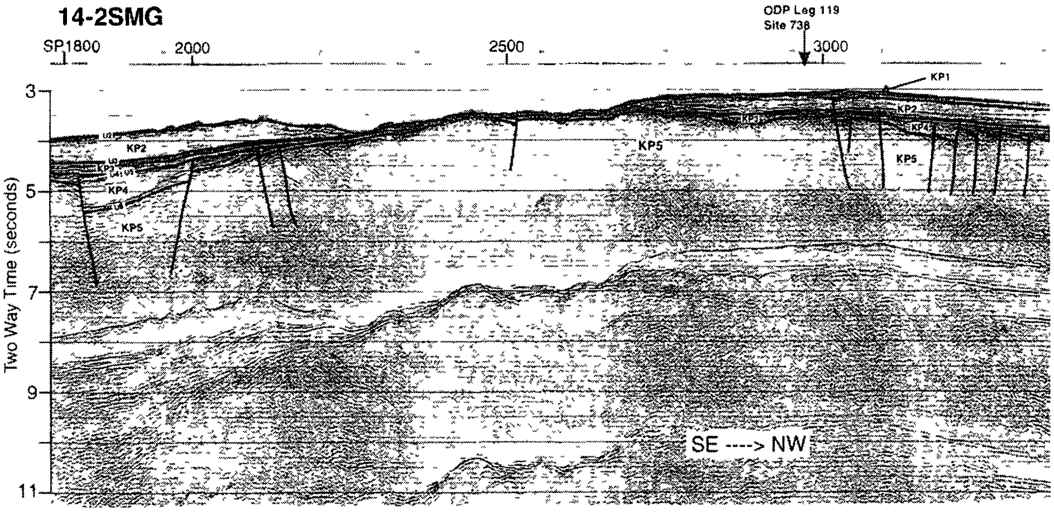

Fig 11 Same as Fig 9a except 14-2SMG (SP number 1780 to 3360) on the Kerguelen Plateau The location of ODP Site 738 is shown on the profile

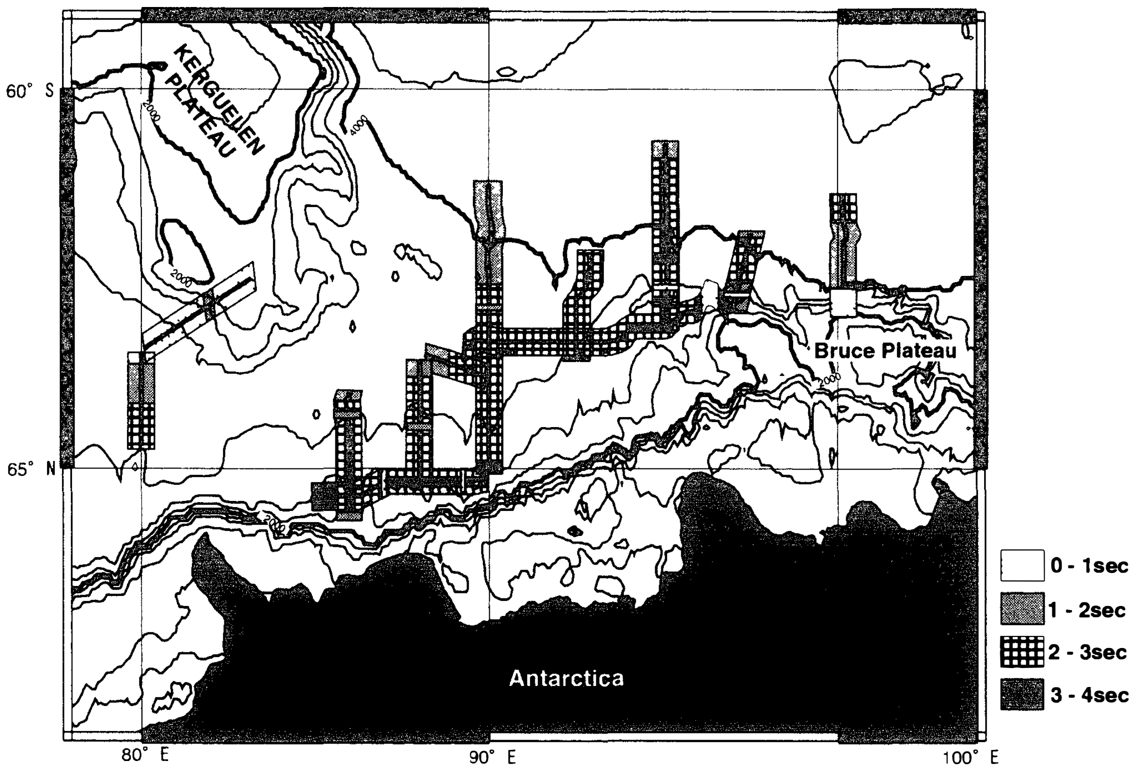

Fig 12 Total thickness of sediments in seconds of two-way time based on the multichannel reflection seismic survey

6. Discussion and conclusions

We discuss the geological time of seismic sequences and geological history of the surveyed area The seismic sequences observed on this cruise are only correlated with the drilling results at Site 738 of ODP Leg 119 on the southern Kerguelen Plateau Figure 14

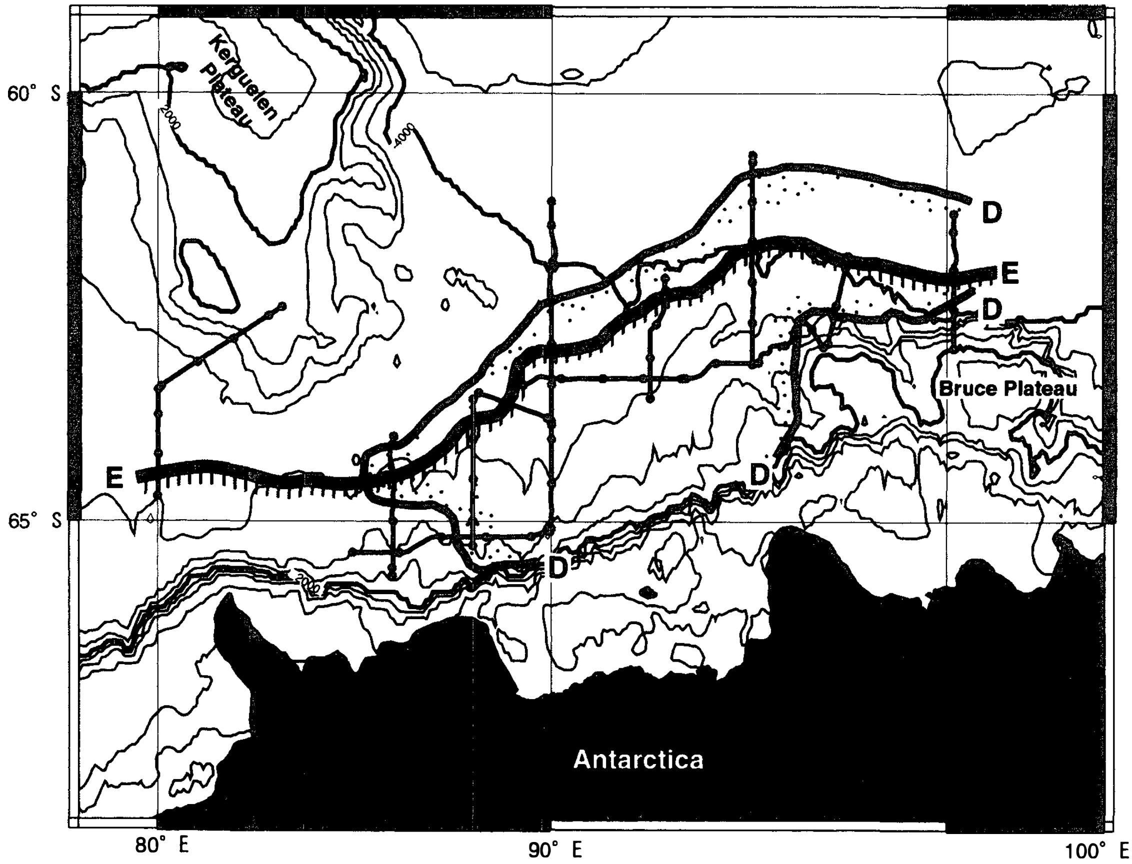

Fig 13 *Distribution area of the sequences D and the northern limit of the sedimentation of the sequence D-D with dotted area distributed area of the sequence D, E-E northern limit of the sedimentation of the sequence E*

shows the correlation between the seismic sequences of a part of 14-2SMG and the stratigraphic summary of Site 738 The acoustic basement KP5 is correlated with the lower Turonian or older basalts, which erupted sub-aerially (Shipboard Scientific Party, 1989) Sequence KP4 is absent at the location of Site 738 KP3 is correlated with sediments during early Turonian to early Eocene time The lowest part of the unit consists of calciclastic limestone, which was deposited in a shallow water environment Sequences KP2 and KP1 are correlated with sediments deposited during early Eocene to early Oligocene time and the late Miocene to Quaternary, respectively

The reconstruction map of East Gondwana at 160 Ma (Powell *et al* , 1988) shows that the location of the Antarctica-Australia-India triple junction approximately corresponds on the Bruce Plateau on the Antarctic side and the Naturaliste Plateau on the Australian side Seafloor spreading between Australia and India started at anomaly M11 time (134 Ma), and magnetic lineation, identified as anomalies M2 to M11, was observed on the Perth Abyssal Plain off southwestern Australia (Markl, 1974) Magnetic lineations in Princess Elizabeth Trough are identified as anomalies M12 to M10, which seem to correspond to magnetic lineations observed north of the Bruce Plateau (Ishihara *et al* , 1999) The conjugate fracture zones are recognized on both the Australian and Antarctic sides on the satellite derived Free-air gravity map (Tikku and Cande, 1999) The fracture zones trend

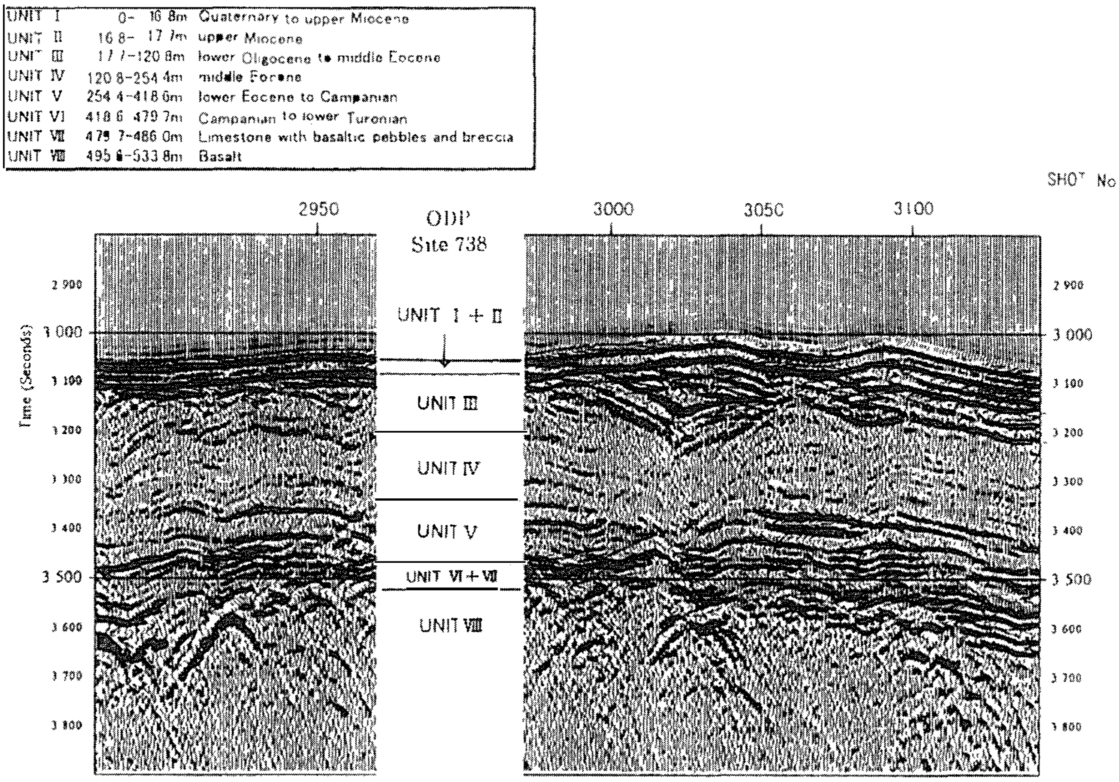

Fig 14 Multichannel seismic reflection profile of 14-2SMG over ODP Site 738 and stratigraphic summary of Site 738 based on Shipboard Scientific Party (1989)

NW-SE and are located southeast of the Naturaliste Plateau, and northeast of the Bruce Plateau, respectively These probably suggest that the Naturaliste Plateau is the conjugate one of the Bruce Plateau and oceanic crusts in Princess Elizabeth Trough and north of the Bruce Plateau were formed after the breakup between Antarctica and India in the Early Cretaceous

Rifted marginal basins were formed by continental extension in the margins of Antarctica and Australia prior to the breakup (Veevers and Eittreim, 1988) The highly faulted structures of sequence F on the continental rise (seismic profiles 17SMG and 29SMG) may be formed with continental extension during the rifting stage of East Gondwana The undulating topography of sequence F, which formed before the faulting, seems to be the erosional surface in the pre-rift stage According to the reconstruction of East Gondwana in the late Jurassic by Falvey and Mutter (1981), thick rift-phase sedimentary accumulations are shown in rift basins off western and southwestern Australia On the Antarctica-India side of East Gondwana, the deposition of rift-phase sediments probably also started in the late Jurassic From the above discussion, we interpreted the evidence to mean that sequence F on the continental rise is a pre-rift sequence and was deposited in late Jurassic or older time On the abyssal plain in Princess Elizabeth Trough, the existence of magnetic lineations suggests that sequence F on the abyssal plain consists of oceanic crusts and was formed in the Early Cretaceous, from the identification of the magnetic lineations The location of continent and ocean boundary (COB) is uncertain on our seismic profiles and magnetic anomaly data

Sequence E unconformably fills the rifted basin of sequence F. Normal faults cut sequence F and extend into sequence E. These suggest that sequence E consists of syn-rift sediments. The interpretation of magnetic profile data suggests that seafloor spreading between Antarctica and India started around 135 Ma in Princess Elizabeth Trough and north of the Bruce Plateau. The sedimentation time of sequence E is estimated to have been after the onset of rifting and before the onset of the seafloor spreading, which is during late Jurassic to Early Cretaceous time.

Sequence D fills sequences E and F unconformably, suggesting that the sequence consists of post-rift sediments. The distribution area of sequence D is not so wide and the thickness is about 0.3 s on average. It is considered that the depositional basin was a small area in the depositional period of sequence D. Results at Site 1136 (water depth, 1930 m) of ODP Leg 183 on the South Kerguelen Plateau suggest that the age of lavas underlain by shallow water sands and clays is close to 110 Ma, and the lavas erupted in sub-aerial condition (Shipboard Scientific Party, 2000). The formation of the Kerguelen Plateau by volcanic eruption may have prevented widening of the depositional basin. The same environment presumably continued until around the onset of breakup between Australia and Antarctica. These facts suggest that sequence D may have been deposited in the Early Cretaceous.

At Site 738 of ODP Leg 119 on the southern Kerguelen Plateau, the volcaniclastic rocks erupted by sub-aerial volcanism are overlain by Turonian limestone deposited in a shallow water environment. After the deposition of the limestone, the surface of the basaltic basement subsided about 2740 m during approximately 90 Ma to the present (Shipboard Scientific Party, 1989). It seems likely that the subsidence of the southern Kerguelen Plateau occurred under broad regional crustal subsidence, and sequence C was deposited during marine transgression associated with the regional crustal subsidence.

The unconformity and different reflection patterns between sequences C and B are interpreted as a result of deposition of both sequences in different environments. The spreading rate between Australia and Antarctica was very slow (4.5 mm/yr) during anomalies 34 to 19 and dramatically increased at anomaly 19 in the middle Eocene around 42 Ma (Cande and Mutter, 1982). In the sedimentary basins in and around the Princess Elizabeth Trough, the sedimentation environment was probably changed by the rapid widening of the gap between Australia and Antarctica, at an increasing spreading rate. The boundary between sequences C and B may be correlated with the change in the sedimentation environment. From the above discussions, we deduced that sequences C and B are correlated with sediments deposited during Late Cretaceous to middle Eocene time and sediments after the middle Eocene, respectively.

Sequences A and B on our seismic profiles are correlated with seismic sequences A and B reported by Ishihara *et al.* (1996) in the western part off Wilkes Land. The correlation between the seismic sequences by Ishihara *et al.* (1996) and lithologic units of DSDP Leg 28 Site 268 (Shipboard Scientific Party, 1975) shows that sequence A is correlated with the early Miocene to Quaternary sediments (Unit 1+2 in lithologic units at Site 268), and sequence B is correlated with the middle Oligocene to early Miocene sediments (Unit 3). In the late Oligocene, unrestricted Circum Antarctic circulation developed through the opened Drake Passage (Barker and Burrell, 1977). We deduced that sequences B and A are correlated with sediments during middle Eocene to early

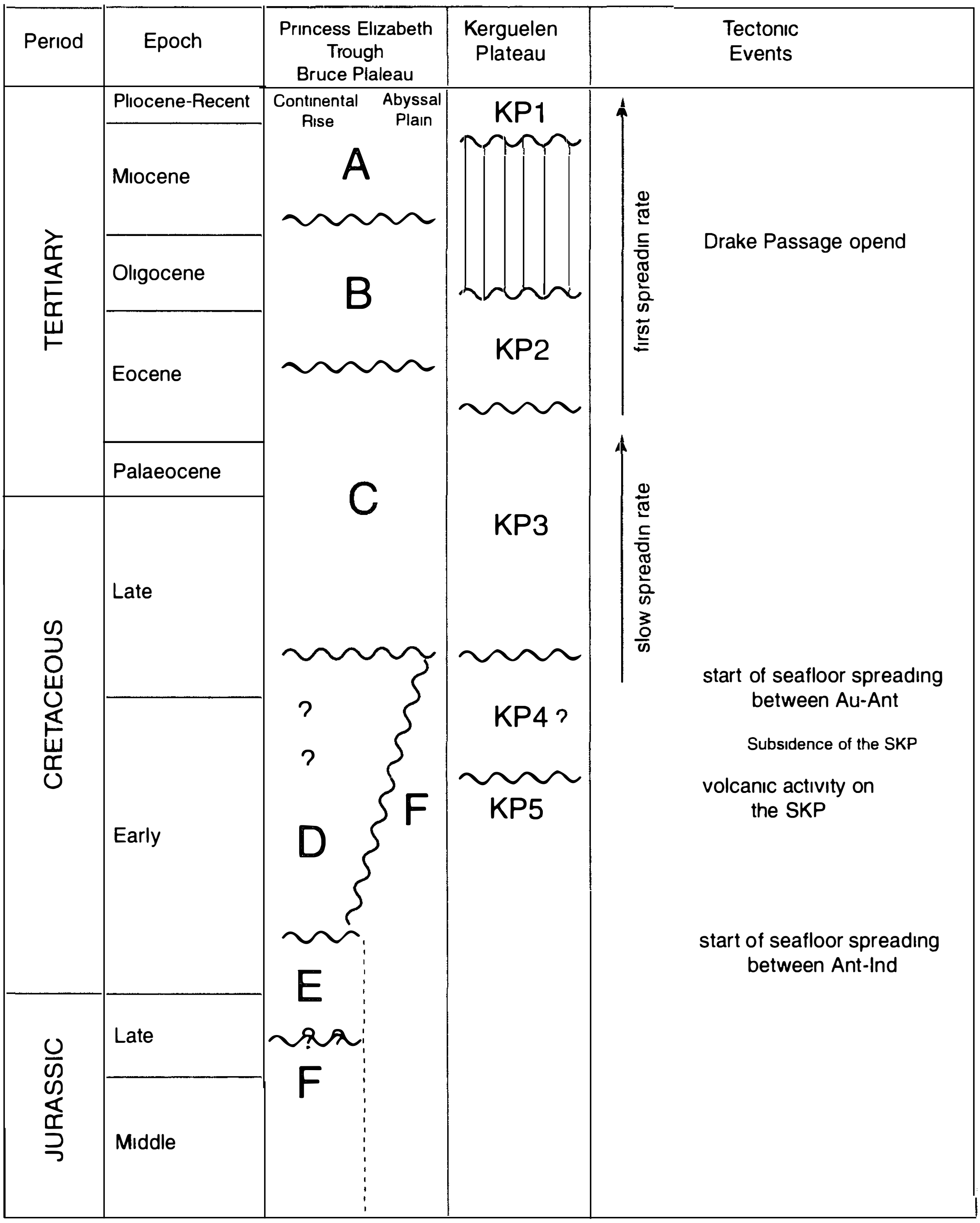

Fıg 15 Correlatıon summary between seısmıc sequences and geologıcal tıme, and relatıonshıp to tectonıc events Au Australıa, Ant Antarctıca, SKP the southern Kerguelen Plateau, Ind Indıa

Mıocene tıme and sedıments durıng early Mıocene to Quaternary tıme, respectıvely

In conclusıon, the geologıcal tımes of seısmıc sequences and tectonıc hıstory ın the Prıncess Elızabeth Trough and the northern part of the Bruce Plateau and on the Kerguelen Plateau are shown ın Fıg 15

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References

Akiba, F (1982) Late Quaternary diatom biostratigraphy of the Bellingshausen Sea, Antarctic Ocean Sekiyu Kôdan Sekiyu Kaihatsu Gijutsu Sentâ Kenkyu Hôkoku (Rep Tech Res Cent, J N O C), **16**, 31-74

Barker, P F and Burrell, J (1977) The opening of Drake Passage Mar Geol, **25**, 15-34

Cande, S C and Mutter, J C (1982) Revised identifications of the oldest seafloor spreading anomalies between Australia and Antarctica Earth Planet Sci Lett, **58**, 151-160

Falvey, D A and Mutter, J C (1981) Regional plate tectonics and the evolution of Australia's passive continental margin BMR J Aust Geol Geophys, **6**, 1-29

Finlayson, D M , Collins, C D N , Lukaszyk, I and Chudyk, E C (1998) A transect across Australia's southern margin in the Otway Basin region crustal architecture and the nature of rifting from wide-angle seismic profiling Tectonophysics, **288**, 177-189

IAGA Division V, Working Group 8 (1995) International geomagnetic reference field, 1995 revision J Geomagn Geoelectr, **47**, 1257-1261

Ishihara, T , Tanahashi, M , Sato, M and Okuda, Y (1996) Preliminary report of geophysical and geological surveys of the west Wilkes Land margin Proc NIPR Symp Antarct Geosci, **9**, 91-108

Ishihara, T , Oda, H and Murakami, F (1999) M-series magnetic anomalies in the Davis Sea, East Antarctica EOS, Trans, **80**, s94-95

Kimura, K (1982) Geological and geophysical survey in the Bellingshausen Basin, off Antarctica Nankyoku Shiryô (Antarct Rec), **75**, 12-24

Leg 123 shipboard scientific party (1989) The birth of the Indian Ocean Nature, **337**, 506-507

Markl, R G (1974) Evidence for the breakup of eastern Gondwanaland by the early Cretaceous Nature, **251**, 196-200

Mitchum, R M , Jr , Vail, P R and Sangree, J B (1977) Seismic stratigraphy and global changes of sea level, part 6 Stratigraphic interpretation of seismic reflection patterns in depositional sequences Mem, Am Assoc Pet Geol, **26**, 117-133

Mizukoshi, I , Sunouchi, H , Saki, T , Sato, S and Tanahashi, M (1986) Preliminary report of geological and geophysical surveys off Amery Ice Shelf, East Antarctica Mem Natl Inst Polar Res, Spec Issue, **43**, 48-61

Okuda, Y , Yamazaki, T , Sato, S , Saki, T and Oikawa, N (1983) Framework of the Weddell Basin inferred from the new geophysical data Mem Natl Inst Polar Res, Spec Issue, **28**, 93-114

Powell, C McA , Roots, S R and Veevers, J J (1988) Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean Tectonophysics, **155**, 261-283

Saki, T , Tamura, Y , Tokuhashi, S , Kodato, T , Mizukoshi, I and Amano, H (1987) Preliminary report of geological and geophysical surveys off Queen Maud Land, East Antarctica Proc NIPR Symp Antarct Geosci, **1**, 23-40

Sato, S , Asakura, N , Saki, T , Oikawa, N and Kaneda, Y (1984) Preliminary results of geological and geophysical surveys in the Ross Sea and in the Dumond d'Urville Sea, off Antarctica Mem Natl Inst Polar Res, Spec Issue, **33**, 66-92

Shimizu, S , Morishima, H and Tamura, Y (1989) Preliminary report of geophysical and geological surveys off the South Orkney Islands, Scotia Arc region Proc NIPR Symp Antarct Geosci , **3**, 52-64

Shipboard Scientific Party (1975) Site 268 Init Rep Deep Sea Drilling Proj , **28**, 153-177

Shipboard Scientific Party (1989) Site 738 Proc Ocean Drilling Prog , Init Rep , **119**, 229-288

Shipboard Scientific Party (2000) Site 1136 Proc Ocean Drilling Prog , Init Rep , **183** (in press)

Smith, W H F and Sandwell, D T (1992) Charting the remote southern oceans with satellite altimetry and shipboard bathymetry EOS, Trans , **73**, 85

Sproll, W P and Dietz, R S (1969) Morphological continental drift fit of Australia and Antarctica Nature, **222**, 345-348

Stagg, H M J (1985) The structure and origin of Prytz Bay and Macrobertson Shelf, east Antarctica Tectonophysics, **114**, 315-340

Talwani, M , Mutter, J , Houtz, R and Konig, M (1979) The crustal structure and evolution of the area underlying the magnetic quiet zone on the margin south of Australia Mem , Am Assoc Pet Geol , **29**, 151-175

Tanahashi, M , Ishihara, T , Yuasa, M , Murakami, F and Nishimura, A (1997) Preliminary report of the TH95 geological and geophysical survey results in the Ross Sea and Dumont d'Urville Sea Proc NIPR Symp Antarct Geosci , **10**, 36-58

Tanahashi, M , Matsuyama, T , Tokuhashi, S and Oda, H (1998) Preliminary report of the TH96 geological and geophysical survey results in Bransfield Strait and its vicinity Polar Geosci , **11**, 90-111

Tanahashi, M , Nisimura, A , Oda, H and Murakami, F (1999) Preliminary report of the TH97 geological and geophysical survey results, north of the Antarctic Peninsula Polar Geosci , **12**, 192-214

Tikku, A A and Cande, S C (1999) The oldest magnetic anomalies in the Australian-Antarctic Basin Are they isochrones ? J Geophys Res , **104**, 661-677

Tsumuraya, Y , Tanahashi, M , Saki, T , Machihara, T and Asakura, N (1985) Preliminary report of the marine geophysical and geological surveys off Wilkes Land, Antarctica in 1983-1984 Mem Natl Inst Polar Res , Spec Issue, **37**, 48-62

Veevers, J J and Eittreim, S L (1988) Reconstruction of Antarctica and Australia at breakup (95$\pm$5 Ma) and before rifting (160 Ma) Aust J Earth Sci , **35**, 355-362

Wessel, P and Smith, W F (1991) Free software helps map and display data EOS, Trans , **72**, 441 & 445-446

Yamaguchi, K , Tamura, Y , Mizukoshi, I and Tsuru, T (1988) Preliminary report of geophysical and geological surveys in the Amundsen Sea, West Antarctica Proc NIPR Symp Antarct Geosci , **2**, 55-67

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