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Tectonic Evolution of the Antarctic Peninsula Area in Cenozoic

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Abstract: Marine geophysical and geological investigation in Bransfield Strait by the Guangzhou Marine Geological Survey, Ministry of Geology and Mineral Resources, P.P. China in 1991 have revealed the complex geological evolution and structure of the Bransfield Strait area. The Bransfield Trough, within Bransfield Strait, has an asymmetrical profile with a steeper slope along the northwestern margin. The reflections can be divided into two reflective sequences by the T_6 reflection, representing that the Cenozoic sediments can be divided into two sedimentary sequences. The unconformity reflection T_g and T_6 represent two rifting events, named the first and second rifting events.

According to the magnetic lineations in the southeast Pacific Ocean, the results studied by scientists and our survey results, we propose a model of tectonic evolution in the area, as a series of collisions of ridge-crest with subducting trench, and lead to the subducting rate of oceanic plate becomed slow, the rifting events appeared behind the subduction zone. These events have produced the Bransfield Strait and Trough.

Key words: magnetic lineation, seismic reflection, half-graben rifting event.

INTRODUCTION

We undertook geological and geophysical survey in Bransfield Strait from Januray 1 to Feburary 25, 1991 with our survey ship Ocean IV. About 4,622.5 km gravity, 2,925 km multi-channel seismic reflection, 2 sonobuoy stations and 43 geological core samples were collected there.

We prepared 48 channel seismic system before, but the seismic streamer was broken in the cold water. Therefore, we had to do 9 channel seismic work with another streamer. The source was the Chinese EH-4 air guns consisting of an array of six guns, with 24.4 liters total volume and 2000 PSI air pressure. The seismic instrument is the DFS-4 with 48 recording channels. The seismic data were processed in our computer system.

The REF TEK-1 low band sonobuoy made by Refraction Technology INC and Raython 12 kHz bathymetric system for echo-sounding were operated during the survey.

In addition, the KSS-5 system made in Germany was used for the gravity survey, and the G801G magnetometer made in USA was used for the magnetic survey. We calculated the survey error that the square root error of gravity in the crossing lines is 2,24 mGal, and 55 nT for the magnetic survey. The survey lines and core stations are showing in Figure 1.

REGIONAL GEOLOGICAL SETTING

As shown by several authors (Dalziel, 1983: Dott *et al.* 1982, Farquarsin, 1982: Forsyth, 1982; Herron *et al.*, 1979; Thomson *et al.*, 1983; Elliot, 1983; Saunders and Tarney, 1982), the geology of the Antarctic Peninsula bears many similarities to that southernmost South America. The plate reconstructions (Lawer and Scotese, 1987; Dalziel, 1983; Barker, 1976; De Wit, 1977) indicated that an active magmatic arc continuously extented from the Andes to the Antarctic Peninsula. This arc was active at least since the Traissic (Smellie and

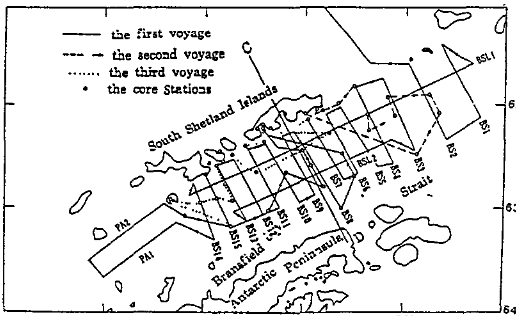

Fig. 1. The survey lines and stations of HY4-901 cruise in Bransfield Stait in 1991.

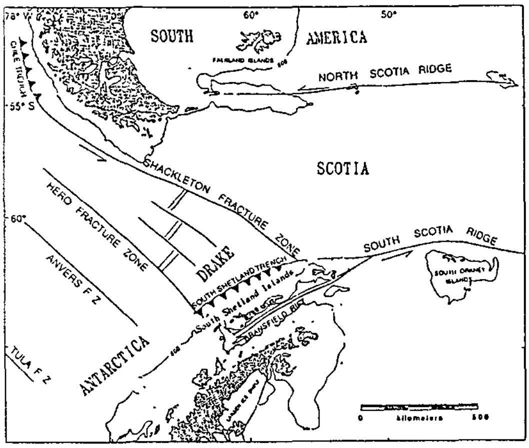

Fig. 2. The geological map of the Scotia Arc region.

Clakson, 1975; Storrey and Carrent, 1985; Thomson *et al.*, 1983). The opening of Drake Passage and the formation of the Scotia Arc isolated the Antarctic continent and the South America after Oligocene (Barker and Burrell, 1977; Barker, 1982).

The evolution history of the western margin of the Antarctic Peninsula has previously been inferred primarily from studies of the magnetic anomalies in the adjacent ocean floor (Herron and Hucholke, 1976; Herron *et al.*, 1981; Barker, 1982; Larter and Barker, 1991). These studies indicate that the Bellingshausen continental margin, to the south of the South Shetland Islands, evolved from an active margin with subduction zone into an inactive margin. The deep sea trench that is visible in front of the South Shetland Islands, is not present along the Bellingshausen continental margin (Fig. 2). Geological and geophysical evidences indicate that the South Shetland Islands were originally a part of the Antarctic Peninsula before the formation of Bransfield Strait (Ashcrot, 1972; Davey, 1972; Barker, 1970; Thomson *et al.*, 1983). A magmatic island arc has existed in the region since the Jurassic. Until the formation of Bransfield Strait, the arc was situated on the Antarctic Peninsula. The Bransfield Strait separates the South Shetland Islands to the present location of the volcanic arc from the Antarctic Peninsula. The age of formation of Bransfield Strait is debated. Existing hypotheses suggest that either the Bransfield Basin was formed less 4 Ma (Barker, 1982, Storey and Garrentt, 1985; Gonzalez-Ferran, 1985; Barker *et al.*, 1991) or the Basin should be as old as Miocene or Oligocene (Gamboa and Maldonado, 1990; Yao and Wang, 1995).

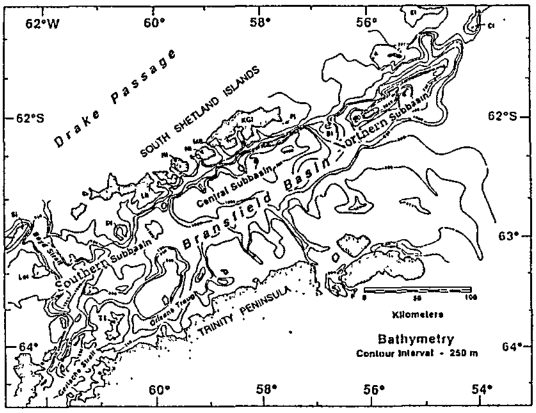

Fig. 3. Bathymetry of the Bransfield Basin, showing locations of western, central, and eastern sub-basins. Contour interval 250 meters. BI = Bridgeman Island, CI = Clarence Island, DI = Deception Island, EI = Elephant Island, KGI = King George Island, LiI = Livingston Island, LoI = Low Island, MB = Maxwell Bay, NI = Nelson Island, PI = Penguin Island, RI = Robert Island, SI = Smith Island, TI = Trinity Island.

TOPOGRAPHY AND GEOMORPHOLOGY

The Bransfield Trough is a deep asymmetrical trough, trending northest-southwest, composing of three separate subtroughs: the north, central and south trough (Fig. 3). The relatively shallow, irregularly shaped southern trough locating south and west of Livingston and Deception Islands trends

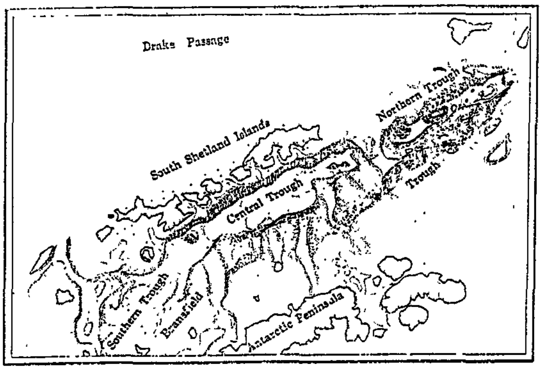

Fig. 4. The geomorphology map of the Bransfield Srait.

northeast-southwest towards the Gerlache Strait and also branches northwestwards trough Boyd Strait. The abrupt northestwards deepening of the trough from 900 m to 1,300 m, marks the eastern limit of the southern trough (Jeffers and Anderson, 1990).

The cetral trough lies south of Robert, Nelson, and King Geoge Islands, and extends northeastwards to a bathymetric divide associated with the Birdgeman Island, it is bounded to the northwest by the steep slope of the South Shetland Islands, which is incised by troughs in the slope. The gradient of the South Shetland Islands slope is 64-194 × 10^{-3}(4°50′-10°54′). Four troughs aligned perpendicular to the axis of the central trough cut into the shallow shelf of the Antarctic Peninsula to the depth of 760 m. The U-shaped cross-sectional profiles of these troughs suggest that they are glacially carved features but their orientation may be structurally controlled. The gradient of the Antarctic Peninsula slope is 38-81 ×10^{-3}(2°10′-4°40′). The shelf break occurs at about 250 m. The bathymetric highs falling on a line connecting Deception and Bridgeman Islands appear to be submarine volcanoes associated with back arc extension in the central trough.

The northern trough, extending northeastwards from Bridgeman Island to Elephant and Clarence Islands, is narrower and deeper than the central trough and reaches to the depth of 2,784 m. Several seamounts may be an extension of the line of submarine volcanoes in the central trough.

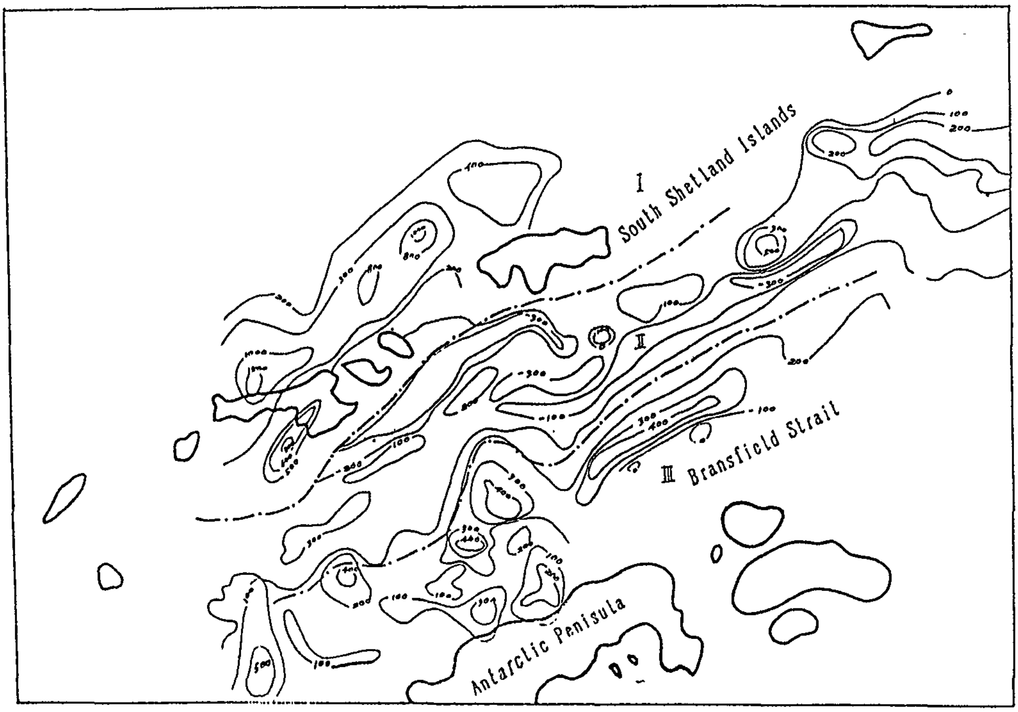

Fig. 5. The magnetic anomaly map of the Bransfield Strait. I. the South Shetland Islands anomaly area. II. the Bransfield anomaly area. III. the Antarctic Peninsula Shelf anomaly area. The unit is nT.

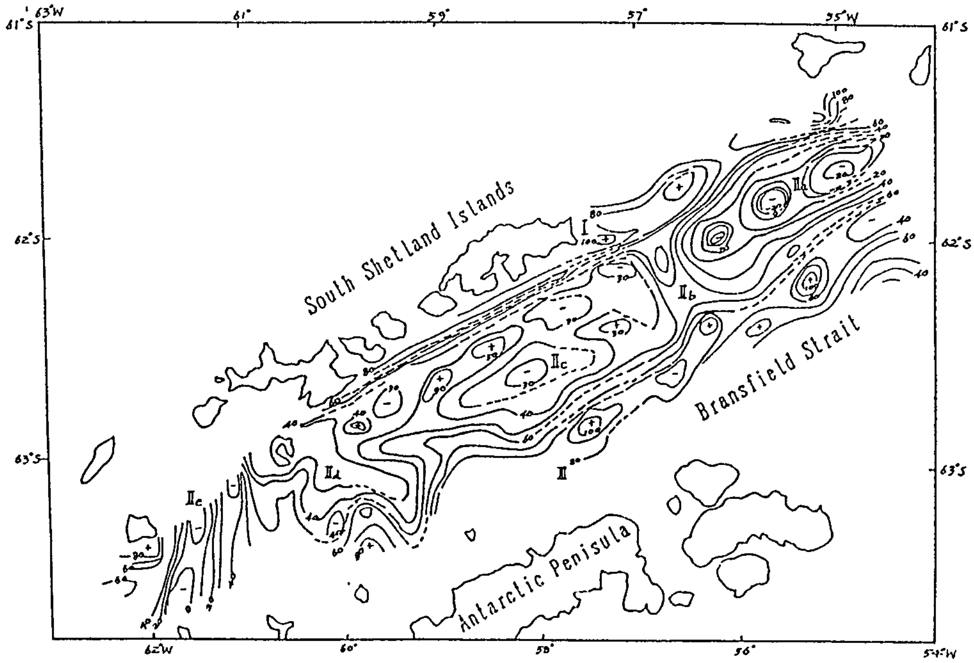

Fig. 6. The free-air gravity anomaly map in the Bransfield Strait. I. the South Shetland Islands anomaly area. II. the Bransfield anomaly area. III. the Antarctic Peninsula Shelf anomaly area. The unit is mGal.

THE CHARACTERISTICS OF GEOPHYSICAL FIELD

The magnetic anomalies in the Bransfield Strait area can be subdivided into three areas (Fig. 5): South Shetland Block anomaly area, Bransfield Trough anomaly area and Bransfield shelf anomaly area. In the Bransfield shelf (Antarctic Peninsula shelf) anomaly area, the magnetic anomaly is positive, the value is 100-400 nT. In the Bransfield Trough anomaly area, the magnetic anomaly is negtive, with –300 nT average anomaly value. However, positive anomalies still cross some seamounts in Bransfield Trough, and it's velue is 200-900 nT. This kind of phenomenon can reflect that the seamounts are younger volcanoes than the basement, because there is a negative anomaly area which reflects the characteristics of the basement. In the South Shetlend Islands there is the South Shetland Block anomaly area. The magnetic anomaly is positive with 300-1,000 nT value. It reveals the magnetic anomaly of oceanic cruct.

The free-air gravity anomaly in Bransfield Srait trends NE direction (Fig. 6), parallel to the Islands, Trough and Peninsula. In the South Shetland Trench there is a negative zone with the value of –20~–120 mGal. In the South Shetland Islands there is a positive anomaly zone with 60-90 mGal. The anomalies in Bransfield Strait vary from -30.8 mGal to 12 mGal. In the northwestern side of the Strait the horizonal gradient of gravity anomaly is 5 mGal/km, and the maximum is 9.6 mGal/km. In the Antarctic Peninsula shelf the anomaly is 60-90 mGal, gentle gradient of 3.2 mGal/km. In the Bransfield Trough the gravity anomaly is low, which can be divided into three areas by Bridgeman Rise (IIb): the northern trough (IIa), the central trough (IIc), and southern trough (IIe). In the northern trough the anomaly is –30~50 mGal. In the central and southern troughs the anomaly is 34 mGal.

According to the analysis there are three anomaly areas in Bransfield Strait. Between South Shetland Islands high anomaly area, Bransfield Strait low anomaly area and Antarctic Peninsula Shelf high anomaly area, there are gravity step zones where the gravity step is steeper in the northwestern of Bransfield Trough. Therefore, the gravity anomalies across Bransfield Strait is asymmetric.

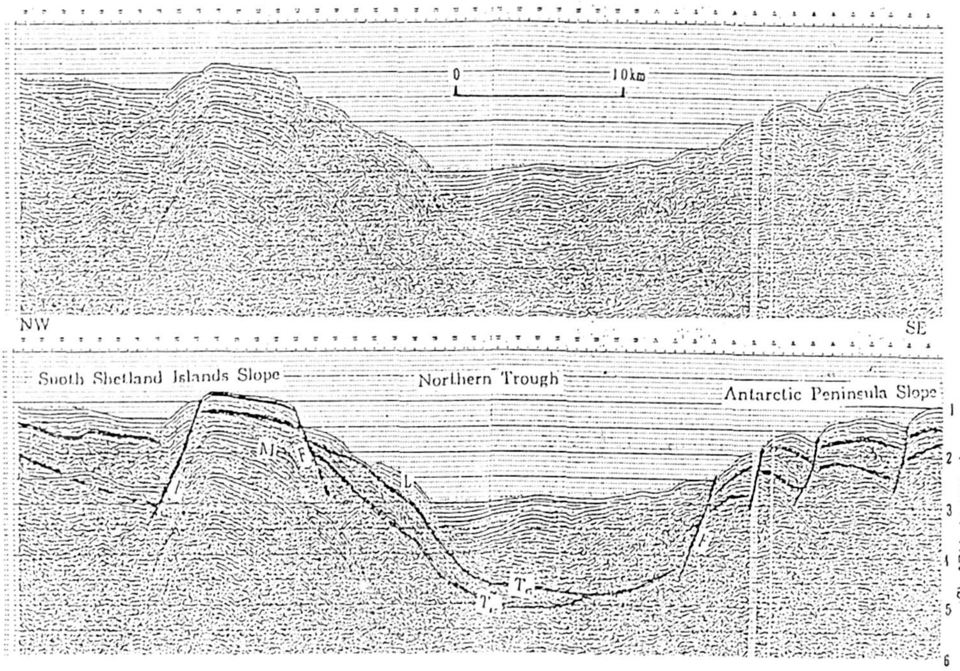

Fig. 7. The seismic profile of BS-1 crossing the northern trough. The F is the fault, the L is the landside.

INTERPRETATION OF SEISMIC PROFILES

The survey lines in the Bransfield Strait trend 333°, perpendicular to the regional tectonics (Fig. 1). The vertical resolution of the seismic profiles is medium about 80-200 m (Yao and Wang, 1995). The BS-1 (Fig. 7) crosses the north trough. In the Figure 7 we can see that the north trough is about 20 km wide. On the South Shetland Islands slope the basement reflection Tg inclines towards the trough. It is a weak and discontinuous reflection. In the lower South Shetland Islands slope there is a basement high. The Cenozoic sediments are very thin on the basement high. In northwestern and southeastern sides of the basement high there are Cenozoic faults (the F in Fig. 7). Off southeastern side of the basement high there is a landslide in the Cenozoic sediment (the L in Fig. 7). The Tg is weak and discontinuous reflection in the northern trough, likes the T_g under the South Shetland Islands slope. Towards to the middle of the trough the T_6 and T_g become a same reflection and the T_6 disappeared. The T_g is a strong and discontinuous reflection on the Antarctic Peninsula slope. There are four faults towards to the trough(the F in the Fig. 7) in sediment and basement on the slope. T_6 in a strong and continuous reflection on the BS-1, but it disappears in the southeastern half of the north trough. So the sediment between T_g and T_6 exists only in the northwestern half of the north trough. On the seismic profile of BS-1 we can see that the reflection between T_6 and sea floor in the north trough is a strong and continuous, but is deformed, representing the faulted sediment in the Antarctic Peninsula slope has moved towards to the trough.

The line BS-10 crosses the central trough (Fig. 8). The basement reflection T_g is weak and discontinuous reflection under the South Shetland Islands slope (Fig. 8), but strong and continuous in the central trough. It was interfered with the multiples under the Antarctic Peninsula slope, so we could not trace it there. The reflection T_6 is strong and continuous, but it disappeared in the middle of the central trough. The reflection between the T_6 and sea floor is strong and continuous can be subdivided into two groups: T_6-T_2 and T_2-sea floor. The reflection between T_6 and T_2 inclined towards to the midle of the trough. The reflection between T_2 and sea floor is horizontal.

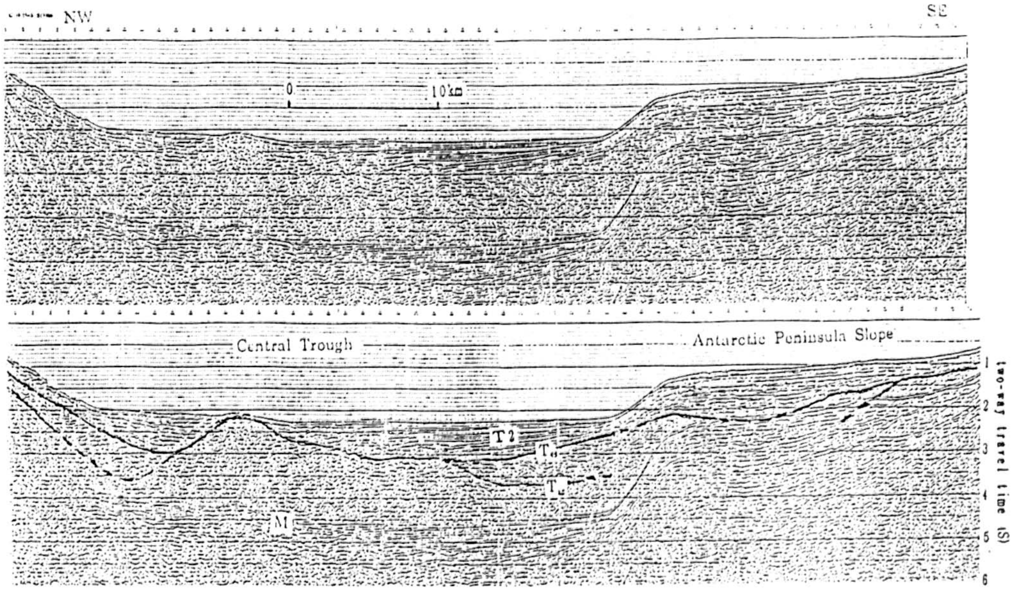

Fig. 8. The seismic profile of BS-10 crossing the central trough.

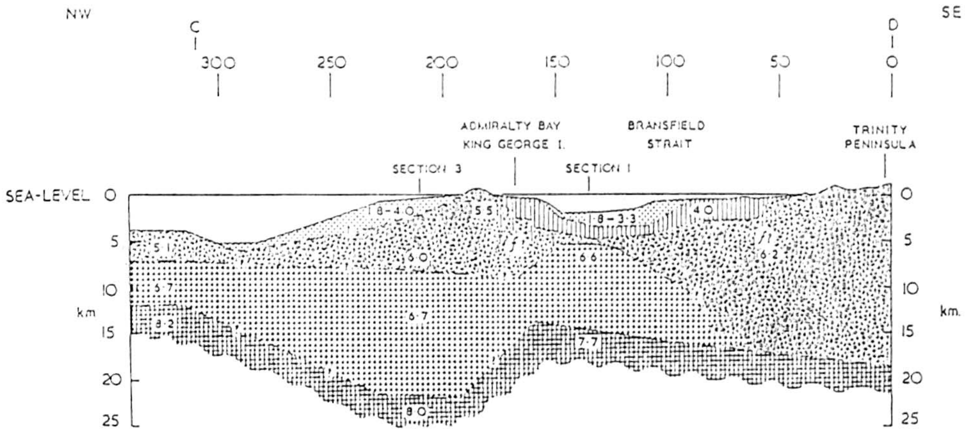

Fig. 9. The crustal section crossing the South Shetland Islands, Bransfield Strait and Antarctic Peninsula. The location is the C-D in Figure 1.

As above discussion there are two sedimentary sequences: T_g-T_6 and T_6-sea floor in the northern and central troughs. The sedimentary sequence between T_g and T_6 exists in both sides of the troughs, and disappeared in the midle of the troughs. The sedimentary sequence between T_6 and sea floor covers the entire troughs. It reflects that the trough was narrow when the sediment between T_g and T_6 was depositing, and become wide when the sediment between T_6 and sea floor was depositing. This means that the Bransfield Trough was a small trough when it firstly rifted and the trough was formed. At the T_6 time there could be another rifting event, and the Bransfield Trough was wide opened at the time.

THE CRUSTAL STRUCTURE

The Cenozoic sediments are 0.1-2.5 km thick in Bransfield Trough (Yao *et al.*, 1995). The interval velocity of the sediments are 1.9-3.2 km/s according to the sonobuoy data. As above discussion it can be divided into two groups: T_g-T_6 and T_6-sea floor. The velocity of the sediment between T_g and T6 is 2.8-3.2 km/s, and 1.9-2.4 km/s in the T_6-sea floor. Ashcroft (1972) did the crustal sounding work in the Bransfield Strait area. He found a layer under the Cenozoic sediments with velocity 4.0 km/s (Fig. 9). He interprated this layer perhaps a mixture of sediment and lava which is older and better consolidated. Following the discovery of Cretaceous metasediments on the offshore islands of Antarctic Peninsula (Halpern, 1964), he believes that the layer of velocity 4.0 km/s represents the same rocks.

Under the layer 4.0 km/s, there is the acidic igneous or metamorphic rocks. It's velocity ranges 5.3-6.2 km/s. The distribution of these rocks is summarized in Fig. 9, which shows that they are best developed in two areas along the line of Antarctic Peninsula and the South Shetland Islands but in between, beneath Bransfield Trough, they constitute a relatively small part of the crust. As in Fig. 9 we can see that in Bransfield Trough this crustal layer is only 2 km thick in maximum, and appropriate velocity range is 5.2-6.3 km/s. This reflects that this layer was extended strongly in the trough than under South Shetland Islands and Antarctic Peninsula.

One of the striking features in the Bransfield Strait area is the widespread occurrence of rocks in the velocity range 6.5-6.9 km/s quite shallow level in the crust. Because the rocks of this velocity consists of the main part of oceanic crust, it probably tepreisents a layer of basic igneous rock. The lower part of the continental crust commonly shows similar velocities (Kominskaya and Riznichenko, 1964), and it may represent very high-grade metamorphic rocks of intermediate composition (Belousov, 1966; Ringwood and Green, 1966), in the Bransfield Trough such rocks with a velocity of about 6.6 km/s occur at particularly shallow depth of between 5 and 6 km. The presence of this crustal layer at shallow depth under the Bransfield Trough invites comparision with the standard section of the oceanic crust (Raitt, 1963). In the Bransfield Strait, the water depth is relatively shallow, more sediment, 6.6 km/s layer is observed and the mantle has a low velocity than the standard oceanic section.

Nevetheless, the crustal structure is much more akin to that of the ocean basins than normal continents, notably in the absence of more than a few kilometers of acidic rocks and in the shallow mantle.

Under Bransfield Trough the upper mantle has a lower velocity of 7.7 km/s than the normal oceanic and continental section. It is similar to the active areas, which lower mantle velocity (down to about 7.6 km/s) are commonly found (Cook, 1962; Pashiser and Steinhart, 1964). It is anomalies mantle representing that in the upper mantle there is active now, because the melting material in the upper mantle with low velocity may go up to the upper crust.

THE TECTONIC EVOLUTION OF BRANSFIELD STRAIT AREA

The Bellingshausen continental margin and adjacent ocean floor contain an important record of tectonic evolution of Antarctic continent. Existing interpretations of the region are based mainly on studies of magnetic anomalies because very few seismic lines have been obtained. A series of magnetic anomalies identified by Herron and Tucholke (1976) indicated that the oceanic crust adjacent to the margin is Eocene to Miocene in age Barker (1977, 1982) made a magnetic anomaly map based on the survey data in the margin of Southeast Pacific Ocean (Fig. 10). He found that off the southern South America the magnetic anomalies are younger towards the South American margin, and the youngest magnetic anomaly lineation is 6, corresponding age is 21 Ma. So he inferred that the sea floor spreading center has been collided with the subducting trench off southern South America at 21 Ma. Off the northwest margin of Antarctic Peninsula and the Bellingshausen margin, the magnetic anomaly lineations are younger towards the margins also. Between the Tharp and Tula fracture zones the youngest magnetic lineation is 23, corresponding age is 55 Ma, the youngest lineation is 6 between Tula and Anvers fracture zones, corresponding age is 21 Ma, and the youngest lineation is 3 between Anvers and Hero fracture zones, corresponding age is 4 Ma. As above discussion we can suppose that there had a series of collision of sea floor spreading center to subducting trench along the Bellishausen margin. The first collision has occurred at 55 Ma between Tharp and Tula fracture zones, the second collision at 21 Ma between the Tula and Anvers fracture zones, and

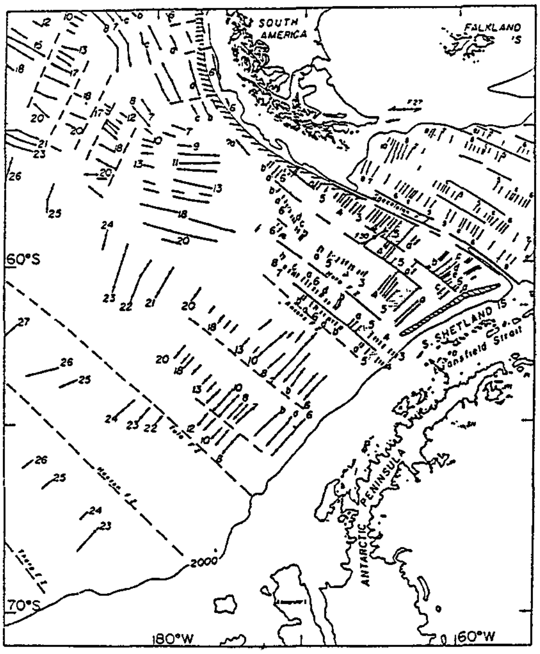

Fig. 10. Magnetic anomalies in the southeast Pacific (from Barker 1982). The two anomaly sets young towards the South American and Antarctic Peninsula margins (except off the South Shetland Islands), showing that the spreading ridge has been subducted. The anomalies form a series of magnetic bights, indicating that the third arm of a RRR triple junction has been subducted completely.

third collision at 4 Ma between the Anvers and Hero fracture zones.

Off the South Shetland Islands the magnetic anomaly lineations are differed from the Bellishausen margin. The youngest magnetic anomaly lineation exists in the middle of Drake plate and is 3, corresponding age is 4 Ma. The lineations become older towards northwest and southeast directions. The oldest lineation is 6b in the northwestern side, corresponding age is 24 Ma, the oldest lineation is 6a in southeastern side, corresponding age is 22 Ma. So we can see that the age of Drake plate is 24-4 Ma.

Based on above discussion, we can propose the tectonic history of the Antarctic Peninsula area as follows: In the mid-Cretaceous to early Cenozoic, the Phoenix plate has moved southeastwards and subducted under the South American and Antarctic plate (Fig. 11a and Fig. 11b). The ridge-crest between Antarctica and Farallon was closing to the subduction zone as the Farallon and Phoenix plates have moved southeastwards (Fig. 11c). At about 24 Ma the sea floor spreading has begun between the South America and Antarctic Peninsula, the South America and Antarctic Peninsula separated each other. The new oceanic crust, the Drake plate has appeared, and it began to subduct under the Antarctic Peninsula Arc. At about 21 Ma, the ridge-crest between the Phoenix and Farallon plates has begun to collide with southernmost South America. So the moving southeastwards of the Antarctica plate has been prevented by the southernmost South America, the subducting rate of the Drake plate has become slow, and the volcanic arc has broken into the South Shetland Islands and Antarctic Peninsula, because the melting matieral in the upper mantle has gone up to the upper crust. This was the first rifting event (Fig. 11d), and a small half-graben has appeared between the South Shetland Islands and Antarctic Peninsula. At about 4 Ma when the last Phoenix plate has consumed by

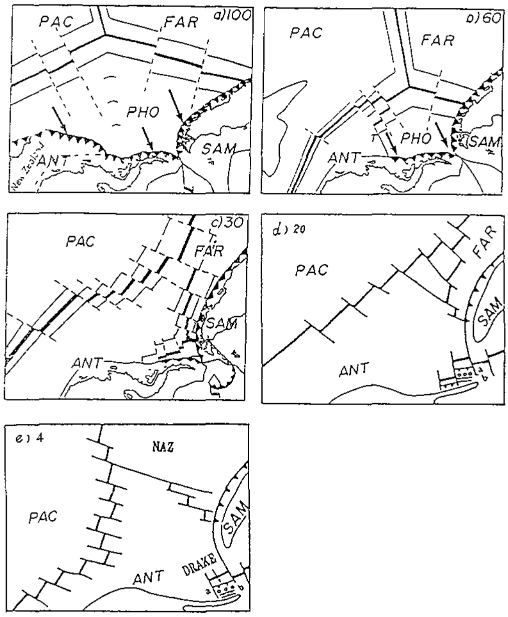

Fig. 11. Southeast Pacific evolution since the mid-Cretaceous, showing the distribution of plates and the directions of subduction. ANT, Antarctic; FAR, Farallon; PAC, Pacific; PHO, Phoenix; SAM, South America; NAZ, Nazca; a, South Shetland Island; b, Bransfield Strait.

the subduction, and the ridge-crest between the Phoenix and Antarctic plates has collided with the Antarctic continent, the subducting rate of the Drake plate has become slow again. So there has another rifting event in Bransfield Strait, i.e. the second rifting event, the halfgraben between the South Shetland Islands and Antarctic Peninsula wide opened. After the first event the small half-graben was received clastic sediment, and after the second event the wided half-graben was received the marine sediment.

SUMMARY

The Btansfield Trough shows an asymmetrical trough in crossing seismic profiles. It can be subdivided into three subtroughs: northern, central and southern troughs. There are half-grabens in the basement. There are two discontinuous reflection on the seismic profiles in the troughs: T_g and T_6, and two groups of seismic reflection: T_g-T_6 and T_6-sea floor. This means that there were two tectonic events: the first and second rifting events, and two sedimentary sequences: T_g-T_6 and T_6-sea floor in the Bransfield Trough. But the sedimentary sequence between T_g and T_6 distributes in the both sides of the trough, the sedimentary sequence between T_6 and sea floor covers the entire trough. Therefore, we believe that after the first rifting event there had appeared a small half-graben, and the volcanic arc was broken into South Shetland Islands from Antarctic Peninsula. After this time, the clastic sediment was received in the small half-grabens. According to the magnetic anomaly lineations and regional tectonic in the southeast Pacific Ocean, the first rifting event occured at about 21 Ma, the second rifting event occured at about 4 Ma. We interpret the tectonic history of the Antarctic Peninsula area in Cenozoic using the model of ridge-crest collision with continental margin and two rifting events 1 think our model is a good interpretation for the tectonic history in Antarctic Peninsula in area in Cenozoic.

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