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Tectonic Deformation in the Shackleton Fracture Zone, Antarctica

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Abstract: New multichannel seismic profiles in the southern Drake Passage show that two sets of tectonic deformation occurred in the Shackleton Fracture Zone. The major deformation is the result of extension accompanied with strike-slip motion of the Shackleton Fracture Zone during seafloor spreading of Drake Passage between 29 Ma and 4 Ma. This extension caused large-scale downfaulting along the fracture zone, forming a deep trough to the north and a half graben to the south of the triple junction in the southern Drake Passage. Recent reverse fault and contractional structures in the recent sediments supports that tectonic regime has changed into compression in response to a westward movement of the Scotia plate after seafloor spreading in the western Scotia Sea stopped at 6 Ma.

Key words: Shackleton Fracture Zone, tectonic deformation, multichannel seismic profiles

INTRODUCTION

During January of 1993, a multichannel seismic (MCS) survey was carried out in the southern Drake Passage to investigate the structure of the Shackleton Fracture Zone (SFZ). The SFZ is an active plate boundary between the Antarctic and Scotia plates, which extends 800 km across Drake Passage to join the southernmost tip of South America with the northern tip of the Antarctic Peninsula (Fig. 1).

Approximately 800 km of seismic profiles were collected on the first Antarctic cruise of the *R/V Onnuri* (KORDI). MCS data were obtained with a 96-channel analog streamer. Each channel consists of 24 hydrophones and the group interval is 25 m. An array of 16 guns with a total volume of 22.6 liters was used as an energy source. Shot interval was 50 m and the sampling interval was 2 ms. Acquired MCS data were processed by conventional processing procedures with GEOVECTEUR® (CGG) on CRAY-2S.

The newly acquired MCS profiles presented in this study (Fig. 2) reveal the detail crustal structure of the SFZ. It provides an insight into the tectonic evolution of the SFZ and plate dynamics in the western Scotia Sea region.

TECTONIC HISTORY

The South America and Antarctic Peninsula have long been recognized as geologically related and contiguous during the early Mesozoic (Suess, 1909; Matthews, 1959). Widespread calc-alkaline magmatism indicates that subduction occurred along the Pacific margins of the two continents during the Mesozoic (De Wit, 1977; Dalziel and Elliot, 1982). In the Scotia Sea more or less continuous tectonic features along the North and South Scotia Ridges suggest that once the continental fragments were dispersed by the formation of the Scotia Sea in Tertiary (Dalziel, 1984). Two continents were finally separated by the seafloor spreading of Drake Passage which started at about 29 Ma.

Recently Cunningham et al. (1995) suggested that the opening of the Scotia Sea was caused by large-scale plate motion as the southernmost South America and the Antarctic Peninsula drifted away from Africa at different velocities along different, nonparallel trajectories. They also proposed that

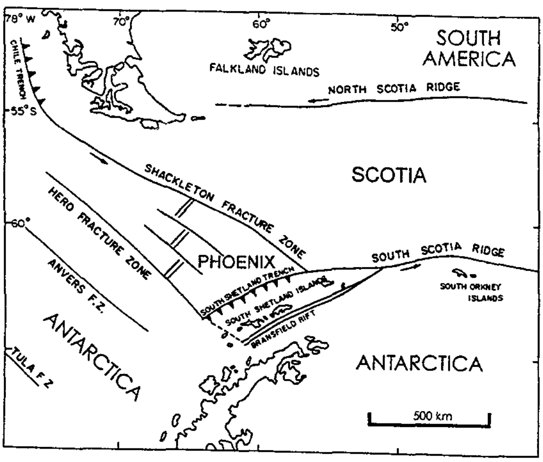

Fig. 1. Tectonic map of Drake Passage (modified from Jeffers and Anderson, 1990).

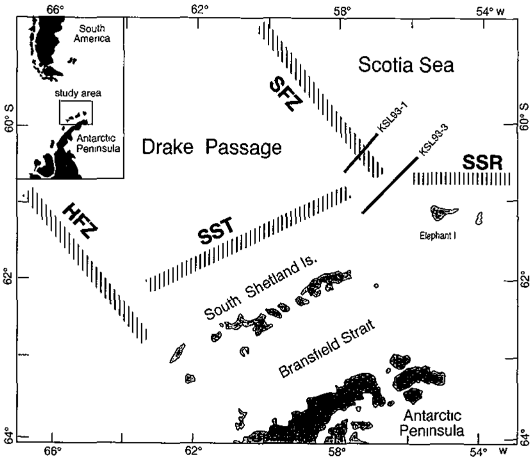

Fig. 2. Location of multichannel seismic lines. HFZ-Hero Fracture Zone, SFZ-Shackleton Fracture Zone, SSR-South Scotia Ridge, SST-South Shetland Trench.

increased separation rates between two continents and a change in the angle of plate divergence at approximately 55-50 Ma marked the onset of accelerated continental separation that eventually led to seafloor spreading in Drake Passage at 30 Ma and the development of the Scotia Arc.

As a product of the Drake Passage opening, the SFZ grew in proportion to spreading rates of seafloor in the passage (Barker and Burrell, 1977). After the spreading stopped in Drake Passage at 4 Ma, the growth of the SFZ was nearly stopped.

SEISMIC PROFILES

KSL93-1

Profile KSL93-1 crosses the SFZ, running 50 km northwest of the triple junction where the SFZ, South Shetland Trench, and South Scotia Ridge are met. The SFZ is characterized by a pronounced ridge 2000 m higher and a bathymetric low 300 m deeper than the surrounding seafloor (Figs. 3 and 4). The width of the SFZ is about 35 km.

The SFZ ridge shows almost symmetrical shape that the eastern slope is slightly steeper than the western slope on profile KSL93-1 (Fig. 3). No sediments are observed on the ridge except at its both foots. The ridge keeps the constant shape to the triple junction (Jin, 1995). The nature of high ridge found in the major fracture zones is still unknown.

Several strong diffractions with low frequency appear symmetrically beneath the bathymetric low (Fig. 4). The depths of diffractions increase from both sides to the center of the low. These signals reflect from the tops of the basement at different depths. It suggests that the deep trough in the SFZ was formed beneath the low by downfaulting along numerous high-angle faults. The maximum thickness of the sediments in the trough exceeds 1500 m. Most of trough-fill sediments show chaotic reflection. An interesting structure is a lens-shaped sedimentary body with strong, well-stratified reflectors on the top of the trough. Such lens shape may be formed by sediment deposition controlled strong bottom currents flowing along the axis of the trough. Kim et al. (1995) proposed a similar origin for the lanticular-shape reflection pattern observed on the South Shetland Trench floor. Between the ridge and trough, sediment pile showing anticlinal structure is laid on a tilted block of the basement. To the east, the lanticular sediments onlap the anticlinal sediments. The basement top of the eastern wall in the trough is about 400 m higher than that of the western wall.

To the northeast of the trough, well-layered sediments with the maximum thickness of 1200 m cover the oceanic basement that belongs to the Scotia plate. These sediments wedge out toward the trough, so the basement is almost exposed on the eastern wall of the trough. A small mound appears on the end of the wedge. In this area, the seafloor becomes shallow by 0.7 s to the northeastern end of

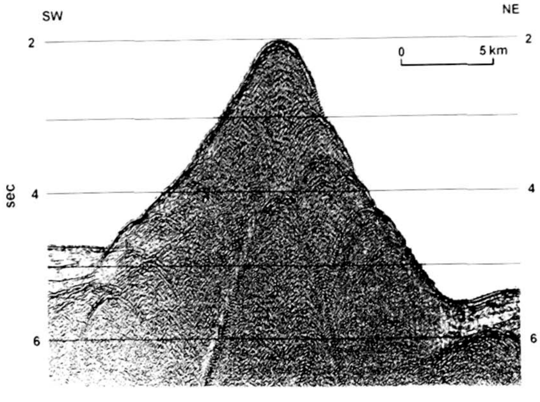

Fig. 3. Part of profile KSL93-1 showing the SFZ ridge. The ridge culminates more than 2000 m high. No sediments are on the slope of the ridge.

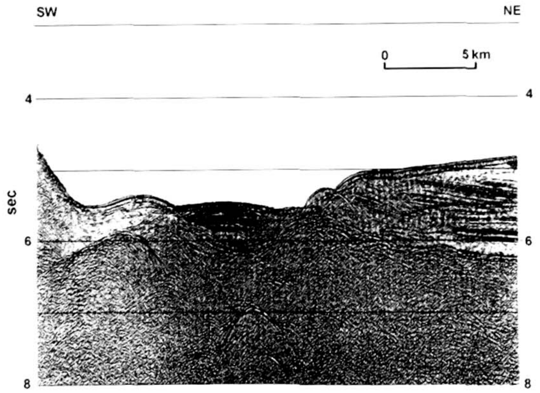

Fig. 4. Part of profile KSL93-1 showing the SFZ trough. Strong diffractions from the top of the oceanic crust appear at different depth in the trough. A lens-shaped sedimentary body with strong, well-layered reflectors is laid on the top of the trough.

the profile, whereas the top of the oceanic crust becomes deep by 0.8 s. The oceanic basement and overlying sediments are disturbed by a large fault 5 km northeast of the trough, and the western block of the fault got tilled by 6°. These features were probably formed by footwall uplift block in response to the downfaulting of the hanging-wall block in the trough. A ridgeward tilting of the top of western wall also may result from the footwall uplift on the other side.

KSL93-3

This line runs just south of the triple junction where the SFZ, South Shetland Trench, and South Scotia Ridge are met (Fig. 2). The SFZ ridge can not be seen in this profile because the ridge collides against the South Shetland Platform at the triple junction and terminates abruptly there. Bathymetric map shows a deep submarine valley between the SFZ ridge and the South Shetland Platform (Jin, 1995). This valley is a gap through which the strong bottom current flow westward from the Weddell Sea to the South Shetland Trench (Nowlin and Zenk, 1988). The shallow sea region on profile KSL93-3 (Fig. 5) belongs to the South Shetland Platform, and the deep sea region is a part of the Scotia Sea. Very steep slope of the platform (up to 28∞) is bounded with the oceanic crust by a large fault at the foot of the slope. A bathymetric mound occurs at the foot. Similar mounds are observed at the foot of the accretionary wedge in the South Shetland Trench (Larter, 1991; Kim and Jin, 1994). These mounds are known to be formed in a regime of compression.

Profile KSL93-3 shows a subtle bathymetric low to the east of the foot of the continental slope. The width of the low is about 3 km. A high amplitude, rough topographic, and gently eastward-dipping reflector at 6.7 s in two-way travel time (twt) beneath the low seems to be the top of the oceanic basement. The overlying sedimentary layers, however, show the westward dip. The thickness of the sedimentary cover is about 1000 m. This cover can be divided by two units showing different seismic characters. The upper unit, which is up to 700 m thick, shows almost transparent reflection. The strong, high amplitude, well-stratified lower unit onlaps the oceanic basement, and its thickness increases eastward up to 300 m.

A remarkable discontinuity of the basement and sedimentary cover occurs by a large-scale fault at the eastern boundary of the low. To the east of the fault, the basement appears at more than 8 s twt. This indicates that the eastern block dropped along the fault, forming a half graben. The throw of the fault is apparently up to 1000 m on the profile. The overlying sediments with thickness of about 2000 m can be also divided into two sedimentary units which are correlated with the western ones. The upper unit shows the same thickness and reflection pattern with the western one, whereas the lower unit is much thicker. The increment of sediments thickness equivalent to the vertical displacement of the fault (about 1000 m) concentrates only in the lower unit. A most significant feature is that a large-scale fault, which is the wall of the half graben, offsets recent sediments and reaches the seafloor. On the contrary, the antithetic faults accompanied with large-scale normal faulting is limited within the lower unit. In addition, the seafloor and the top of the lower unit to the east of the major fault is both about 100 m shallower than those to the west.

IMPLICATIONS FROM THE SEISMIC PROFILES

Profiles KSL93-1 and KSL93-3 show well-defined deformations in the SFZ in respose to two sets of tectonic stresses. The major deformation can be observed in the SFZ trough. Profile KSL93-1 shows that the oceanic crust dropped largely along high-angle faults in the trough. This indicate that the SFZ experienced very strong extensional deformation. The effect of extensional deformation along the SFZ can be traced to the south of the triple junction. In profile KSL93-3, a half graben was built by the normal faulting along a large-scale fault. This half graben seems to be an extension of the SFZ trough. Apparent vertical offset of the fault is more than 1000 m. Such large-scale extension resulted from transtensional movement of the SFZ through the period of the Drake Passage opening between 29 Ma and 4 Ma (Barker and Burrell, 1977). The main structure of the SFZ with a huge ridge and deep trough, was probably built during the opening period.

To the south of the triple junction, profile KSL93-3 reveals distinct features that are indicative of the recent change in tectonic regime in this area. The large fault, that bounds the half graben, extends to the sea floor and cuts recent sediments as well as the oceanic basement. The depth of the basement to the eastern side of the fault is 1000 m deeper than that to the western side, whereas the sea floor and upper unit in the sedimentary cover are rather 100 m shallower (Fig. 5). The former is considered to be formed by normal faulting, but the latter by reverse faulting. The antithetic faults due to major normal faulting along the large-scale fault are observed only in the lower unit, not extending to the upper unit. Relatively less deformed upper unit keeps constant thickness across the large-scale fault. These features suggest that extensional movement of the SFZ had ceased before the upper unit was deposited, and after then the SFZ has shown compressional movement. In other words, the large-scale fault, which once showed normal sense, has reactivated recently with reverse sense. A bathymetric mound at the foot of the continental slope was probably formed by recent compression. Also on profile KSL93-1, the contractional structures around the top of the trough, including a bathymetric mound and the anticlinal sedimentary cover, may be produced by compression.

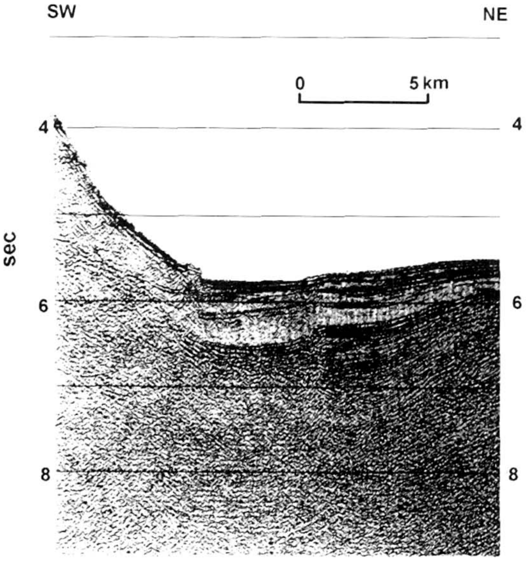

Fig. 5. Part of profile KSL93-3 showing a half graben. Large-scale fault, which is the wall of half graben, offsets the oceanic crust and recent sediments. The top of the oceanic crust to the east of the fault, appears 1.2 s twt deeper than that to the west, whereas the top of upper sedimentary unit and seabottom is about 0.2 s twt shallower. It suggests that the normal fault reactivated as reverse fault.

The recent compression in this area is the result of the important change in the mode of Scotia Sea evolution occurred at 6 Ma. At that time South Georgia collided with the northeast Georgia Rise, consequently which caused the cessation of sea floor spreading in Drake Passage and the central Scotia Sea (Barker et al., 1991). Cessation of the

Drake Passage spreading led to lessen subducting activity along the SST. The buoyant ridge of the Shackleton and Hero Fracture Zone may have played an important role to stoppage of subduction (Henriet et al., 1992). The Scotia plate now shows a slow westward motion with respect to the Antarctic plate. This east-west compressive stress by the movement of the Scotia plate is assumed to be sufficient to overcome the ridge-push force of the Antarctic-Phoenix spreading center (Larter and Barker, 1991). Based on focal mechanism study, Pelayo and Wiens (1989) suggested the relative motion of the Scotia plate at a rate of 1.4 cm/yr toward the WSW and east-west convergence in the Drake Passage region at 1.1 cm/yr. They reported the earthquakes with a component of compression in Drake Passage, and also concluded that convergence between the Scotia and Antarctic plates in the Drake Passage region is taken up through diffuse compressional deformation in the passage as well as strike-slip faulting along the SFZ.

CONCLUSIONS

The SFZ is the plate boundary between the Antarctic and Scotia plates as a product of the Drake Passage opening. The multichannel seismic profiles collected in the southern Drake Passage images the structure of the SFZ in detail. Two sets of tectonic deformation are observed in the SFZ. First, large-scale downfaulting by extension formed a deep trough to the north and a half graben to the south of the triple junction where the SFZ, South Shetland Trench, and South Scotia Ridge are met. This deformation is the result of transtenstional motion of the SFZ during seafloor spreading in Drake Passage. After seafloor spreading in Drake Passage and the Scotia Sea stopped at 6 Ma, tectonic regime in the Drake Passage area changed into compression by a westward convergence of the Scotia plate. The reverse fault and contractional structures in the recent sediments on the profiles are indicative of recent compression in this area.

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