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# Is subduction ongoing in the South Shetland Trench, Antarctic Peninsula?: new constraints from crustal structures of outer trench wall

Young Keun Jin*
Joohan Lee
Jong Kuk Hong
Sang Heon Nam
*Korea Polar Research Institute, KORDI, Songdo Techno Park, 7-50, Songdo-dong, Yeonsu-gu, Incheon 406-840, Korea*

**ABSTRACT: The South Shetland Trench (SST) northwest of the South Shetland Islands is the only trench along the Pacific margin of the Antarctic Peninsula. Multichannel seismic reflection profile shows very narrow normal faulting zone (about 20 km) on the outer wall of the SST and thick trench-fill sediments (up to 1000 m) on two distinct crustal horst and graben structures in the trench. These structures are rare in the active subduction trenches. On the basis of the implications from these seismic structures and known tectonic history, the following scenarios of subduction activities of the former Phoenix plate are proposed: (1) normal faulting has not occurred since subduction rate in the SST sharply decreased after cessation of seafloor spreading at the West Scotia Ridge at about 6 Ma; and (2) subduction almost stopped after the cessation of spreading in Drake Passage at about 3.3 Ma. Recent contractional structures around the SST are indicative of current crustal shortening (not subduction) accommodating trenchward movement of South Shetland Islands caused by the ongoing extension of Bransfield Basin behind the South Shetland Islands.**

**Key words:** South Shetland Trench, Antarctic Peninsula, subduction, seismic structure, Bransfield Basin

## 1. INTRODUCTION

The South Shetland Trench (SST), a unique trench along the Pacific margin of the Antarctic Peninsula, is located to the northwest of the South Shetland Islands, which is bounded to the northeast by the Shackleton Fracture Zone (SFZ) and to the southwest by the Hero Fracture Zone (HFZ) with their high submarine mountains (Fig. 1).

The Pacific margin of the Antarctic Peninsula had been an active margin since the breakup of Gondwana (Pankhurst, 1990). During the Cenozoic, ridge-crest segments of the Antarctic–Phoenix (ANT–PHO) spreading center arrived at the margin (Barker, 1982). The ridge-crest segments arrived progressively later to the northeast along the margin. The last segment arrived obliquely just southwest of the HFZ between 6.4 and 3.3 Ma (Larter et al., 1997). As subduction stopped at the part of the margin where each ridge-crest segment arrived, the whole margin southwest of the HFZ became passive (Larter and Barker, 1991).

Between the HFZ and the SFZ, the last surviving segments of ANT–PHO spreading center exist to the northwest of the SST (Fig. 1). The small oceanic part in Drake Passage bounded by the ANT–PHO center, the SST, the SFZ, and the HFZ has been called ‘the former Phoenix plate’ (hereafter, Phoenix plate). Spreading of the ANT–PHO center is known to have ceased at about 3.3 Ma (Livermore et al., 2000), but shortening at the SST is thought to be still going on (Kim et al., 1995).

Ongoing extension of the Bransfield Basin at the back-arc basin position between the Antarctic Peninsula and the South Shetland Islands has led many scientists to believe that the continued sinking of the subducted slab by roll-back of the hinge of subduction at the SST has given rise to the extension (Barker, 1982; Maldonado et al., 1994). However, there is a lack of direct evidences for the current subduction, such as subduction-related seismicity and arc volcanism. Alternatively, sinistral transcurrent movement between the Antarctic and the Scotia plates has been proposed as another possible tectonic model for the Bransfield Basin extension (Gonzalez-Casado et al., 2000; Klepeis and Lawver, 1996; Lawver et al., 1996). In conclusion, the nature of the extension is still controversial.

In this study, the subduction-related crustal structures and sediments in the SST are examined in detail using multichannel seismic (MCS) reflection profile. New constraints from the seismic structures provide us with important evidence in relation to the question of whether or not subduction is undergoing in the SST.

## 2. SEISMIC DATA ACQUISITION

Multichannel seismic and multibeam echosounder profiles used in this study were acquired onboard R/V Onnuri during January and February 1993, as part of the Korea Antarctic Research Program (Fig. 3). The MCS data were obtained using a 96-channel analog streamer with 25 m group interval and a 16-Sleeve airgun tuned array with a

*Corresponding author: ykjin@kopri.re.kr

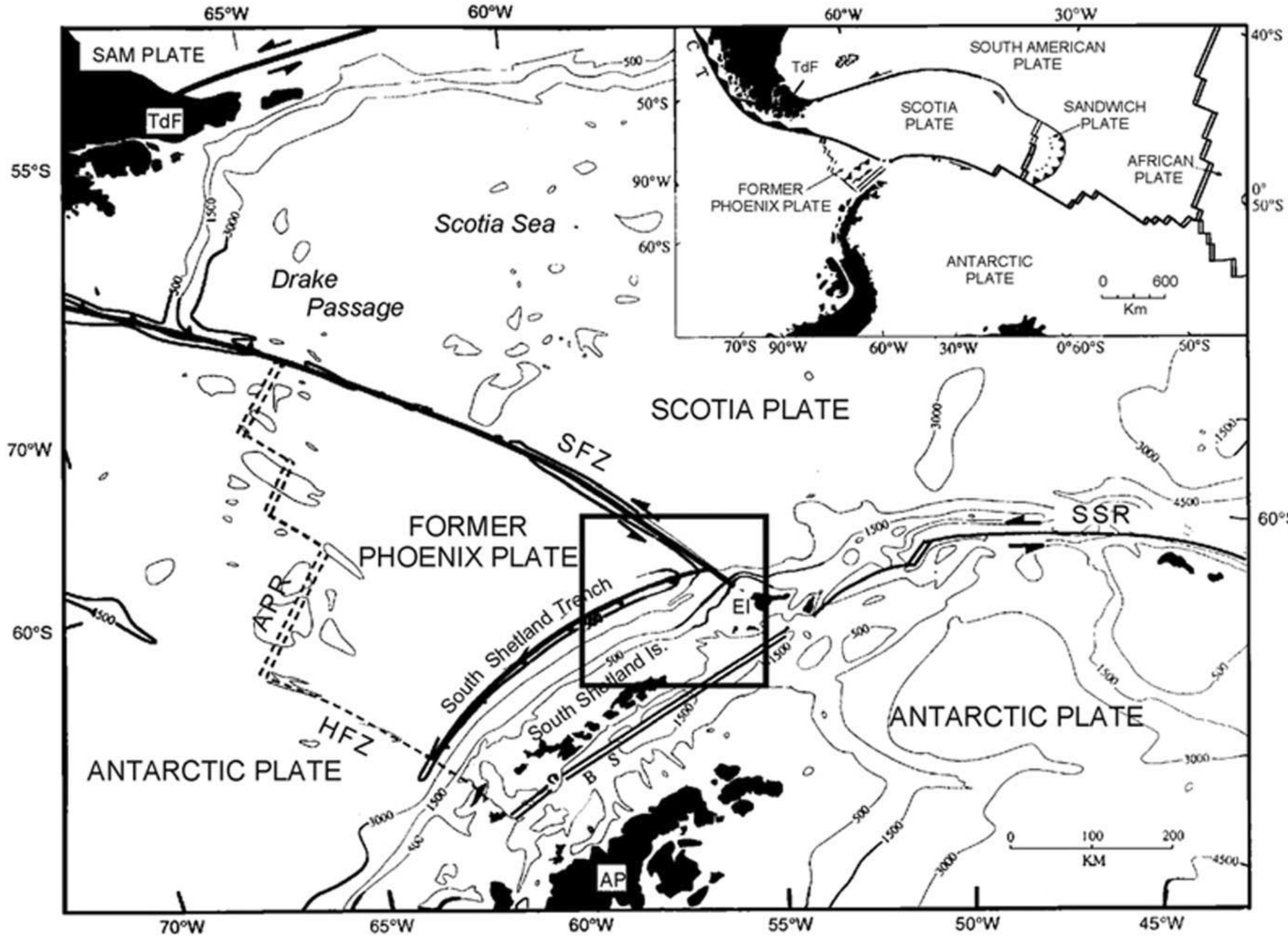


**Fig. 1.** Tectonic map of the northern Antarctic Peninsula (AP) and the Scotia Sea region. APR-Antarctic-Phoenix spreading ridges, BS-Bransfield Strait, EI-Elephant Island, HFZ-Hero Fracture Zone, SAM-South American, SFZ-Shackleton Fracture Zone, SSR-South Scotia Ridge transform system, and TdF-Tierra del Fuego. Box indicates the study area. (slightly modified after Klepeis and Lawver, 1996).

total volume of 22.6 l at a minimum pressure of 13.3 MPa (1930 psi). The acquired MCS data were recently reprocessed with standard procedures including dip move-out correction and relative true amplitude recovery using Promax® system. The multibeam swath bathymetry data were corrected using Sea Beam® 2000 system and processed using MB system. The bathymetry was plotted using GMT software.

## 3. SEISMIC STRUCTURES

The SST is characterized with the flat trench floor with the deepest depth (> 5000 m) in the Antarctic Peninsular area (Figs. 2 and 3). On MCS profile KSL93-6, the inner slope is an accretionary wedge with rugged and steep topography, whereas the outer slope shows a gentle seafloor becoming shallow seawards. A small topographic mound appears between the trench floor and the toe of the accretionary wedge (Figs. 3 and 4).

The outer slope has undisturbed pelagic/hemipelagic sediments with a thickness of 400–700 m. Subtle crustal depressions occur on the oceanic basement at 8–11 km and 34–37 km from the northwest end of the profile (Figs. 3 and 4). The latter one closer to the trench is more distinct to be an incipient graben structure (IG)). A seafloor depression appears directly above the IG.

At least two distinct grabens, G1 and G2, are identified beneath the flat-lying sediments at the trench. The G1, a 3 km wide and 600 m deep graben, occurs at the northwestern edge of the trench floor (Figs. 3 and 4). The other graben, G2, having a size similar to G1, appears beneath the toe of the accretionary wedge. These grabens, including the IG on the outer slope, are somewhat constantly spaced at about 10 km.

The width of the trench floor on profile KSL93-6 is 12 km (Fig. 4), which is 4 km wider than the average width (8 km) on other nearby profiles crossing the SST (Kim et al., 1995). Incidentally, this extra width is the same as the width of the G1 formed at the seaward edge of the trench. In the trench, two main sedimentary units with different dips are clearly

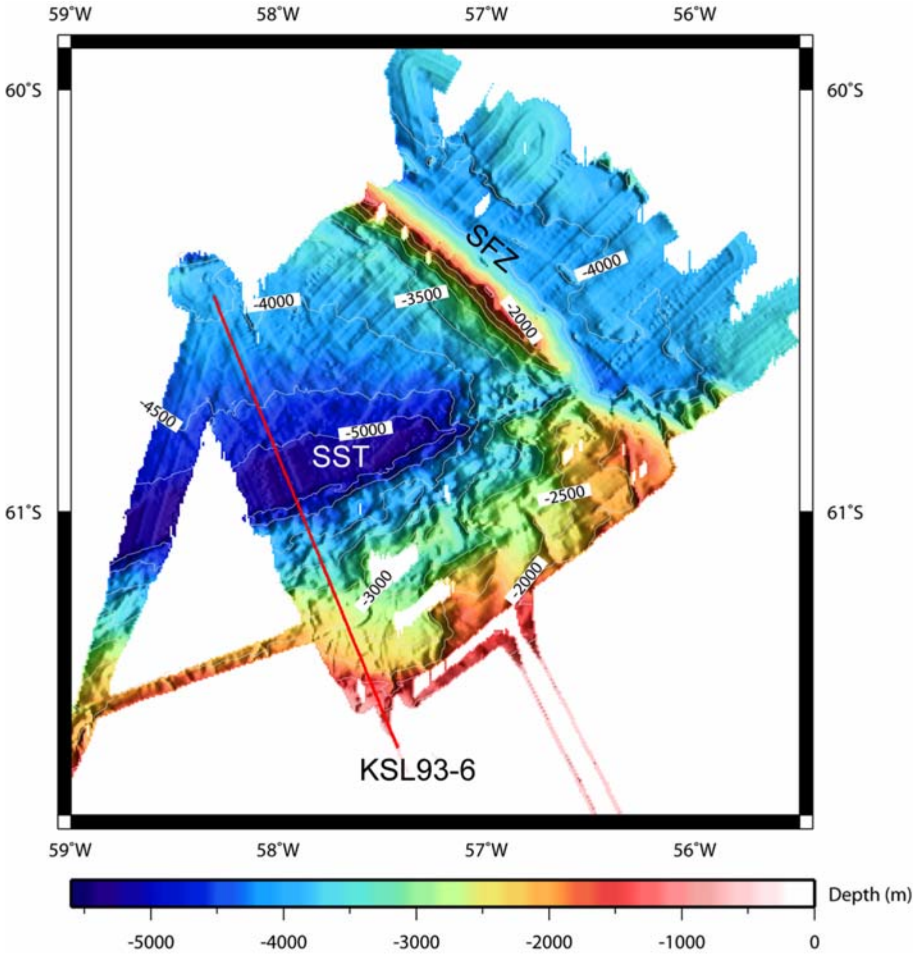


**Fig. 2.** Location of multichannel seismic profile KSL93-6 shown in Figure 3 overlaid on bathymetric map. Contour interval is 500 m. SFZ-Shackleton Fracture Zone, SST-South Shetland Trench.

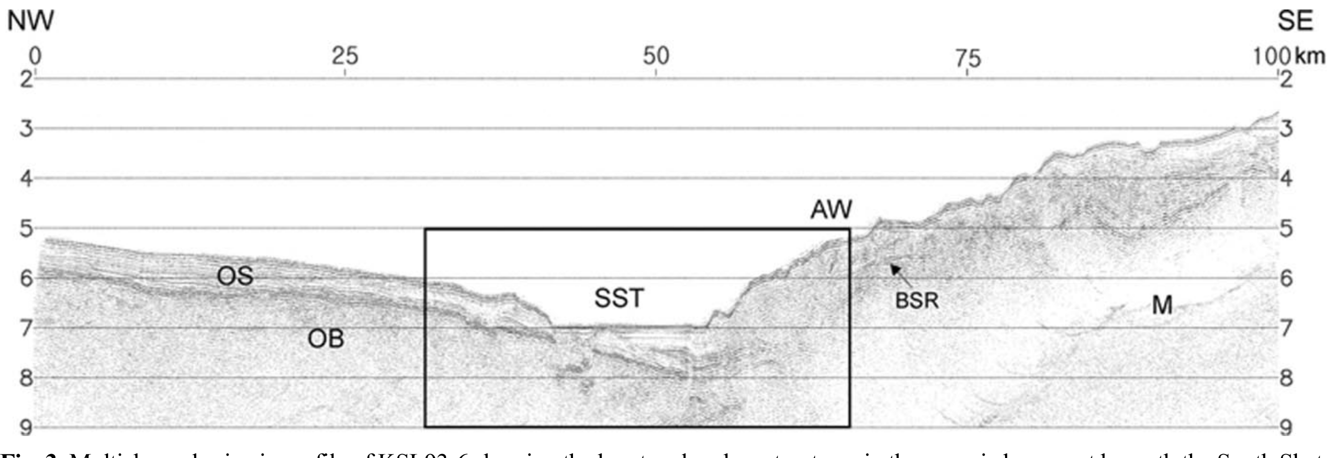


**Fig. 3.** Multichannel seismic profile of KSL93-6 showing the horst and graben structures in the oceanic basement beneath the South Shetland Trench (SST). AW-accretionary wedge, BSR-bottom simulating reflector, M-multiple, OB-oceanic basement, and OS-oceanic sediments. Box indicates the location of Figure 4.

discerned. The lower unit dips landward and is parallel to the descending oceanic crust. This unit consists of pelagic and hemipelagic sediments that were carried on the oceanic crust. The upper unit is trench-fill sediments with parallel and flat-lying reflectors. The unit has a maximum thickness of 1300 m beneath the toe of the accretionary wedge. The unit can be divided into two subunits. The upper subunit shows weak amplitude and high frequency in comparison with the lower subunit that is going down beneath the accretionary wedge.

At the toe of the accretionary wedge, the frontal thrust (FT) overrides the upper youngest unit of the trench-fill

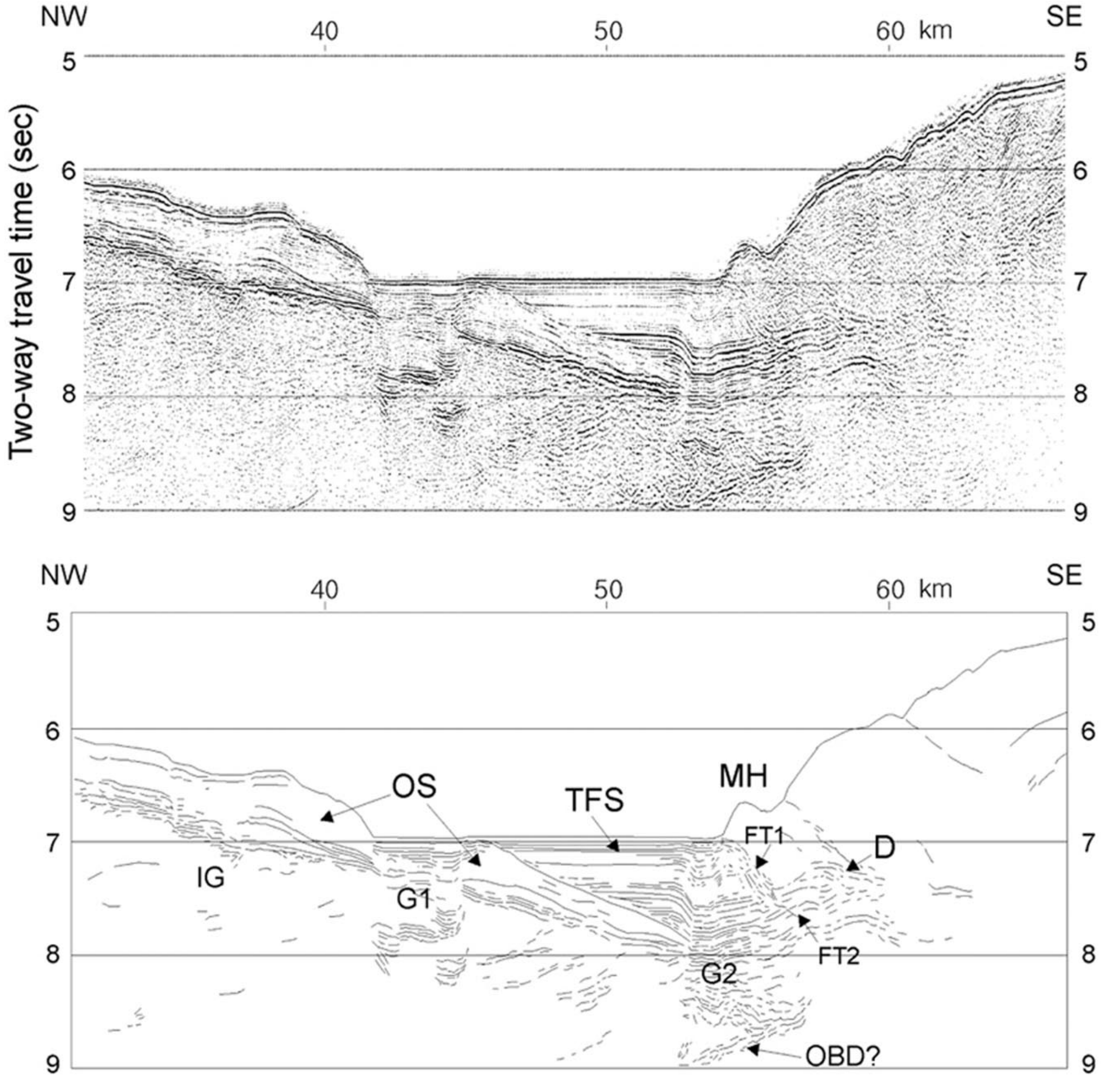


**Fig. 4.** A seismic section of profile KSL93-6 and interpreted line drowing showing thick trench-fill sediments on the horst and graben structures in the oceanic basement. D-decollement, FT1 and FT2-brenchs 1 and 2 of the frontal thrust, G1 and G2-graben structures 1 and 2, IG-incipient graben structure, MH-mound-shaped topographic high, OBD-obduction, OS-oceanic sediments, and TFS-trench-fill sediments. See text for discussion.

sediments. The thrust is divided into two branches in the lower part: one branch (FT1) merging with a basal decollement developed between two trench-fill subunits and the other (FT2) cuts though the subducted lower subunit (Fig. 4). The second thrust occurs topographically lower and behind the small mound and also merges with the decollement overriding the lower unit of the trench-fill sediments. The dip of the second thrust is rather shallower than that of the frontal thrust.

The oceanic sediments subducted beneath the trench and the accretionary wedge appear to be squeezed and deformed. This apparent decrease in the thickness of the subducted sedimentary layer may result from the following factors: (1) depositional loading of the hemipelagic/pelagic sediments by turbidites producing a decrease in oceanic sediment thickness because of compaction and (2) loss of porosity during compaction, thereby increasing acoustic velocity to exaggerate the actual change in sediment thickness (MacKey and Moore, 1990). The seaward dip of the oceanic crust and sediments beneath the accretionary wedge

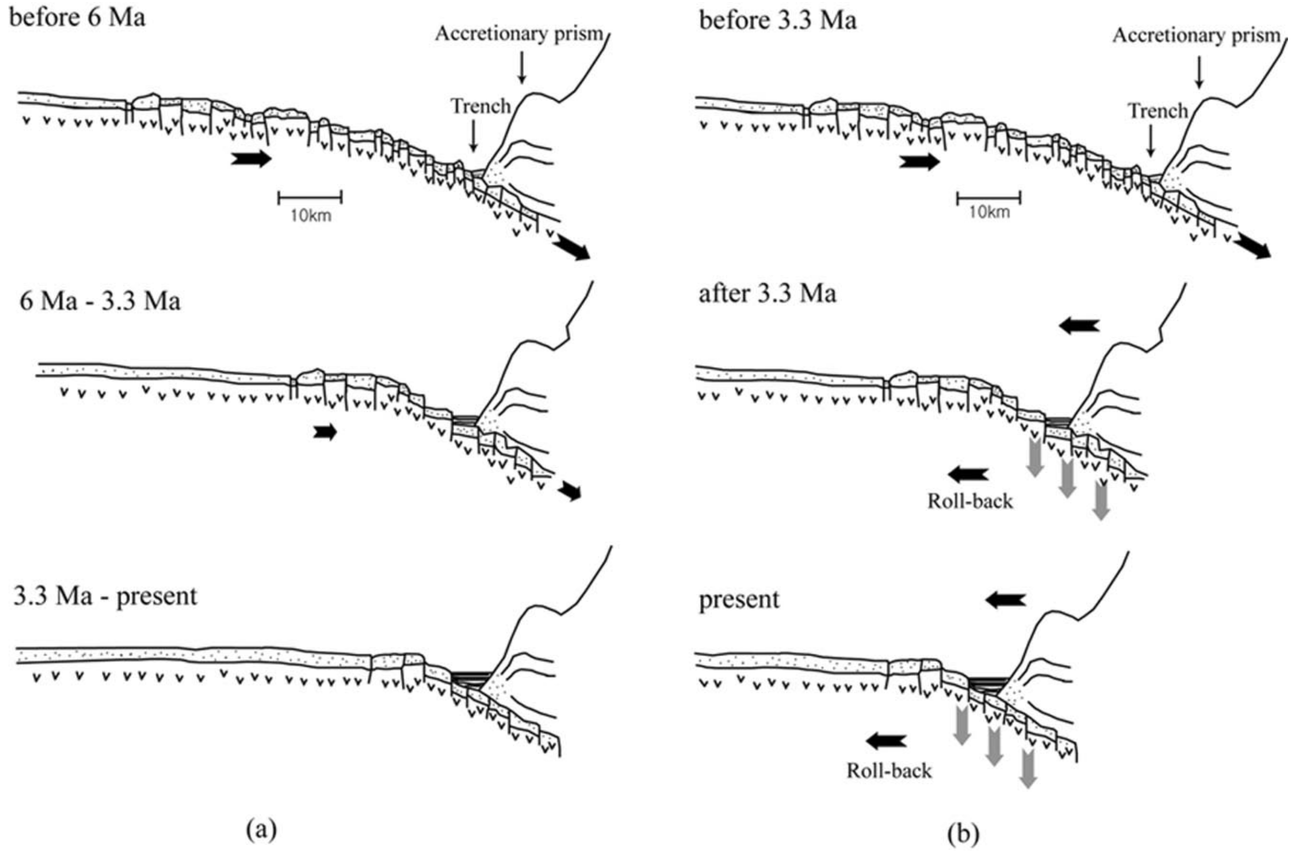


**Fig. 5.** Sketches of subduction history of the former Phoenix plate at the South Shetland Trench since 6 Ma. (a) (top) before 6 Ma, fast subduction made well-developed normal faulting with large horst and graben structures on the outer slope extending more than 50 km, (middle) during 6 Ma-3 Ma, normal faulting zone became narrow due to slow subduction and no new faulting, (bottom) after 3.3 Ma, current morphology of the SST has been kept. (b) (top) same as (a), (middle) trench has moved seaward as trench roll-back without normal faulting on the outer wall began after 3.3 Ma, (bottom) trench roll-back style subduction without normal faulting is still ongoing.

should be corrected into the landward dip after applying depth conversion that removes the velocity pull-up effect by overlying sediments. The subducted trench sediments can be traced for more than 10 km landward beneath the wedge on the profile.

A very remarkable reflector is the strong seaward dipping reflector occurring beneath the toe of the accretionary wedge between 8.5 s in a two-way travel time at 57 km to 9 s at 52 km (OBD in Fig. 4). A number of weak and short reflectors subparallel to the obduction (OBD) appear on the oceanic basement beneath the center of the trench. These seaward-dipping reflectors may be attributed to anisotropy in the oceanic crust, acting as a weak surface along which obduction could take place during landward thrusting. A similar anisotropy was reported by Seely, (1977) in the seafloor basalt of the Cascadia basin off Washington and northwestern Oregon.

The accretionary wedge of about 800–1500 m thick is characterized by chaotic reflections (Fig. 3). Although thrust faults on the wedge are not clearly seen on the profile, these are subparallel to the frontal thrust beneath the bathymetric breaks on the lower slope of the wedge. A very flat terrace 3 km wide is seen at 68 km, below which gas-hydrate bottom simulating reflector (BSR) (Fig. 3) appears. The BSR is subparallel to the seafloor as a smooth reflector with negative polarity of seafloor reflector, but it does not completely mimic to the seafloor with step-like morphology. On the south Shetland continental margin, these smooth BSRs widely occur beneath the very rough seafloor (Jin et al., 2003). It is likely that this morphology of the seafloor may have been formed by faulting and recent erosion processes related with glacial movement. It would take somewhat long time for the BSR to rearrange with recent deformation of the seafloor topography.

## 4. DISCUSSION

### 4.1. Normal Faulting Zone on the Outer Wall

Profile KSL93-6 shows large-scale two graben structures (G1 and G2) in the trench (Figs. 3 and 4). The G1 beneath the seaward edge of the trench is about 3 km wide and about 600 m deep, and the G2 below the toe of the accretionary wedge is as large as G1. Although a subtle crustal depression appears at 10 km of profile distance from the NW end of the profile (Fig. 3), it is proposed that the IG with a seafloor depression is the last distinct normal faulting structure in the fault zone formed during active subduction on the outer slope from the trench (Figs. 3 and 4). Thus, the width of normal faulting zone on the outer slope from trench axis to the IG is less than 20 km, which is very narrow compared to the widths of faulting zones in other current active trenches extending 50–75 km (Masson, 1991). Furthermore, the throw of normal faults significantly decreases off the trench, that is, from about 600 m at G1 to less than 100 m at IG (Fig. 4). These grabens in the SST are likely to have a considerable lateral extent of at least 30 km because similar structures in the trench are observed on other nearby seismic profiles (Kim et al., 1995). These grabens are generally formed by tensional stress in the upper part of a subducting ocean plate at the hinge where it bends into a trench (Ludwig et al., 1966; Masson, 1991).

We interpret that these features on the profile are indicative of rapid diminishment of normal faulting-associated subduction on the outer slope of the SST after two major grabens formed, and that finally no more normal faulting occurred after IG formed. If it is assumed that IG was the last and farthest graben structure formed at the distance of 50–75 km from the trench axis, IG should have moved toward the trench by several kilometers (30–55km) from the original position. However the width of normal faulting zone would be highly dependent on many factors of each subduction zones like slab age, slab strength and convergence rate, so our interpretation not based on such kinds of information would be a very simplified one.

Accordingly, two questions have been posed: (1) when did the IG form and (2) when did the IG arrive at the present position. These questions are directly related to (1) the time when no normal faulting on outer slope took place and (2) the subduction rates of oceanic plate since normal faulting stopped.

For the past convergence rates in the SST, Henriet et al. (1992) proposed the convergence rates of 40–50 km/m.y. averaged over the past 25 Ma, whereas Maldonado et al. (1994) suggested that the rates were about 40–60 km/m.y. since 30 Ma, and that the sharp drop of the rates occurred at about 6.7 Ma; the present-day rate is about 10–20 km/m.y. Maldonado et al. (2000) proposed that the Phoenix plate has been moving toward the SST at a rate equal to the full spreading rate at the ANT–PHO ridge crest and the full spreading rate decreased from about 58 km/m.y. to less than 22 km/m.y. before magnetic anomaly 3A (6 Ma) when spreading at the West Scotia Ridge ceased . However, they did not clearly mention the full spreading rate after magnetic anomaly 2A (3.3 Ma) when spreading at the ANT–PHO ridge stopped.

To answer the first question, the aforementioned two important points of time (6 Ma and 3.3 Ma) are regarded as the time when normal fault-forming graben structures on the outer slope of the trench rapidly diminished.

The sharp drop of the rates at time 6 Ma is closely related to the time when the Scotia plate east of the Phoenix plate changed its moving direction toward the Phoenix plate (westward) after seafloor spreading in the Scotia Sea had ceased (Maldonado et al., 1994). The other event that possibly reduced convergence rates could be the cessation of spreading of the ANT–PHO spreading centers remaining in the Drake Passage at about 3.3 Ma. Although the main force of subduction is known to be a slab pull of the subducting plate, the cessation of spreading could play a role enough to break the exhausted subducting plate. Actually, the subduction rate at the SST was equal to the full spreading rate of the ANT–PHO spreading ridge (Larter and Barker, 1991; Maldonado et al., 2000).

If it is assumed that IG formed at about 6 Ma and recently arrived at the present position 30–55 km trenchward from the original position, the average subduction rates are 5–9 km/m.y. since 6 Ma. Such subduction rates are quietly slow compared to the rates (> 20 km/m.y.) proposed in the earlier studies (Henriet et al., 1992; Maldonado et al., 1994; Maldonado et al., 2000). In case it is assumed that IG formed at 3.3 Ma when spreading ceased at the ANT–PHO ridge, the average rates of 9–17 km/m.y. are somewhat close to the proposed rates in the earlier studies. However, it is likely that subduction at the SST would have stopped at 3.3 Ma. Thus, the scenario that IG formed at 6 Ma and arrived at the present position at 3.3 Ma, and that IG later anchored at the position is proposed. In that case, the average subduction rates are 11–20 km/m.y.

### 4.2. Thick Trench-fill Sediments on Horst And Graben Structures in the Trench

Thick trench-fill sediments more than 1000 m cover over the two graben structures (G1 and G2) in the trench (Fig. 4). The horst and graben structures are common along the subduction zones around the Pacific, except where thick sedimentary deposits (more than 400 m) cover the oceanic plate and fill the trench axis (Ludwig and Houtz, 1979). As the graben structure acts like ‘buckets’ that fill up with sediments and are carried down to the subduction zone, it appears that essentially all the sediments reaching the trench axis are subducted with the descending plate at the trench with well-developed graben unless there is excessive sediment supply from the fore-arc region (Hilde, 1983; Ruff, 1989).

If the volume of supplied sediments were greater than that of subducted sediments in the SST, thick trench-fill sediments and thick accretionary wedge would be expected.

However, sufficient data is not available to precisely examine sedimentation rates in the SST. Porebski et al. (1991) proposed a sedimentation rate of 120 m/m.y. from a piston core data acquired in the SST. This rate is close to a sedimentation rate of 287 m/m.y. measured at the lowermost part of trench slope near the Chile Triple Junction (Behmann, 1992). Maldonado et al. (1994) referred to a sedimentation rate of 1400 m/m.y. in the Nankai Trough of the SST, which is almost 10 times higher than the rate of Porebski et al. (1991). On the other hand, Nowlin and Zenk (1988) reported the existence of the strong westward bottom current along the trench, which is likely to act as a factor to reduce the sedimentation rate in the SST.

If subduction continues along the SST, the graben structures should provide a mechanism for removing trench-fill sediments. On the basis of seismic profile obtained from this study, a preliminary estimate can be made of the volume of trench sediments carried down into the subduction zone with the proposed subduction rates at the SST.

On Profile KSL93-6, a rough calculation of a profile area of the graben G1 accommodating trench-fill sediments can be made (Fig. 4). An average thickness of the oceanic sediments on the oceanic basement on the outer slope near the trench is about 500 msec in two-way travel time. The G1 located at the seaward edge of the trench shows the basement at a depth of 800 msec below the trench floor. Thus, the G1 captured the well-defined trench-fill sediments 300 msec thick underlain by the oceanic sediments 500 msec thick. The other graben, the G2 beneath the toe of the accretionary wedge trench-fill sediments, seems to carry more trench-fill sediments. A rough estimation of profile area of G1 for carrying trench-fill sediments is about 0.75 $km^2$ (3 km in width × 0.25 km depth).

From the width of trench floor (12 km) and moderate sedimentation rates (120–300 m/m.y.), two-dimensional amount of trench sediment supply is as much as 1.4–3.6 $km^2$/m.y. (width of trench floor × sedimentation rates). Assuming convergence rates of 40–50 km/m.y. proposed by Henriet et al. (1992) and a graben spacing of 10 km, four to five G1-sized grabens could move down beneath the overriding plate per million years. Calculated amount of sediment consumption by the grabens is 3.2–3.75 $km^2$/m.y. (number of grabens × profile area). This amount is more than the amount of the sediment supply in the trench, indicating that no trench sediments are accumulated in the SST. In case of assuming the slower rates of 10–20 km/m.y. since 6.7 Ma proposed by Maldonado et al. (1994), total sediment consumption of 0.75–1.5 $km^2$/m.y. by the grabens could accommodate nearly one half of the amount of sediment supply. In that case, it would take 6–15 m.y. to accumulate present-day trench-fill sediments of 1000 m thickness.

If the trench-fill sediments 1000 m thick in the SST have been deposited since 3.3 Ma, the average sedimentation rate at the trench is approximately 300 m/m.y. which is close to the rate (287 m/m.y.) at the lowermost of trench slope near the Chile Triple Junction (Behmann, 1992). If it is assumed that the trench sediments have been accumulated after 6 Ma when the subduction rates sharply decreased, the average rate is about 170 m/m.y. similar to the present-day rate (120 m/m.y.) proposed by Porebski et al. (1991).

### 4.3. Scenarios for Subduction History in the South Shetland Trench

Shortening of normal faulting zone of the outer trench wall and thick accumulation of the trench sediments in the SST imply that active subduction activity of the Phoenix plate in the SST became slow at certain points in time. Subduction here means active going-down motion of the oceanic plate beneath the continental plate.

In order to explain how these seismic structures formed, we propose a scenario that (1) normal faulting had taken place on the outer trench wall of the SST before subduction activity sharply decreased at 6 Ma when seafloor spreading ceased in the Scotia plate (top, Fig. 5a), (2) very slow subduction without normal faulting followed during 6 Ma and 3.3 Ma (middle, Fig. 5a), and (3) subduction ceased simultaneously with the cessation of spreading in the ANT–PHO spreading ridge at about 3.3 Ma, and thick trench sediments have been deposited in the SST since 3.3 Ma (bottom, Fig. 5a).

Trench-rollback style subduction in the SST proposed by many scientists (Barker, 1982; Larter and Barker, 1991; Maldonado et al., 1994; Galindo-Zaldívar et al., 2004) may offer an alternative scenario. In case of combining the tectonic model of Galindo-Zaldívar et al. (2004) and current short width of normal fault zone in the SST, another possible scenario is that (1) subduction with normal faulting had continued up to 3.3 Ma or before (top, Fig. 5b); (2) trench roll-back without normal faulting began at 3.3 Ma (middle, Fig. 5b), causing opening of the back-arc Bransfield Basin; and (3) trench roll-back without normal faulting is still ongoing (bottom, Fig. 5b).

Consequently, the major differences between the two scenarios are (1) whether the trench has been fixed or moved seaward since 6 Ma and (2) when/how normal faulting zone on the outer trench wall has been shortened. For the scenarios, it is unclear how fast is the subduction rate to give rise to normal faulting on the outer wall of the trench. However, very slow subduction rate is likely to be difficult to produce normal faulting.

### 4.4. Shortening in the South Shetland Trench

A recent GPS study demonstrates that the South Shetland Islands are moving northwestward (toward the SST) with a horizontal station velocity of about ~1 cm/year (~10 km/m.y.) relative to the Antarctic Peninsula (Dietrich, 2001).

This northwestward movement is thought to be caused by pushing from present-day Bransfield Basin extension behind the islands. However it is hard to say that the movement of the islands is an evidence of ongoing trench roll-back that some scientists strongly believe. It is still possible that the trench could move northwestward or be fixed at the position.

Profile KSL93-6 shows some contractional structures around the toe of the accretionary wedge, that is, a mound-shaped topographic high and a landward-dipping frontal thrust-like fault (MH and FT in Fig. 4). The high laterally extends several kilometers along the toe (Kim et al., 1995). As mentioned earlier, the frontal fault is divided into two branches as sub-bottom depth increases, that is, FT1 of the frontal thrust merging with a basal decollement and FT2 cutting though the lower subunit. F2 is interpreted as an indication of the current shortening being applied to the trench sediments rather than ongoing subduction.

As pointed by Gonzalez-Casado et al. (2000), if the roll-back-style subduction is continuing along the SST, the entire South Shetland margin area should be under extension. Normal faulting on the outer slope of the trench is likely to take place easily. However, the contractional structures observed in the accretionary wedge in the SST are indicative of the compression rather than extension. The compression is thought to be a consequence of northwestward moving of the South Shetland Block because of recent extension of the Bransfield Strait. It suggests that the Bransfield Strait extension is accommodated by diffuse deformation along the SST. If subduction in the SST has ceased already as proposed in our scenario, the Bransfield Strait extension is likely to be caused by a recent sinistral transtentional movement between the Antarctic and the Scotia plates, not by a back-arc extension related to subduction in the SST (Klepeis and Lawver, 1996; Lawver et al., 1996; Gonzalez-Casado et al., 2000).

## 5. CONCLUSIONS

The SST northwest of the South Shetland Islands is the only trench along the Pacific margin of the Antarctic Peninsula. A small oceanic plate, so called ‘former Phoenix plate’, exists between the SST and ANT–PHO spreading centers in Drake Passage. Spreading activities in ANT–PHO spreading centers are known to have stopped at 3.3 Ma. Nevertheless, many scientists believe that subduction in the SST is ongoing accompanied with active extension in Bransfield Basin at the back-arc position.

Multichannel seismic reflection profile shows normal faulting zone about 20 km in width on the outer wall of the SST, which is quite narrow as compared with those (generally 50–75 km) of other present-day active trenches in the world. It is interpreted that normal faulting zone was shortened after normal faulting had ceased. Because graben structures on the subducting oceanic crust in the trenches are known to efficiently carry most trench-fill sediments beneath the accretionary wedge, thick accumulation of trench-fill sediments up to 1000 m thick on the graben structures in the SST would indicate that the trench-fill sediments has deposited since subduction rates dramatically decreased.

Such multichannel seismic structures enable us to propose a scenario that normal faulting no longer occurred since subduction activity decreased sharply after 6 Ma and stopped or became very slow after the cessation of spreading in Drake Passage at about 3.3 Ma.

Shortening forming contractional structures around the SST would be resulted from the trenchward movement of South Shetland Islands due to ongoing extension of Bransfield Strait behind the South Shetland Islands.

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