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Tectonic Evolution of the Southwestern South Shetland Margin, Antarctic Peninsula

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ABSTRACT. In present-day tectonic map, the Hero Fracture Zone (HFZ) is a boundary between passive margin to the southwest and active margin to the northeast along the Pacific margin of the Antarctic Peninsula. New seismic reflection profiles obtained from the southwestern margin of the South Shetland Islands to the northeast of the HFZ show an extensive prograded outer shelf on the seaward flank of the mid-shelf high (MSH). This feature on the outer shelf is typical of the passive margin to the southwest of the HFZ. The propagation of the MSH to the northeast of the HFZ may have been caused by the thermal effect resulting from the subduction of the last ridge-crest segment directly to the southeast of the fracture zone. The strike of the MSH may have changed from NE to NNE to the northeast of the HFZ as a result of the seaward push by the extension of Bransfield Strait. The MSH may not have been a considerable barrier with a positive topography to restrict cross-shelf sediment transport during its formation. The morphological and sedimentary variations in the outer shelf appear to be closely related to vertical motion associated with the formation of the MSH and the change in the strike of the MSH from Smith Island.

Key Words: South Shetland Margin, seismic data, mid-shelf high, tectonic evolution, Hero Fracture Zone

Introduction

The Pacific margin of the Antarctic Peninsula has been an active margin since the breakup of Gondwana (Pankhurst 1982). During Cenozoic, ridge-crest segments of the Antarctic-Phoenix spreading center began to arrive at the Antarctic Peninsula margin. These arrivals moved progressively northeastward along the margin since then. The last arrival of the ridge-crest segment took place directly southwest of the Hero Fracture Zone (HFZ) between 6.4 Ma and 3.3 Ma (Larter *et al.* 1997). As subduction stopped where ridge-crest segment arrived, all of the margin southwest of the HFZ became passive (Barker 1982; Later and Barker 1991). To the northeast of the HFZ, however, three segments of Antarctic-Phoenix ridge still remain in Drake Passage (Fig. 1). Although spreading at the ridge ceased at about 4 Ma, shortening is considered to be active along the South Shetland Trench (SST) to the northwest of the South Shetland Islands (SSI) (Kim *et al.* 1995).

The SSI is a tectonic block bounded by four major structures: on the northeast by the Shackleton Fracture Zone (SFZ), on the southwest by the HFZ, on the northwest by the SST, and on the southeast by Bransfield Strait (BS) (Fig. 1). BS is a marginal basin formed by recent extension between the SSI and the Antarctic Peninsula. The alignment of the SST, SSI and BS has led many scientists to interpret BS as a back-arc basin. In the southwestern SSI, Boyd Strait is a seaway sub-parallel to the HFZ, and is perpendicular to BS (Fig. 2).

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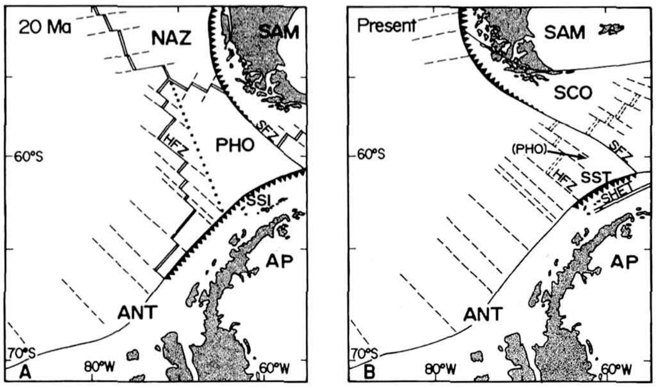

Fig. 1. 20 Ma reconstruction (left) and present day tectonic setting (right) of the south-east Pacific. Double lines indicate active ridge segments, and sawtooth lines are trenches. Double dashed lines represent no longer active ridge crest segments and single dashed lines show fracture zone trends. Dotted line indicates the approximate position of the bight between ocean floor formed at the Antarctic-Phoenix ridge and ocean floor formed at the Nazca-Phoenix (formerly Farallon-Phoenix) ridge. NAZ, Nazca Plate; SAM, South American Plate; PHO, Phoenix Plate; SCO, Scotia Plate; ANT, Antarctic Plate; SHET, South Shetland Microplate; AP, Antarctic Peninsula; HFZ, Hero Fracture Zone; SSI, South Shetland Islands; SST, South Shetland Trench. Modified from Larter and Barker (1991), and Tomlinson *et al.* (1992).

On Dec. 1996, we collected seismic data in the southwestern SSI (Fig. 2). The data were obtained using a 75-m streamer with 12 hydrophones and two airgun sources with a total capacity of 6 liters on R/V *Yuzhmorgeologiya*. In this study, we will examine seismic structure of an area in the southwestern SSI in order to understand tectonic evolution of the tectonic boundary between passive and active margins.

Interpretation of seismic reflection data

Mid-shelf high (MSH)

To the SE end of all profiles in this study, we can see the structural highs occurring just beneath the seafloor, on whose seaward flank extensive sedimentary sequences are developed. The highs are characterized by very weak internal reflection, a series of strong bubble noises, and multiples of the seafloor (Figs. 3, 4, and 5). These highs show the

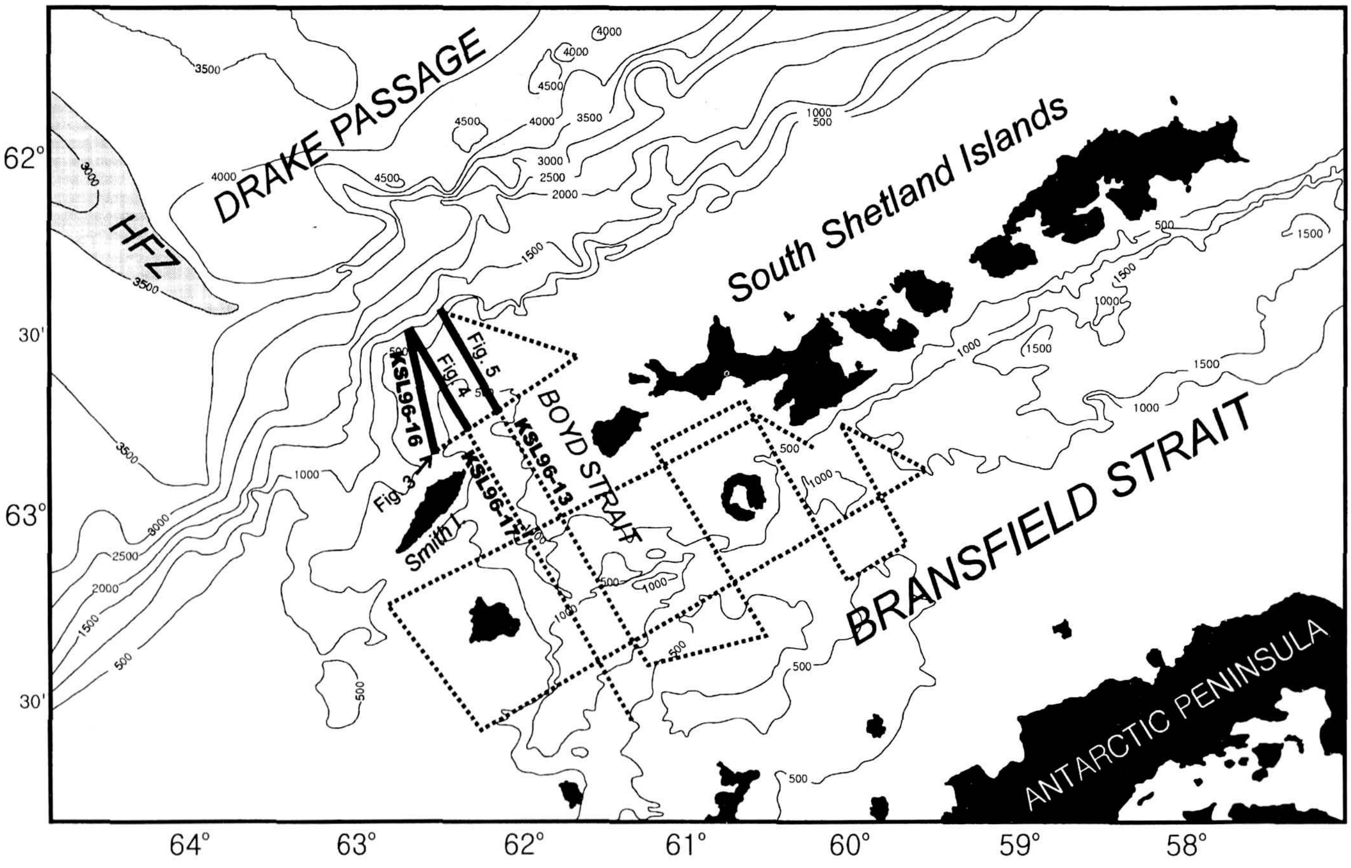

Fig. 2. Location of seismic lines (dotted lines) in this study. The heavier lines indicate seismic sections shown in Fig.s 3, 4, and 5. HFZ, Hero Fracture Zone.

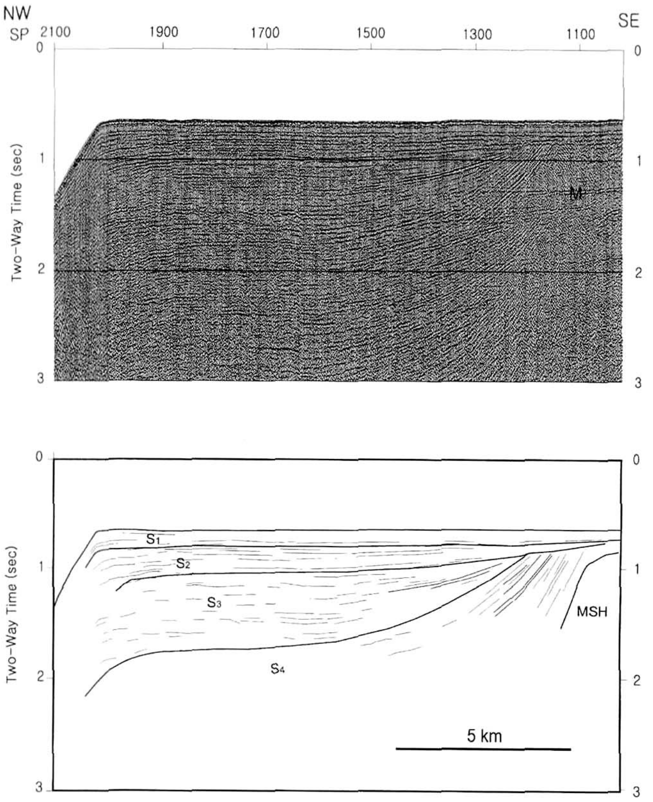

Fig. 3. Seismic profile and interpretive line drawing of KSL96-16 showing the MSH, extensive prograding/aggrading sequences in outer shelf. See discussion in the text and Fig. 2 for location. M is seafloor multiple.

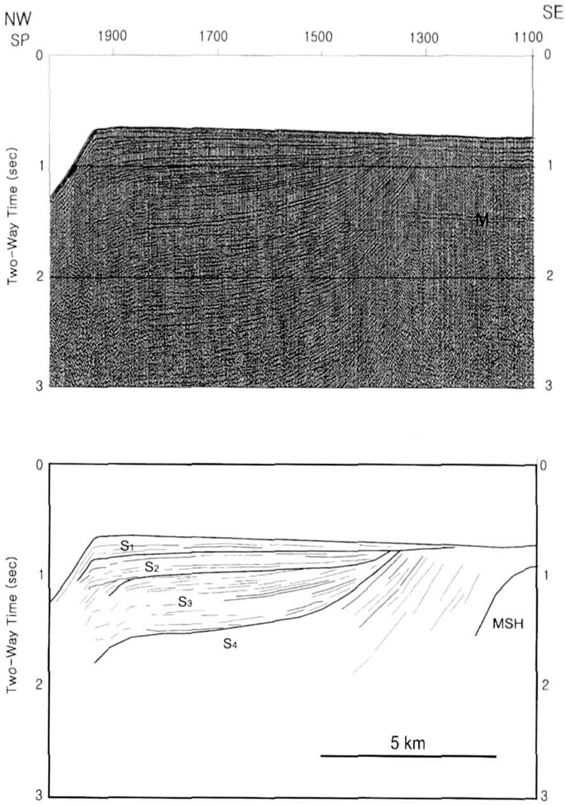

Fig. 4. Seismic profile and interpretive line drawing of KSL96-17 showing the MSH, extensive prograding/aggrading sequences in outer shelf. See discussion in the text and Fig. 2 for location. M is seafloor multiple

same seismic characteristics, occurring position, and overlying sedimentary stratigraphy with the mid-shelf highs (MSH) generally recognized to the southwest of the HFZ.

On free-air gravity anomaly map, there is a gravity high associated with the MSH continuously extending from 63°S to 69°S along the Antarctic Peninsula margin (Larter *et al.* 1997). The MSH runs parallel to the margin in the NW direction. The strike of the structural highs in this study is traced to Smith Island which has been known to be the northeasternmost sub-aerial part of the MSH (Larter *et al.* 1997). We strongly consider that the structural highs are part of the MSH extending whole Antarctic Peninsula to the southwest of the HFZ. The MSH has been interpreted as a result of Miocene-Pliocene interaction between the margin and ridge-crest segments of the Antarctic-Phoenix ridge (Bart and Anderson 1995; Larter *et al.* 1997).

However, there is no arrival of ridge-crest segment in front of the study area. The last arrival of ridge-crest segment took place directly to the southwest of the HFZ. Instead dead spreading ridges still remain off the SSI to the northeast of the HFZ.

The distance from the shelf edge to the MSH on the profiles decreases northeastward along the margin: 27 km on profile KSL96-16, 22 km on profile KSL96-17, and 18 km on profile KSL96-13. Although profile KSL97-16 is slightly oblique with respect to the other profiles (Fig. 2), the axis of the MSH in this study area has NNE strike from Smith Island.

Outer shelf

Profiles of KSL96-13, KSL96-16 and KSL96-17 reveal a well-developed outer shelf basin, with four depositional sequences (S1-S4) on the seaward flank of the MSH (Figs. 3, 4, and 5). On profiles KSL96-16 and KSL96-17, S4 reflectors dip steeply and are erosionally truncated near the MSH. This feature implies that uplift of the MSH took place after the deposition of S4. S4/S3 boundary is generally conformable except locally onlap near the MSH. S3 is

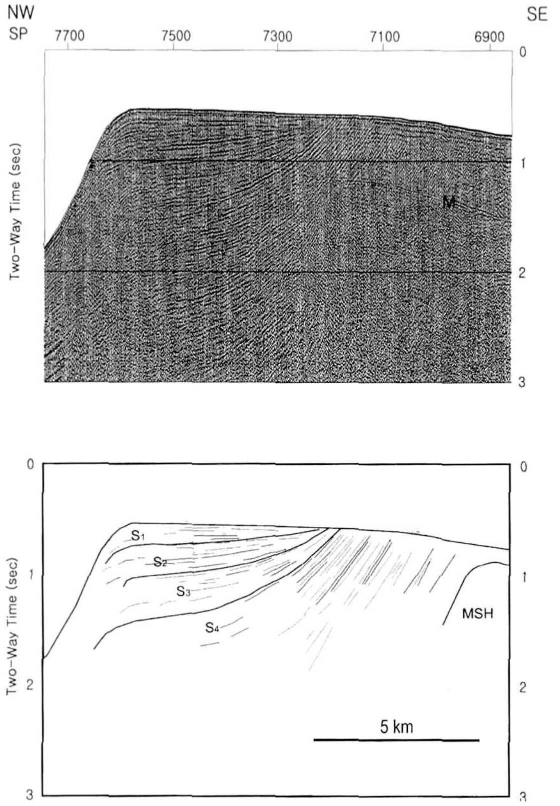

Fig. 5. Seismic profile and interpretive line drawing of KSL96-13 showing the MSBH, dipping sequences in outer shelf. See discussion in the text and Fig. 2 for location. M is seafloor multiple

relatively thick beneath the shelf edge (up to 600 m), and rapidly pinches out toward the MSH. The dip of S3 reflectors increases toward the MSH and becomes gentle upward with time. These stratigraphic configurations suggest that a major uplift occurred during the deposition of S3. The top of S3 is erosionally truncated. Just over the S3/S2 boundary, paleo-shelf edges in S2 advanced about 1.5 km seaward without aggrading sequences, and its foresets are erosionally truncated. It implies a strong erosion by grounded ice sheets during glacial times. This boundary is similar with the S3/S2 boundary observed along the margin further southwest along the Antarctic Peninsula (Larter *et al.* 1997). S2 and S1 show several prograding/aggrading sequences. S2/S1 boundary, recent major erosional unconformity, varies progressively into S3/S1 and S4/S1 boundaries toward the MSH. The seafloor is flat about 500 m in water depth, whereas S1 on profile KSL97-16 is thicker than on profile KSL96-17. This means that S2/S1 boundary get shallow toward northeast.

On profile KSL96-13, all sequences have dipping layers and are truncated by the seafloor. S4 is very thick and well developed, but the upper prograding/aggrading sequences (S1, S2, and S3) are poorly developed. The later feature represents erosion by grounded ice sheets. The elevation of the shelf edge is about 100 m higher than those of profiles KSL96-16 and KSL96-17. Water depth increases landward rapidly.

Discussion

MSH formation and its strike change to the northeast of Smith Island

According to present-day tectonic map, our study area belongs to an active margin between the HFZ and SFZ. Maldonado *et al.* (1994) first reported the occurrence of the structural high extending along strike from Smith Island. They interpreted it as an extension of the MSH, which is typical of structural high along the Antarctic Peninsula margin, and proposed that the MSH may have been formed by the thermal effect of a subducted ridge crest or "slab window" as it propagated from the southeast to the northeast beyond the HFZ.

However we should consider the role of the HFZ against propagation of thermal effect. The HFZ now has a buoyant ridge 1500 m higher than the surrounding area. Thus the fracture zone ridge is likely to have deep root, which would act as a barrier to thermal propagation. Furthermore, the subduction of ridge itself would also provide large effects like thermal effect and topographic abrasion beneath the margin. In fact, Smith Island with remarkable elevation appears on the landward projection of the HFZ, and the bathymetrical reentrant is well developed between the ridge and island. These structures is throught to be a result of subduction of the HFZ ridge. In addition, it is questionable whether the thermal effect could be expanded beyond the HFZ.

The NE strike of the MSH is uniform along the whole Antarctic Peninsula margin southwest of the HFZ. To the northeast of Smith Island, however, the strike of the MBH changes slightly to NNE, which change may have been caused by the recent extension of Bransfield Strait.

The extension of Bransfield Strait was the last tectonic event that let to present-day tectonic setting of the study area. Although there are many arguments about the starting time of the extension, Bransfield Strait is thought to begin to extend at about 4 Ma (Barker 1982; Perra *et al.* 1984, González-Ferrán 1991). Based on aeromagnetic data, González-Ferrán (1991) suggested a 5 to 15 km extension during the past 2 m.y. Bathymetric characteristics and seismic structures suggest that major rifting occurred within the Central Bransfield Basin and propagated progressively into both sides of the basin (Lawver *et al.* 1996; Gracia 1996; Barker and Austin 1998; Jin *et al.* 1999). Jin *et al.* (1999) presented a seismic profile showing highly stretched crust by many normal faults in the Western Bransfield Basin which is evidence of recent extension.

As a result of the Bransfield Strait extension, the SSI block has been pushed toward the northwest and separated from the Antarctic Peninsula. As the extension propagated southwest in time, the width of the net rift decrease from the Central Bransfield to the Western Bransfield Basin. It is possible that the landward projection of the HFZ crossing Smith Island may have been an end point of the Bransfield Strait extension. The arc-shaped southeastern margin of Smith Island may be caused by this push. The maximum displacement of the MSH to the northeast of Smith Island is very roughly estimated to be more than 10 km. Fig. 6 is a very simplified tectonic map based on this interpretion.

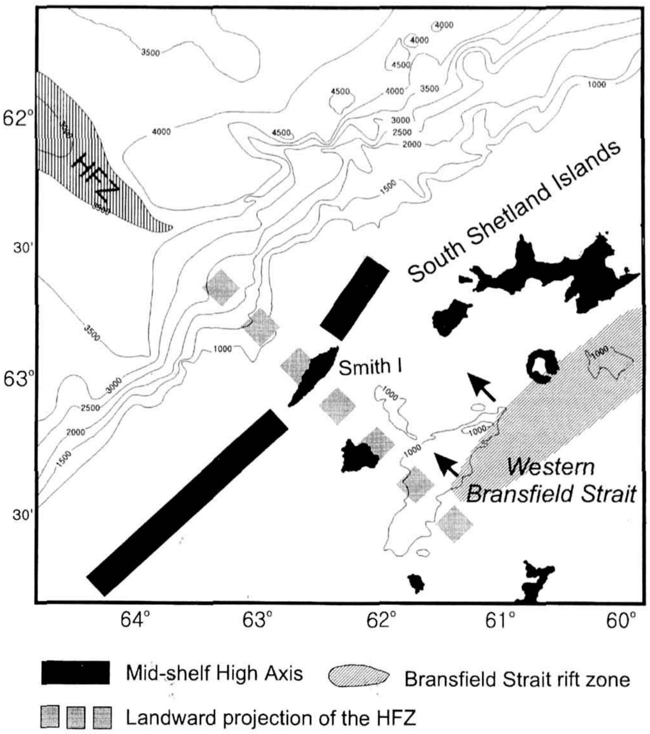

Fig. 6. A simplified tectonic chart of the study area showing the mid-shelf high axis, Bransfield Strait rift zone, and a landward projection of the Hero Fracture Zone (HFZ). Solid arrows represent the postulated direction and magnitude of Bransfield Strait extension. See discussion in the text.

Implications from seismic stratigraphy of the outer shelf

All profiles in this study show an outer shelf basin with four depositional sequences on the seaward flank of the MSH. We can identify two principle sequence boundaries (S4/S3 and S3/S2), which are evident on all seismic profiles crossing the Antarctic margin southwest of the HFZ. The S4/S3 and S3/S2 boundaries correspond to an uplift unconformity (S4/S3) and 'base of glacial-margin sequences' (BGMS) (S3/S2) presented on profile AMG845-03 (Larter *et al.* 1997), respectively. The uplift unconformity is considered to be related to the uplift of the MSH. Since the up lift was a result of the interaction between ridge-crest segment and margin, the arrival timing of the segment at the margin is thought to be diachronous along the margin. The BGMS is considered to be synchronous, which would be caused by greater lowering of sea level at times of glacial maximum in the late Pliocene (Barker, 1995; Larter *et al.* 1997).

The arrival of ridge-crest segment nearest to the study area occurred directly southwest of the HFZ at about 6.4 Ma (Larter *et al.* 1997). Despite about 150 km difference in the distance, profile KSL96-17 shows a similar seismic stratigraphic pattern with two profiles further southwest (AMG845-07 and AMG845-08) present by Larter and Barker (1991). These AMG profiles cross the outer shelf near Anvers Island southwest of the HFZ. The age of ridge-crest arrival near Anvers Island is 6.5-6.9 Ma

(Larter *et al.* 1997). Since both ridge-crest arrivals occcurred almost simultaneously, it is possible to correlate the sequences on profile KSL96-17 with AMG profiles. S3 on profile KSL96-17 shows more extensive prograding/aggrading sequences (about 500 m thick) to the continental slope than those on two AMG profiles. It suggests that the MSH on profile KSL96-17 did not act as a considerable topographic barrier to restrict the cross-shelf sediment transport during the deposition of S3. The seaward dip of S3 reflectors increases progressively moving toward the MSH and become stable. This implies that the uplift of the MSH continued during the deposition of S3, but the degree of uplift diminished with time.

In this study, three profiles show systematic structural variation in the outer shelf. While S4 becomes rapidly thick and advances seaward, the widths of overlying sequences (S3, S2, and S1) become narrow and their dips increase (Figs. 3, 4 and 5). The top of the MSH becomes deep toward southwest from profile KSL96-13 to profile KSL96-16. This variation reflects the change in vertical motion associated with the arrival of ridge-crest segment. Futhermore, the southwestward deepening of the MSH implies that net subsidence increases toward southwest. On the northeasternmost profile of KSL96-13, all sequences with dipping layers indicate that uplift has continued until recent. In addition, the high elevation of the outer shelf is an evidence of a less amount of subsidence after uplift.

Larter and Barker (1991) suggested that, under their assumption, the predicted thermal subsidence on their profiles along the Antarctic Peninsula margin are about 640 m on profile AMG 845-07 (5.6 Ma arrival), about 960 m on profile AMG845-08 (10.0 Ma arrival), and about 1310 m on profile AMG 845-19 (16.5 Ma arrival). This implies that the amount of subsidence is closely related to the arrival time. As mentioned earlier, the MSH to the northeast of the HFZ was probably formed by the thermal effect of the last arrival of ridge-crest segment directly at the southwest of the HFZ. This means that thermal effect decreased and the time of the MSH formation was later toward northeast. Consequently, subsidence after uplift of the MSH was taken place relatively weakly on the KSL96-13. It appears that subsidence would be an important factor to control the marginal morphology of the Antarctic Peninsula.

Conclusions

The HFZ is the boundary between the passive margin to the southwest and the active margin to the northeast along the Antarctic Peninsula margin. New seismic reflection profiles obtained from the continental margin of the southwestern SSI to the northeast of the HFZ show an extensive outer shelf basin with four depositional sequences on the flank of the MSH. This feature of the outer shelf is very similar to those observed seismic profiles from the southwestern margin of the HFZ.

The MSH to the northeast of the HFZ may have been formed by thermal effect from ridge-crest segment that arrived at the margin directly southwest of the HFZ. The strike of the MSH changed from NE to NNE northeast of Smith Island. This change could have been caused by the seaward push from recent rifting of the western Bransfield Strait.

S3 is the very extensive prograding/aggrading sequence to the northeast of the HFZ. The MSH was not a considerable high enough to restrict cross-shelf sediment transport during deposition of S3. The increase in dip of S3 reflectors toward the MSH implies that the uplift of the MSH continued during deposition of S3.

The top of the MSH becomes shallow, and the dips of sedimentary sequences and the elevation of the shelf edge in the outer shelf increase toward northeast. This morphological variation is considered to be strongly controlled by vertical motion associated with subsidence following uplift of the MSH. We consider that thermal effect propagated from the last arrival of the ridge-crest segment just southwest of the HFZ diminished toward northeast. The uplift timing of the MSH would be progressively later, and the amount of the MSH uplift decreases rapidly toward the northeast in the study area. Therefore the net subsidence associated with the uplift may have not occurred enough at the northeasternmost part of the study area yet.

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