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# SEISMIC STRATIGRAPHY, TECTONICS AND ICE SHEET CONFIGURATION OF CONTINENTAL MARGIN SEQUENCES IN THE BELLINGSHAUSEN SEA, WEST ANTARCTICA

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***Abstract:*** Recent advancement in Sequence Stratigraphy indicated that the stratigraphic signature in the Antarctic continental shelf profiles could serve as a gage of tectonics and ice sheet configuration change during the Neogene. To accomplish this purpose, two profiles from the continental shelf off Adelaide Island, Bellingshausen Sea are reexamined. The layers of S4 are recognized at the base of the continental slope as an accretional sediment and at the mid-shelf high as a tectonically uplifted stratum before and during oceanic ridge crest to trench (RC-T) collision. The age of S4 is assigned to be Early Miocene and the RC-T collision occurred in the Middle Miocene. During the following subsidence period in the Late Miocene, S3 and S2 were deposited as seaward progradational sequences in a passive margin condition. The sequence boundary between S2 and S1 was interpreted to be produced by shelf edge grounding of ice sheets after a period of large deglaciation in the Early Pliocene. The boundary corresponds to the time when the levee channel complexes were formed in the slope fan areas. The S1 reflects more frequent ice sheet grounding in the Pleistocene.

## 1. Introduction

The Antarctic continental shelf is characterized by its great depth of average 500 m, rugged topography sloping toward the continent, commonly broad width of 200 km in most of West Antarctica, and its glacial setting. Theoretical models for glacial isostasy indicate that the continental shelf seaward of the ice sheet is depressed nearly 200 m with a proglacial isostatic depression extending 180 km seaward of the ice sheet edge (WALCOTT, 1970).

Glacial erosion has contributed significantly to overdeepening and rugged topography of the continental shelf. During the Pliocene and Pleistocene, the Ross Sea Unconformity was formed on the Ross Sea continental shelf; it was caused by expansion of ice sheets onto the shelf. An estimated 200 to 800 m of sediment was eroded from the shelf during this event (ANDERSON, 1991).

The notion that the mainly continental ice sheet in East Antarctica formed in the Early Neogene and remained more or less stable throughout the Late Neogene has been criticized by DENTON *et al.* (1984).

The high-elevation of Sirius basal till deposits occurs on the Transantarctic Mountains from 2700 to 4100 m high. Some basal tills contain far-traveled erratics of Shackleton Limestone, granite and gneiss originated from the East Antarctic continent that show outlet ice flows across the Transantarctic Mountains (DENTON *et al*., 1991). Two possibilities are raised: a Late Pliocene (3.0 or 2.4 Ma) glaciation was responsible for the high-elevation Sirius basal till, which suggests that the Antarctic ice sheet achieved a 'robust' configuration to override the Transantarctic Mountains (*e.g.* DENTON *et al*., 1984); or there has been massive tectonic uplift since the Early Pleistocene along the Transantarctic Mountains without any 'robust' ice sheet (*e.g.* MCKELVEY *et al*., 1991). However, these problems are so complex that those who are interested in these subjects refer to a paper by MORIWAKI *et al*. (1993).

Development of natural levees on the western side of submarine canyons in the Bellingshausen Seä indicated that meltwater and eroded sediments from extending grounded ice sheets provided a potential source for natural levees. It also indicated that activity of levee formation was much greater in the past than at present (KAGAMI and IWASAKI, 1991; KAGAMI *et al*., 1991).

To understand these problems, this study attempts to reexamine the stratal signature of the Bellingshausen continental shelf profiles from the Sequence Stratigraphical point of view.

## 2. Bellingshausen Sea Margin

The Bellingshausen Sea margin was surveyed during the TH-80 cruise of HAKUREI MARU of the basic research program on geology of Antarctica, Technology Research Center of Japan National Oil Corporation (JNOC) (KIMURA, 1982). During the 1980-81 field season, a multichannel seismic (MCS) system (KAGAMI *et al*., 1980) obtained two profiles from the continental shelf near Adelaide Island, West Antarctica (Fig. 1).

The tectonic evolution of this continental margin has been controlled by a series of oceanic ridge crest to trench (RC-T) collisions which took place episodically between major fracture zones. Once, the area was an active margin and the Phoenix plate was subducted with the mid-oceanic ridge under the Antarctic continent (TUCHOLKE *et al*., 1983).

Since fracture zones were developing parallel to the direction of subduction, the boundaries between segments of different aged section of seafloor stayed at the same point on the margin (LARTER and BARKER, 1989). Southwest of the Tula Fracture Zone, the ridge subducted in the Middle to Late Eocene (35 Ma), and the segment of the margin became passive. The ridge segment between the Tula and Anvers Fracture Zones subducted in the Early Miocene (16 Ma). This is the study area, from where the multichannel seismic lines were obtained. Magnetic anomaly '6' was recognized near the margin with an additional 'magnetic quiet zone', which indicates that the ridge collided with the trench at around 16 Ma. The ridge segment between the Anvers and Hero Fracture Zones was subducted during the Late Miocene, around 6 Ma (LARTER and BARKER, 1991).

Very similar Neogene stratal geometries have been observed at almost all continental margins of the world including the Ross Sea, Antarctica, and their similarity is thought to be a manifestation of glacioeustatic fluctuations (BARTEK *et*

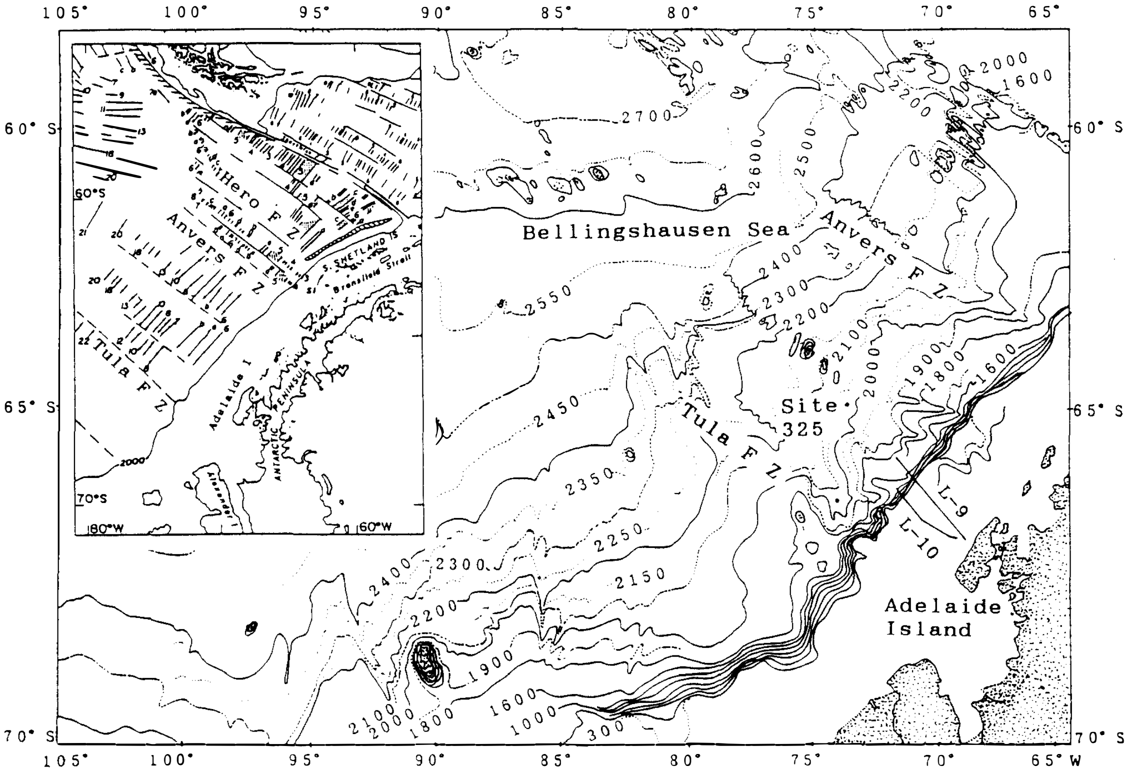


*Fig. 1. Map of location of Line TH-80-9 (L-9) and Line TH-80-10 (L-10) off Adelaide Island, West Antarctica. The location of DSDP Site 325 is also shown. Bathymetry is in meters. Inserted figure is the magnetic anomaly map of* LARTER *and* BARKER *(1991).*

*al*., 1991).

According to ANDERSON (1991), the following four sequences in seismic reflection profiles were observed on the continental shelf southeast of the Tula Fracture Zone in the Bellingshausen Sea. The oldest stratum is Sequence 4 (S4) characterized by folded and faulted features, and consists of pre- and syn-tectonic deposits of presumable subduction-accretion material. Sequence 3 (S3) drapes over S4 and is consistent with passive margin development. This sequence is deeply eroded to form an unconformity which is parallel to the S3 layering and extends to the shelf edge. Sequence 2 (S2) is characterized by numerous glacial erosional surfaces which bound acoustically massive units interpreted as till tongues. Finally, Sequence 1 (S1) is a draping unit over the shelf that is interpreted as consisting mainly of glacial marine deposits.

## 3. Interpretation of MCS Data

Five major sequences have been identified on the studied profiles from the shelf of Bellingshausen Sea. They are series of progradational sequences at the shelf margin and are labeled S1 to S5 following ANDERSON (1991) and LARTER and BARKER (1991).

Figure 2 shows an onboard monitor record of Line TH-80-9 obtained from the shelf margin off Adelaide Island. Sequence boundaries are clearly identified on this profile, because a shelf margin profile is devoid of multiple reflections. S1 to S5 are shown in the figure.

Seismic reflection profile of the entire continental shelf is shown in Fig. 3. Oceanic basement is observed at around 6 s in two-way travel time on SP 5000. The mid-shelf structural high (MSH) is clearly observed on SP 7000. This uplifting structure is mainly identified on the upper surface of the S4 layer and is similar to the mid-slope structural high observed in the present trench areas which may have been formed by the RC-T collision and subduction into the basement of the continental shelf.

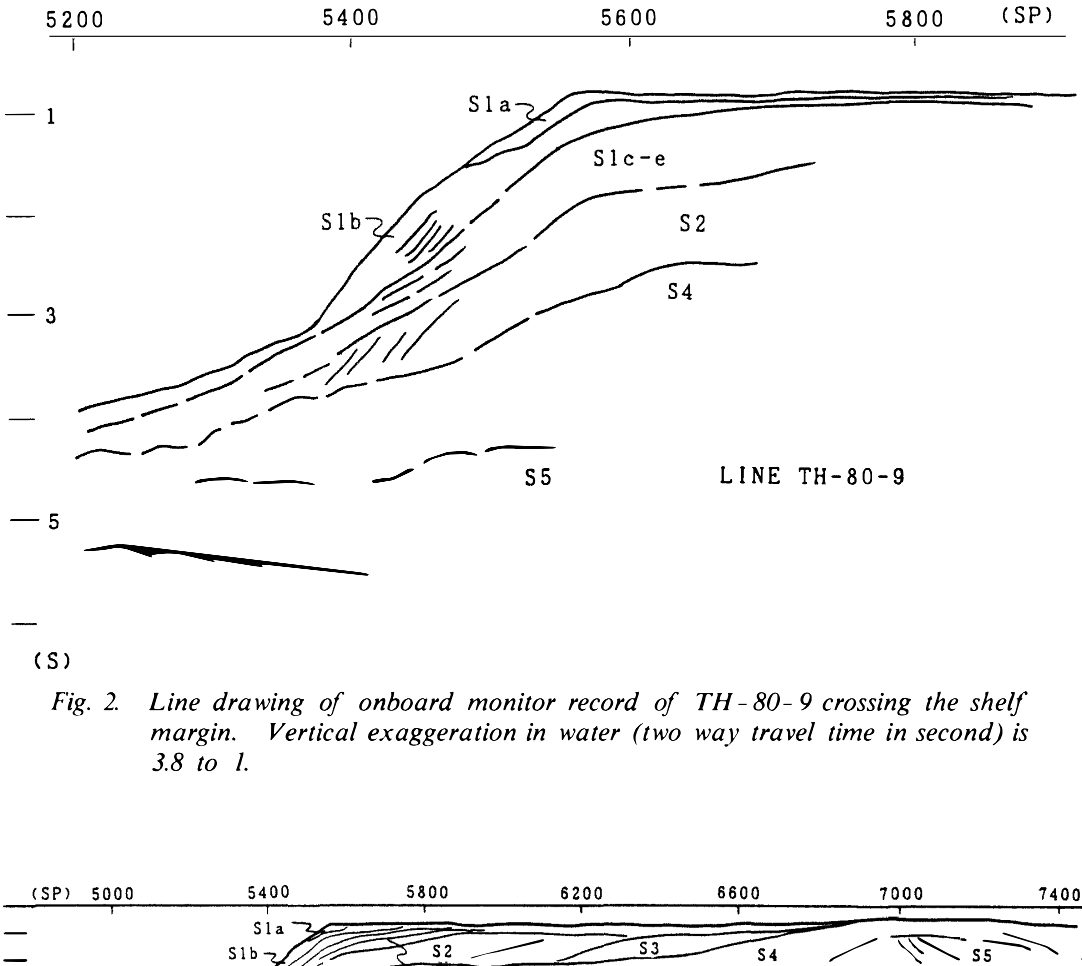


*Fig. 2. Line drawing of onboard monitor record of TH-80-9 crossing the shelf margin. Vertical exaggeration in water (two way travel time in second) is 3.8 to 1.*

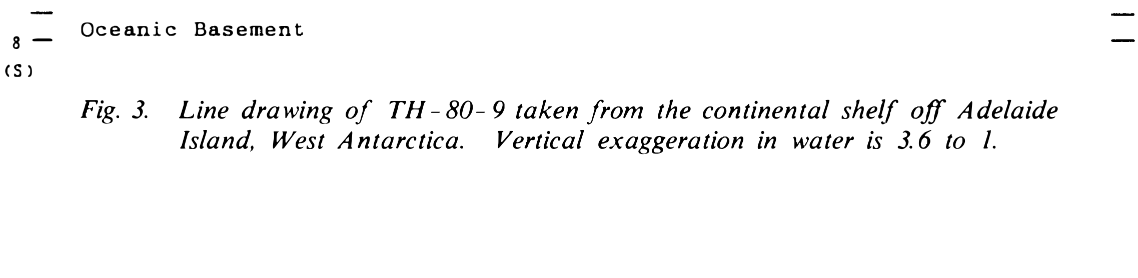


*Fig. 3. Line drawing of TH-80-9 taken from the continental shelf off Adelaide Island, West Antarctica. Vertical exaggeration in water is 3.6 to 1.*

It can be seen also that the S4 layer was erosionally truncated toward the MSH and erosionally overlain by deposition of S3 and S2. The S3 indicates a palaeoshelf break at the far retreated position of the shelf. The onlap situation observed at the base of the S3 onto the MSH may indicate continued subsidence of the MSH during deposition of the S3. From these observations, it is thought that S4 and S5 were subduction sediments formed at the active margin, while S1, S2 and S3 were deposited under the passive margin condition.

S1 is divided into five subsequences, S1a to S1e (Fig. 2), which are shelf-wide draping units comprising the shelf break and are characterized by steeply dipping foreset on the continental slope. These S1 subsequences constitute extreme oceanward advancement of the slope beyond the shelf edge which may have been formed by expansion of the West Antarctic ice sheet during the Plio-Pleistocene (LARTER and BARKER, 1991). The bounding unconformity between the S1 and S2 on the continental shelf records the first of several glacial erosions of the succeeding glacial episodes.

S2 is a seaward progradational wedge formed above the truncation unconformity caused by tectonic subsidence of the shelf consisting of the S4 after subduction of the oceanic ridge crest. Glacial erosions may provide additional modifications. Downward tilting reflection observed on the continental slope is evidence of rapid progradation of sediment supply at the end of this period when a barrier on the shelf (MSH) disappeared completely so that ponded sediments could freely arrive at the continental margin. S2 might be assigned to the highstand systems tract at the shelf margin (VAIL *et al*., 1991).

S3 filled a subsiding forearc basin with an onlap relation toward the MSH (Fig. 3). The remnant of the MSH still existed as a barrier for sediment supply that provided the smaller amount of deposition for S3. Although S3 was a small stratum, it shows a seaward progradational sequence and might be assigned to the shelf margin systems tract (VAIL *et al*., 1991).

S4 and S5 represent accreted sediments during the subduction period, when the Phoenix plate subducted into the trench along West Antarctica (LARTER and BARKER, 1991).

Line TH-80-10 runs almost parallel to Line TH-80-9 ; therefore, sequences are seen having similar geometry (Fig. 4).

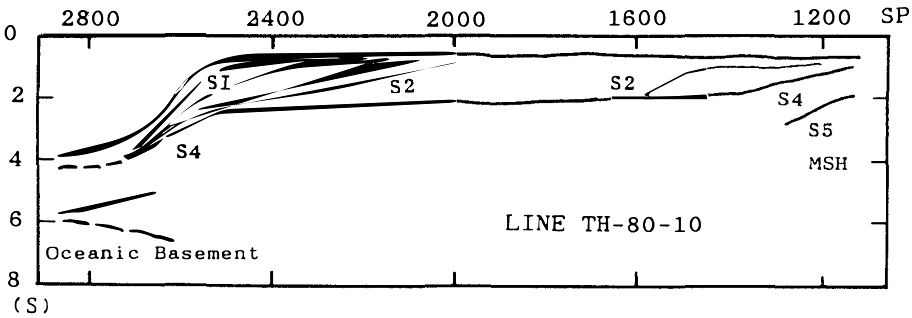


*Fig. 4. Line drawing of TH-80-10. Vertical exaggeration in water is 3.6 to 1.*

## 4. Estimated Age of Observed Sequences

The ages of S1–S4 are inferred from tectonic relationship and stratigraphic correlation with DSDP Leg 35 sites on the adjacent continental rise.

At DSDP Site 325, a reduced sedimentation rate is thought to be a hiatus between 15 and 8 Ma, and a high sedimentation rate is observed between 3 and 4 Ma (TUCHOLKE *et al*., 1983).

S4 is assigned to be an accreted stratum in an active margin condition, which is evidenced by rugged features of the profile at the base of the continental slope and by the structural high observed at the middle of the continental shelf. The active margin existed before and during RC-T collision. The estimated age of RC-T collision in the segment between the Adelaide FZ and Anvers FZ is 16.5+0.7 Ma (LARTER and BARKER, 1991). Therefore, the age of S4 is the Early Miocene or older.

S3 and S2 mark the onset of passive margin conditions, which are evidenced by seaward progradational wedges of shallow marine deposits. After the RC-T collision in the Middle Miocene, they might deposit from the Late Miocene or partly latest Middle Miocene to Early Pliocene.

S1 are essentially glaciomarine in nature and occurred during Plio-Pleistocene time. BARTEK *et al*. (1991) proposed that the oceanward advancements of the last several sequences such as S1a–S1e were observed worldwide and dated back to 3–4 Ma. Gravelly and sandy turbidites were deposited at DSDP Sites 322, 323, 324 and 325 on the Bellingshausen continental rise during the Plio-Pleistocene (TUCHOLKE *et al*., 1983; WRIGHT *et al*., 1983). These deposits are inferred to be supplied from adjacent shelves through canyons.

Estimated ages of these sequences and correlation with DSDP Site 325 where an accumulation rate was obtained through time are shown in Table 1.

A chronostratigraphic section for the outer shelf between SP 5500 and 8000 of Line TH-80-9 was prepared (Fig. 5). The time scale was adapted from Table 1. A hiatus observed between S4 and S3/S2 was formed by uplifting of the middle of the shelf caused by RC-T collision. The collision took place when the ridge crest met the base of the continental slope. Upon colliding of the ridge crest, the continental shelf experienced tectonic upheaval which might have continued from 16 to 8 Ma. The sequence boundary between S2 and S1 shows a marked reflector beneath the shelf edge, which may have been produced by actions of ice sheet grounding extended to the shelf edge and correspond in age between 3 and 4 Ma.

*Table 1. Correlation of units at DSDP Site 325 (TUCHOLKE et al., 1983) with sequences from TH-80-9 off Adelaide Island.*

| Age | Accumulation rate (cm/1000 a) | Corresponding formation |
|---|---|---|
| Early Miocene | 10 | S4 |
| | Hiatus (Ridge-trench collision) | |
| Late Miocene | 7 | S3 |
| Pliocene | 20 | S2 |
| Quaternary | 2 | S1 |

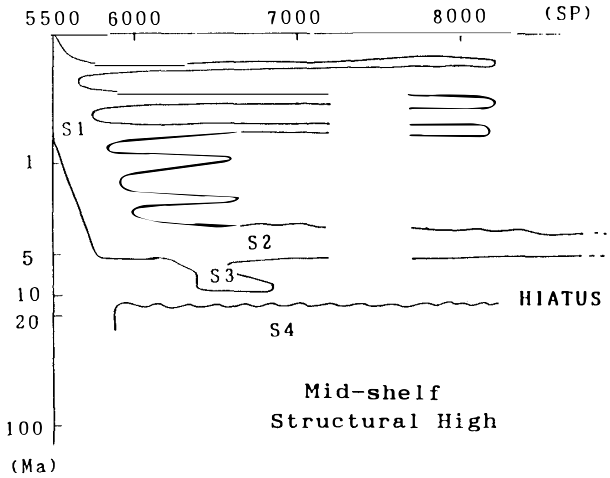


*Fig. 5. Chronostratigraphic section for shelf sequences of TH-80-9.*

## 5. Discussion

There are no generally accepted criteria between West Antarctic ice volume and the flux and spatial distribution of Southern Ocean ice rafted detritus (IRD). At DSDP sites 513 and 514 (47°S) in the Southern Atlantic, BORNHOLD (1983) reported that a significant increase in IRD started from 6.7 Ma, with a modest increase between 5.5 and 5.0 Ma and a peak flux of IRD reached between 4.1 and 3.6 Ma. During the Late Pliocene, IRD was generally low with a modest increase between 2.7 and 2.6 Ma. High input of IRD generally characterizes the Pleistocene, with peaks at 2.1 to 1.8 Ma, 1.5 to 1.1 Ma, and 0.9 to 0.7 Ma. The highest IRD between 0.9 and 0.7 was attributed to accelerated melting rates.

In the Kerguelen area of the Indian Ocean, the relatively higher amounts of IRD in the Late Miocene to Early Pliocene (7.0–3.6 Ma) were attributed to relatively warmer conditions with retreats of ice sheets (BARRON *et al*., 1991).

There are different interpretations of the deep-sea oxygen isotope records on Cenozoic Antarctic glaciation ; 1) SHACKLETON (1987) proposed that very little ice existed on Antarctica in the earliest Oligocene with stepwise growth during the Neogene ; 2) MILLER *et al*. (1987) argued that significant ice was present in the Earliest Oligocene but that ice sheet disappeared during parts of the Oligocene and Early Miocene, followed by growth and decay of several ice sheets ; 3) PRENTICE and MATTHEWS (1988) noted that Antarctic ice volume was never significantly greater than at event 2.2 (approximately 2 Ma) when up to about twice the volume of the modern Antarctic ice sheet existed, and never significantly less than today since the latest Middle Eocene.

After ODP Leg 119 in Prydz Bay of East Antarctica, it has become clear that a significant late Middle-Late Eocene glaciation was present on East Antarctica, that a major continental-sized ice sheet was present in the Earliest Oligocene which was likely temperate in character, and that periods of ice sheet retreat were recognized in the Late Miocene (7.4 to 6.6 Ma), Early Pliocene (4.6 to 3.6 Ma) and Late Pliocene (2.22 to 1.89 Ma) (BARRON *et al*., 1991).

Thus, it becomes clear that IRD, oxygen isotope record and ODP drilling indicate very fragile Antarctic ice sheet through time.

A peak value of sedimentation rate in the Pliocene noted at DSDP Site 325 in Table 1 might be produced by accelerated melting or deglaciation rather than by more severe glaciation. A possibility of the robust ice sheet (DENTON *et al.*, 1991) and its large grounding on the continental shelf to the high sedimentation rate in the Pliocene deep waters might not be counted, because such a large ice sheet was invariably grounded when it entered the sea, but could not advance onto the shelf edge without sea level falling. Evidently such a single large ice sheet did not exist as mentioned in the preceding paragraphs. The shelf break of S2 indicates that the S2 ice sheet was smaller than the S1 ice sheets (Figs. 2 and 3).

The sequence boundary between S2 and S1 was correlated with the Middle Miocene tectonic hiatus by LARTER and BARKER (1991). However, it is proposed in this paper that the boundary was produced by shelf edge grounding of the ice sheet after relatively large deglaciation in the Early Pliocene. The grounding of the ice sheet did not reach the present shelf edge, but it traveled far from inland, for a longer distance to the shelf edge, thus marking a greater length of erosion and producing a larger amount of coarse detrital materials. This might be the reason that a levee channel complex was formed in the fan area.

## 6. Conclusions

The effect of RC-T collision on the continental shelf is clearly observed at the hiatus between the S4 and S3/S2. 1) Tectonic uplift of the mid-shelf structural high occurred as a result of high-angle reverse faulting associated with prolonged subduction of the oceanic plate under West Antarctica, which is analogous to the mid-slope structural high in the trench areas; and 2) the uplift has been followed by erosion of the uplifted area (MSH) and by subsequent steady subsidence of the continental shelf.

During the steady subsidence period in the Late Miocene, a basal sequence consisting of seaward prograding wedges of shallow water origin (S3) was deposited with onlap relation on the shelf.

By the Early Pliocene, the shelf had been lowered enough by glacial erosion. Fairly uniform deposition of the S2 could be achieved by sediment supply through accelerated melting of the ice sheets. A higher rate of deposition was observed in the deep sea fans as levee channel complexes of the lowstand systems tract (VAIL *et al.*, 1991) developed. This could have resulted from decoupling and retreat of the ice sheet from the continental shelf during the Early Pliocene, and from supplying more abundant sediments by the succeeding ice sheet grounding to the shelf edge in the Late Pliocene.

In the Plio-Pleistocene, deposition of glaciomarine sediments (S1) occurred on the shelf. Waxing and waning of the ice sheet became maximum amplitude, strongly linked to sea level change and deposited S1 subsequences. Fluctuations in sea level in the late Pleistocene partly resulted from the build-up of ice sheets in the northern hemisphere (ANDERSON, 1991).

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