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SUBMARINE CANYONS IN THE BELLINGSHAUSEN AND RIISER-LARSEN SEAS AROUND ANTARCTICA

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Abstract: Submarine canyons in the Bellingshausen and Riiser-Larsen Seas are compared. It is pointed out that the canyons in the Bellingshausen Sea are so incorporated to build up a deep-sea fan or an apron slope, that they develop dominantly on an upper fan at the upper continental rise and disappear apparently on a lower fan at the lower continental rise. The deep-sea fan or the apron slope was formed by supply of the great amount of sediments from the shelf area due probably to grounded ice sheets on the continental margin. On the contrary, the canyons in the Riiser-Larsen Sea have a large-scale entrenching throughout their course and construct a canyon-deep sea channel complex. This is caused by thermal cooling effect of lithosphere to deepen the old ocean basin.

Buried canyons observed on the seismic profiles indicate that activation of the canyon formation was triggered by advancement of the Antarctic ice sheet toward the outer edge of the continental shelf sometime between 4 and 7 Ma BP. The meltwater and eroded sediments by the extended grounded ice sheet provided a potential source for turbidity currents and debris flows into the canyons, thus causing rigorous development of the canyon.

1. Introduction

Most submarine canyons in the Antarctic seas show the existence of leveed channels. From development of natural levees on the west side of the canyons, contour-currents of Antarctic Bottom Water were discussed (KAGAMI and IWASAKI, 1991). During the discussion, submarine canyons off Dronning Maud Land are recognized to be larger in width and height than those of other areas of the Antarctic seas. This paper discusses why canyons off Dronning Maud Land are giant, and that buried submarine canyons seen on the seismic reflection records were formed in conjunction with a dynamic process of ice sheet expansion on the Antarctic Continent.

Despite the recent active sampling by Ocean Drilling Program around Antarctica, geologic knowledge on deep-sea environment is quite limited. There are only a few controlling sites for seismic stratigraphy in the Antarctic deep-sea waters, which were taken by DSDP Legs 28 and 35 (WEBB, 1990).

Topographic source of information off Dronning Maud Land comes from GEBCO Bathymetric Charts (INTERNATIONAL HYDROGRAPHIC ORGANIZATION, 1983), MORIWAKI and YOSHIDA (1989), and the 29th Japanese Antarctic Research Expedition (JARE, 1988) when Bathymetric Chart of Breid Bay (MARITIME SAFETY AGENCY OF JAPAN, 1989) was achieved. Seismic reflection data are provided by SAKI *et al.* (1987).

Topographic data in the Bellingshausen Sea are from TUCHOLKE (1977), TUCHOLKE and HOUTZ (1976), JOHNSON *et al.* (1982) and GEBCO Bathymetric Charts (INTERNATIONAL HYDROGRAPHIC ORGANIZATION, 1983). Seismic reflection data are from TUCHOLKE and HOUTZ (1976), TUCHOLKE (1977) and KIMURA (1982).

2. Topographic Setting for Canyon Formation

The continental margin of the Bellingshausen Sea is separated by fracture zones; Eltanin Fracture Zone around 92°W, Tula Fracture Zone around 75°W and Hero Fracture Zone around 67°W. These fracture zones were originally recognized in the abyssal plain by magnetic anomalies (TUCHOLKE and HOUTZ, 1976), and can be traced into the continental margin by their complex topography, especially of trough-like features.

Morphology of the Bellingshausen Sea is summarized in Fig. 1. The second characteristics is development of deep-sea fans or apron slopes termed from its sediment distribution swept by grounded ice sheets (LARTER and BARKER, 1991) on the continental rise between fracture zones. The Charcot Canyon and the Smyley Canyon build up the

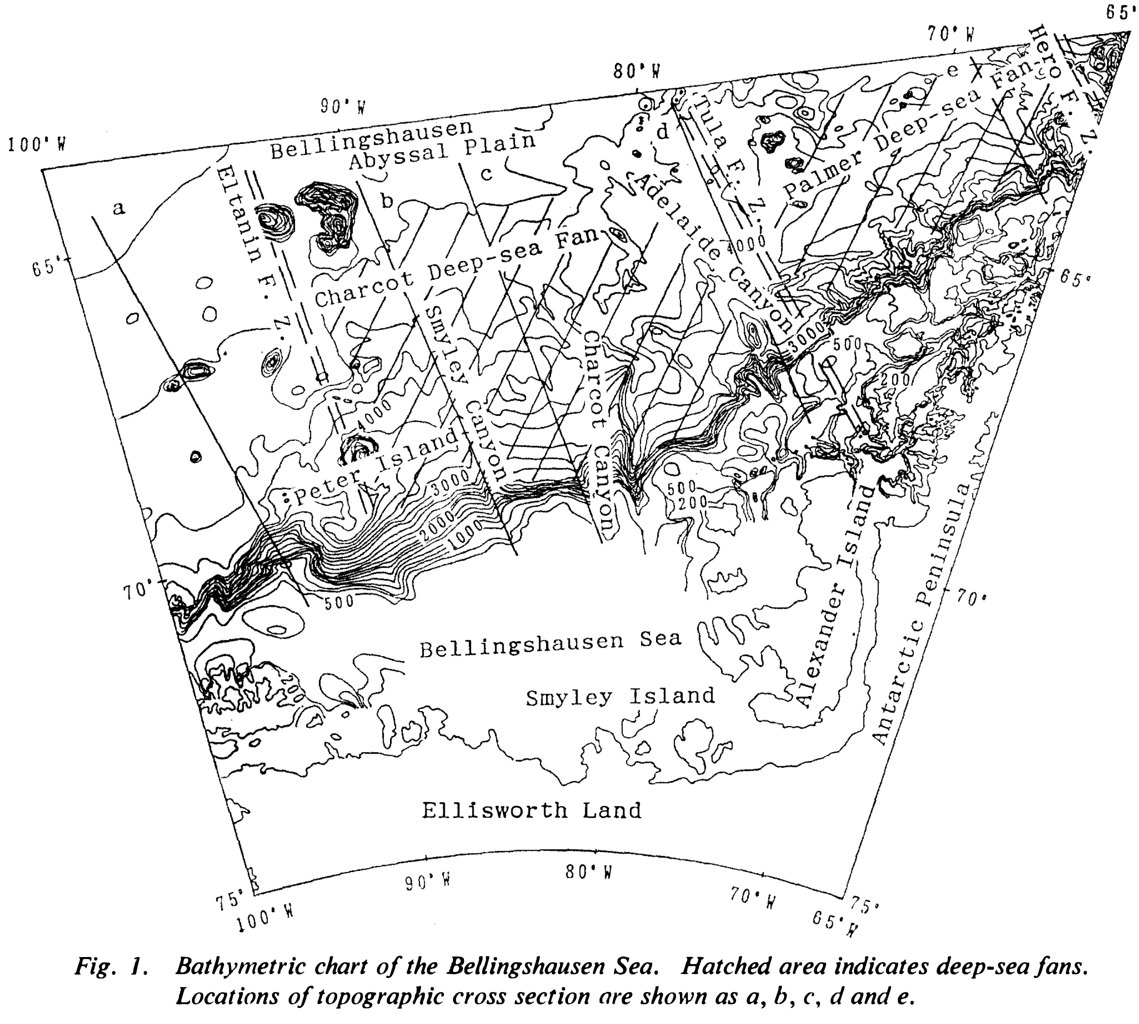

Fig. 1. Bathymetric chart of the Bellingshausen Sea. Hatched area indicates deep-sea fans. Locations of topographic cross section are shown as a, b, c, d and e.

Charcot Deep-sea Fan which is developing between Eltanin and Tula Fracture Zones. The Smyley Canyon is tentatively named after Smyley Island on the continental shelf. The Palmer Deep-sea Fan is developing between Tula and Hero Fracture Zones.

The morphological classification and gradient of the continental margin of the Bellingshausen Sea are summarized as follows;

	Depth (m)	Gradient
Continental shelf		
	500	
Continental slope		1 : 30
	3300	
Upper continental rise		1 : 300
	3980	
Lower continental rise		1 : 500
	4700	
Abyssal plain		1 : 1300

Topographic profiles are shown in Fig. 2. Profile 'a' represents an older area west of Eltanin Fracture Zone where gradient of the slope is the gentlest and the abyssal plain is the deepest. Profiles 'b' and 'c' represent an area of the Charcot Deep-sea Fan and show typically a gentle upper continental rise and an intermediate depth of the abyssal plain. Profiles 'd' and 'e' are located at the Palmer Deep-sea Fan. They show a very steep continental slope and shallowest abyssal plain. The area had been an active margin until Early Miocene due to subduction of the Aluk Ridge beneath the Antarctic Peninsula (WEISSEL *et al.*, 1977).

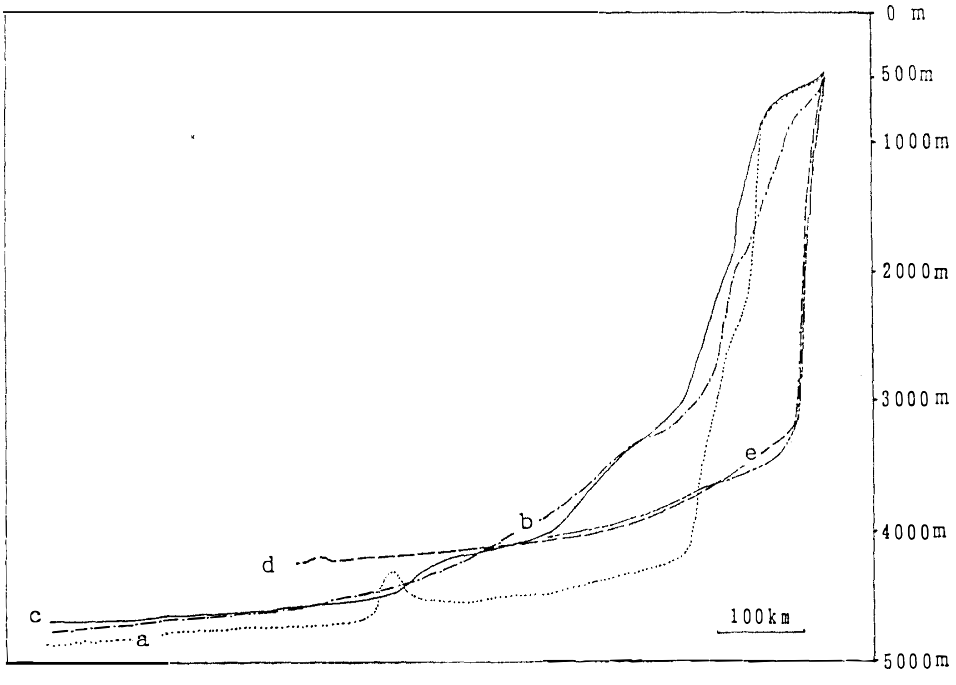

Fig. 2. Topographic cross sections across the continental margin of the Bellingshausen Sea. Locations are shown in Fig. 1.

Morphology off Dronning Maud Land is complied in Fig. 3. The morphological classification and the gradient of the continental margin in the Riiser-Larsen Sea are summarized as follows;

	Depth (m)	Gradient
Continental shelf		
	750	
Continental slope		1 : 45
	3250	
Upper continental rise		1 : 150
	4000	
Lower continental rise		1 : 200
	4750	
Abyssal plain		1 : 1000

Profiles of the continental margin in the Riiser-Larsen Sea are shown in Fig. 4. The gradient of the lower continental rise is extremely steep compared with that of the Atlantic margin which has 1 : 400 to 800 (KENNETT, 1982). Deepening of the Riiser-Larsen abyssal plain might reflect constant renewal of the baseline of erosion to make the steep gradient at the lower continental rise.

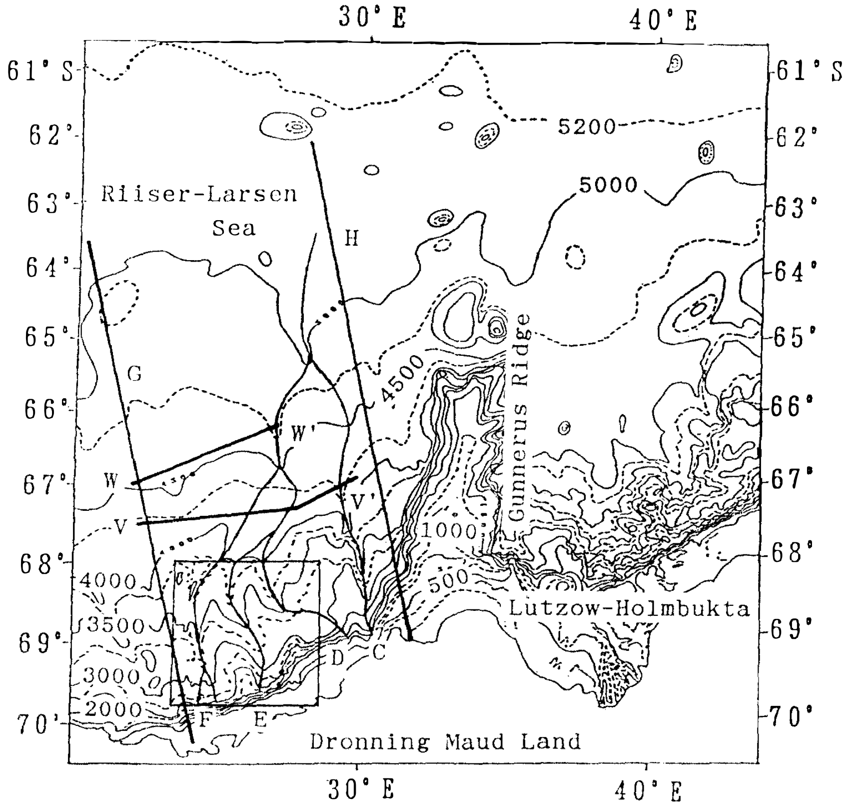

Fig. 3. Bathymetric chart of the Riiser-Larsen Sea. Locations of seismic reflection profiles (V-V′ and W-W′) and topographic cross sections (C, D, E, F, H and G) are shown. A square area is shown in detail in Fig. 6.

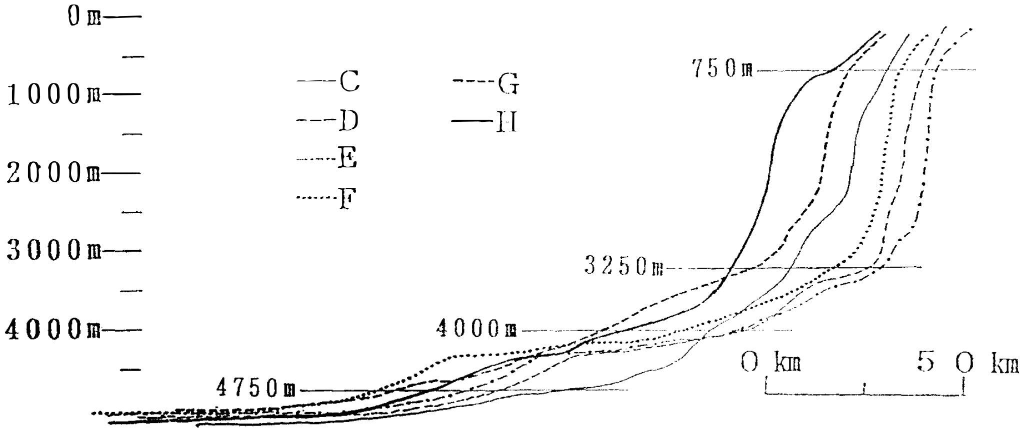

Fig. 4. Topographic cross section along the continental margin of the Riiser-Larsen Sea. Profiles C, D, E and F are longitudinal profiles along the canyon.

3. Submarine Canyons

3.1. Canyons in the Bellingshausen Sea

There are the Adelaide, Charcot and Smyley Canyons in the Bellingshausen Sea (Fig. 1). Seismic profile across the Smyley Canyon is shown in Fig. 5. Profile B-B′ located at the foot of the continental slope crosses the Smyley Canyon with width of 5 km and height of 300 m. Profile C-C′ is located on the upper continental rise. The Smyley Canyon is here 14 km wide and 300 m high, although ship's track crosses the canyon obliquely. This is the biggest in scale among the whole course. Profile E-E′ is located on the upper part of the lower continental rise. This is a branching tributary of the canyon 3 km in width and 50 m in height (TUCHOLKE, 1977). Profile A-A′ is located on the lower part of the lower continental rise. The Smyley Canyon becomes smaller in scale with 3 km width and 120 m height. Thus, it is clear that the canyon develops in full scale at the upper continental rise and appears to diminish near the border of the abyssal plain. This is also shown by downward branching development of the canyon tributaries on the deep-sea fan (Fig. 5). The so-called 'leveed channel complex' and 'lowstand fan depositional system' are thought to be the characteristic facies in seismic stratigraphy during the sea withdrawal below the shelf edge (HAQ *et al.*, 1987).

3.2. Canyons in the Riiser-Larsen Sea

JARE-29 in 1988 made a bathymetric grid survey on the continental slope and rise area of Breid Bay between 24° and 28°E in longitude and between 68° and 69°40′S in latitude. Survey lines run from the continental shelf edge northward at intervals of 10 miles.

Three big canyons were clearly contoured on the bathymetric chart (Fig. 6). The middle canyon, labeled E, is the main channel of this canyon system (also see Fig. 3). The cross section of canyon E at 3000 m depth located at the lower continental slope has 45 km width and 450 m height. At the upper continental rise, it is 50 km wide and 450 m high at 3400 m depth, which is the biggest in scale of the whole canyon system. The 3.5-kHz profile (X-X′) of 3650 m depth at the upper continental rise shows canyon

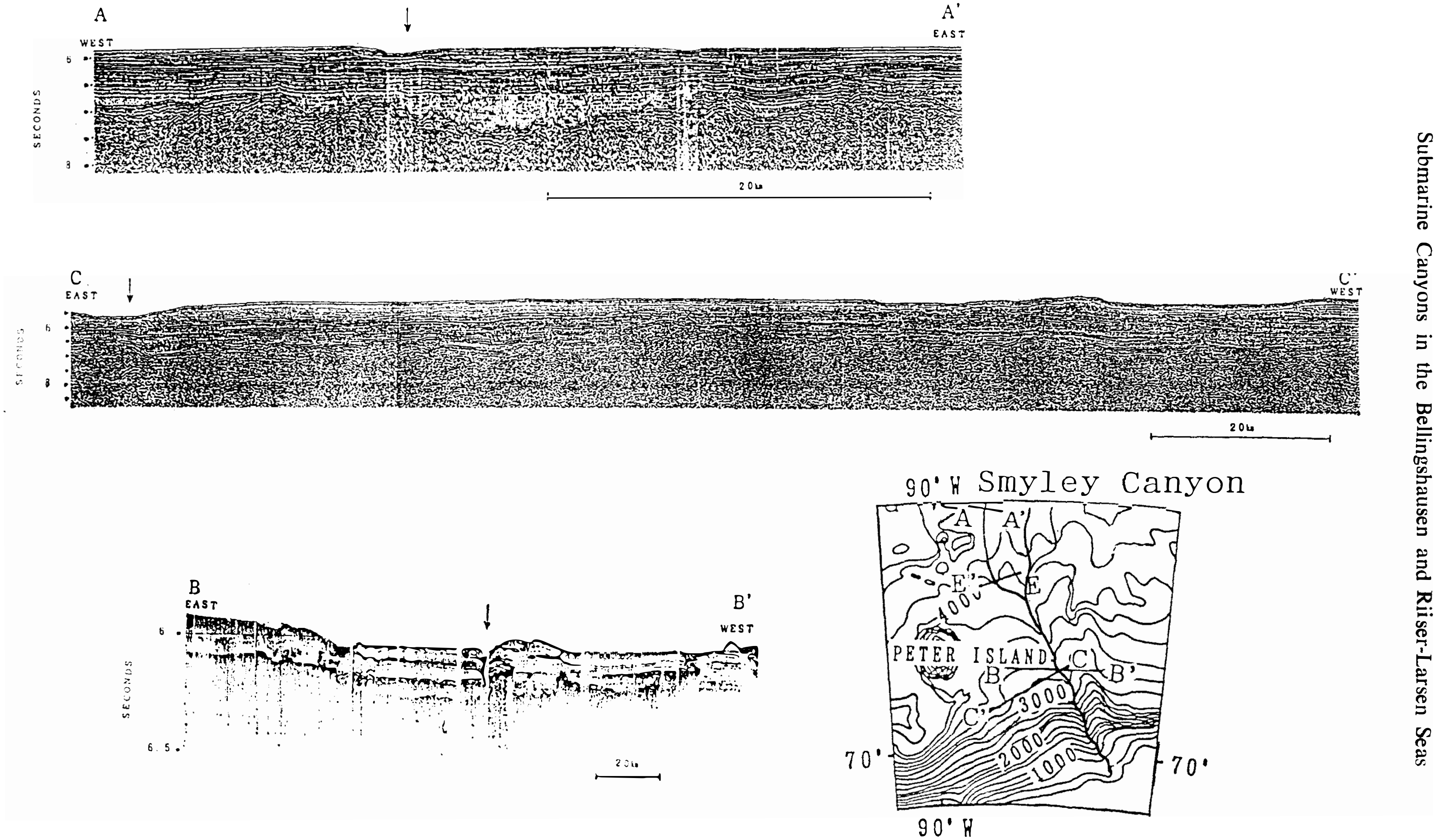

Fig. 5. Cross section of the Smyley Canyon revealed on seismic reflection profiles. Arrows are indicated channels of the Smyley Canyon. Profiles are from Tucholke *(1977) and* Kimura *(1982).*

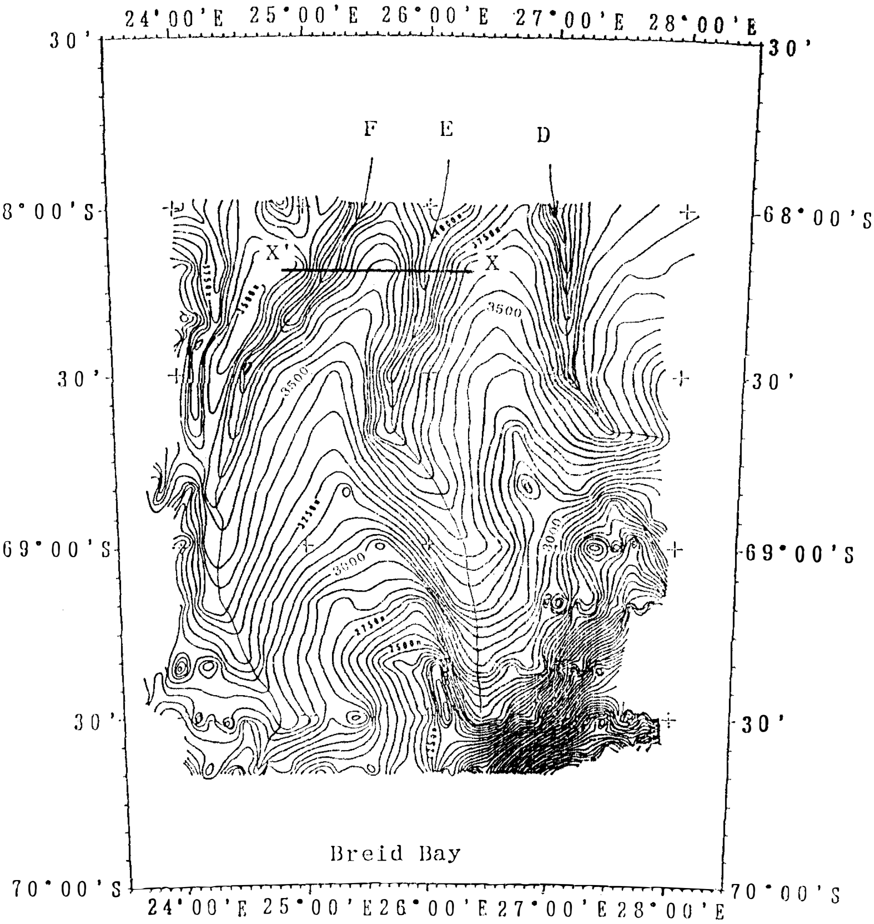

Fig. 6. Bathymetric chart of Breid Bay. Location of 3.5-kHz profile (X-X') in Fig. 7 is shown. Canyons D, E and F are indicated by curved lines.

E to the left of Fig. 7. It is 35 km wide and 300 m high with an erosive wall to the west side and a slippery wall to the east of the canyon. Judging from reflection characteristics of the canyon profile, it is a sedimentary channel upgraded on the continental margin. Canyon F is seen to the right of the figure. The seismic reflection profile (V-V') of 4250 m depth at the lower continental rise shows three canyons (Fig. 8). The east canyon seen at SP 4700 (SP is shooting point in the seismic reflection survey and indicates increment number from the beginning of the survey at every 50 m) is only 12 km in width, which has been shown in GEBCO Bathymetric Chart as the Ritscher Canyon. Despite of the name, it is a small tributary labeled C in Fig. 3. The central canyon seen at SP 6500 is the main canyon labeled D/E in Fig. 8 with 30 km width and 300 m height. The west canyon seen at SP 8700 is only 5 km wide and thought to be a continuation of canyon F in Fig. 3. The seismic reflection profile (W-W') crossing at 4700 m depth at the lower continental rise shows a large canyon wall (Fig. 9). Inspection of the profile indicates that the canyon (D, E, and F) is 30 km wide (with some question) and 300 m high. Thus, it is clear that the canyon does not decrease its scale throughout the course and maintains a large-scale canyon system by joining small tributaries. This may be caused by deepening of the baseline of erosion. The so-called

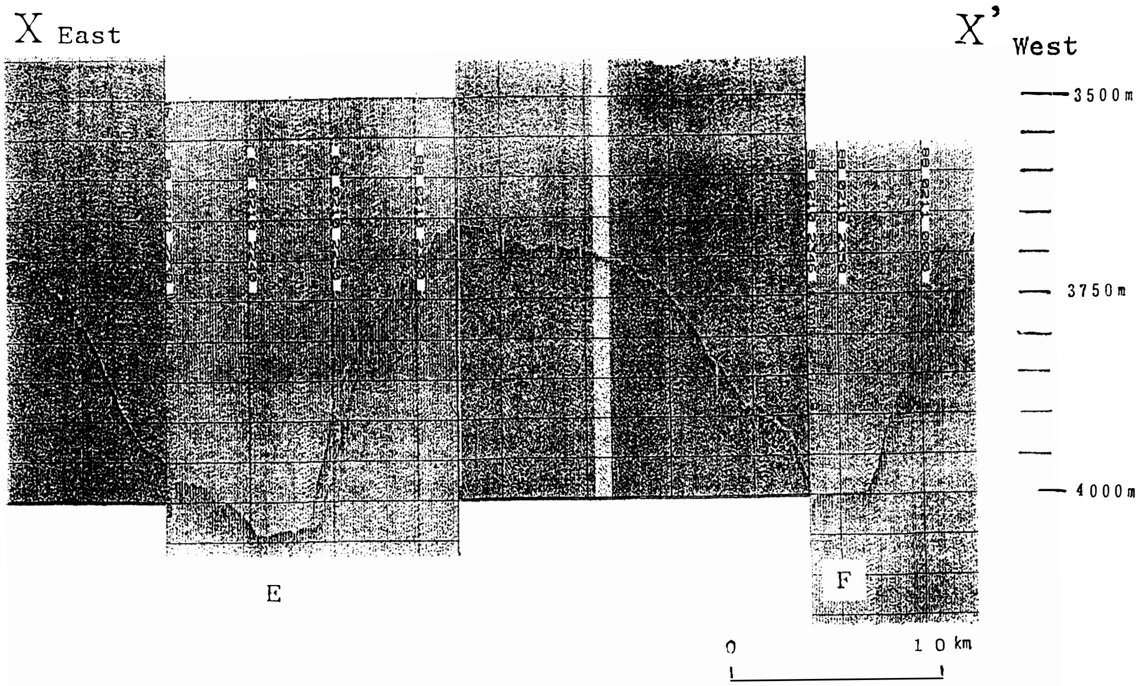

Fig. 7. *Canyons E and F on 3.5-kHz profile along Line X-X'. Location is shown in Fig. 6.*

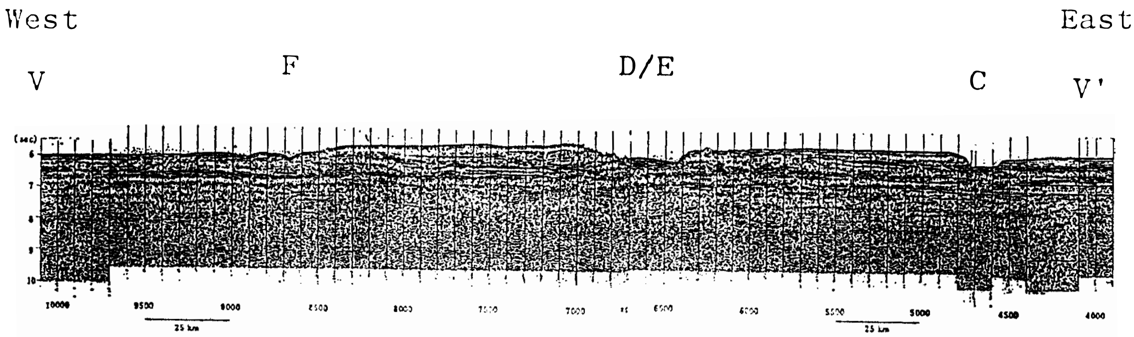

Fig. 8. *Seismic reflection profile of the Ritscher Canyon system along Line V-V' (SAKI et al., 1987). The central canyon (canyon D/E) is the main channel of the Ritscher Canyon system.*

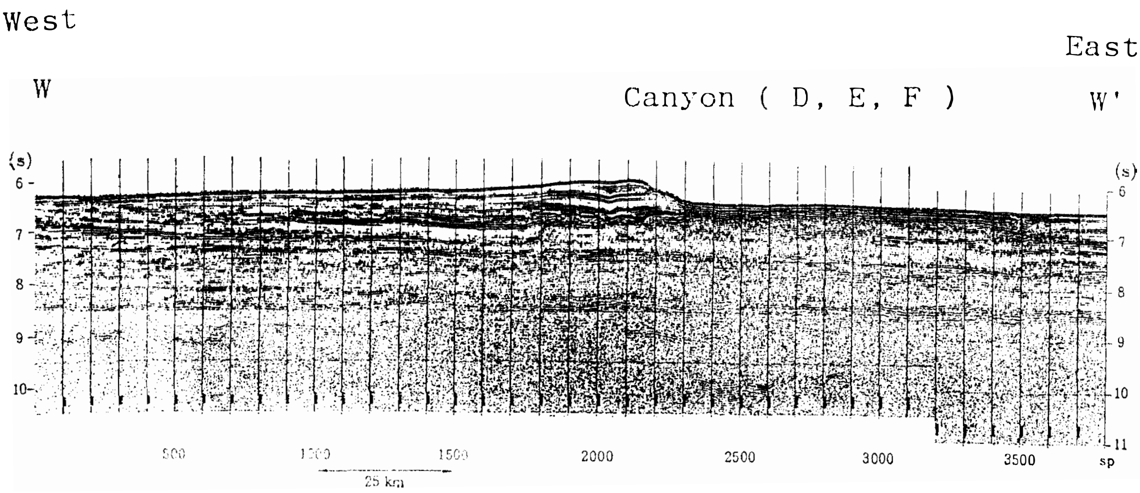

Fig. 9. *Seismic reflection profile of the canyon (D, E and F) at the lower continental rise along Line W-W' (SAKI et al., 1987).*

Ritscher Canyon (canyon C) joins the main canyon (D, E and F) at around 5000 m depth to form a deep-sea channel. We are now convinced that the canyon C is a part of the large canyon system which we here propose the Ritscher Canyon system.

3.3. Buried canyons in the Bellingshausen Sea

Dimensions of the canyon can be defined by its width and height in the following way. As shown in Fig. 10, the width is measured from the erosive channel to the top of the levee. Therefore, the defined width is a half of the true canyon width. The height of the canyon is measured from the bottom of erosive channel to the top of the levee. We will discuss only canyon width in this paper, because canyon height is easily deformed by burial processes.

An example of the buried canyon is seen on the profile in Fig. 11. The buried depth is measured from the surface of seabed to the erosive channel floor of the buried canyon in second.

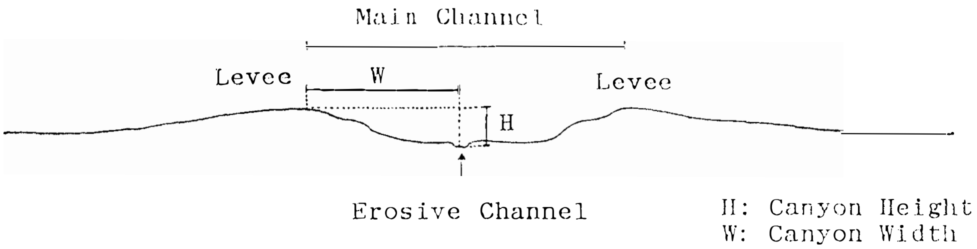

Fig. 10. Definitions of the canyon-natural levee system.

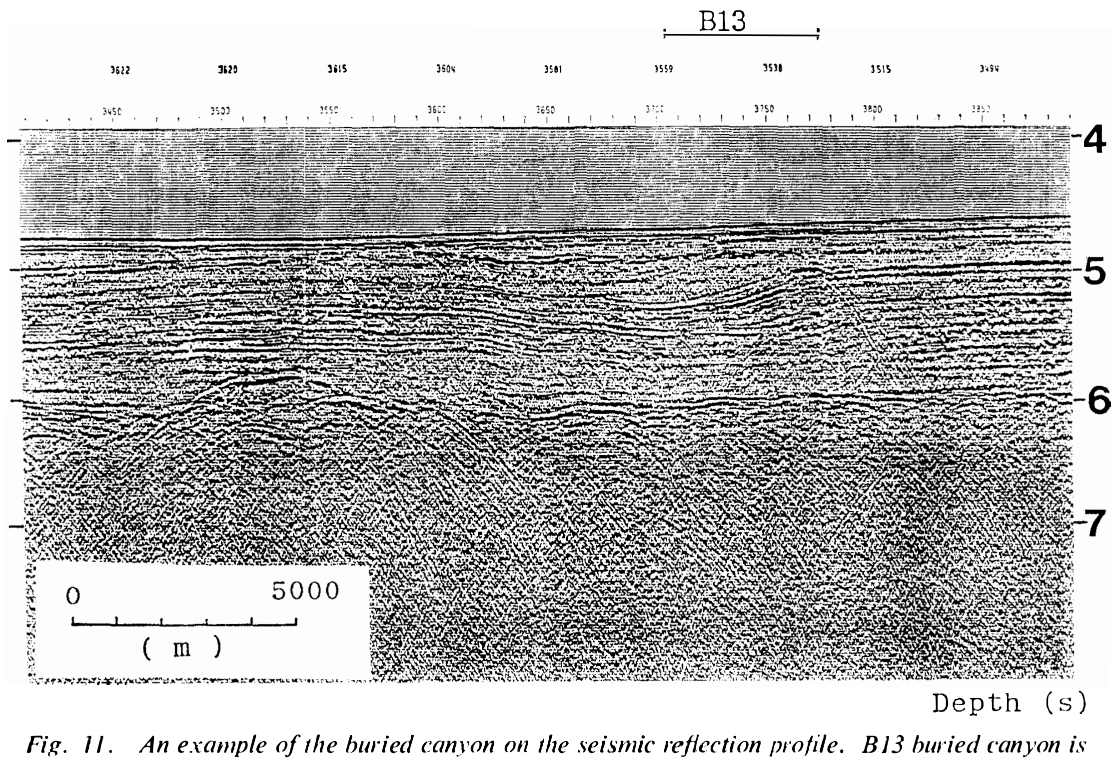

Fig. 11. An example of the buried canyon on the seismic reflection profile. B13 buried canyon is seen around 5.1 s depth. A half canyon width is shown as a horizontal bar at the top of the figure.

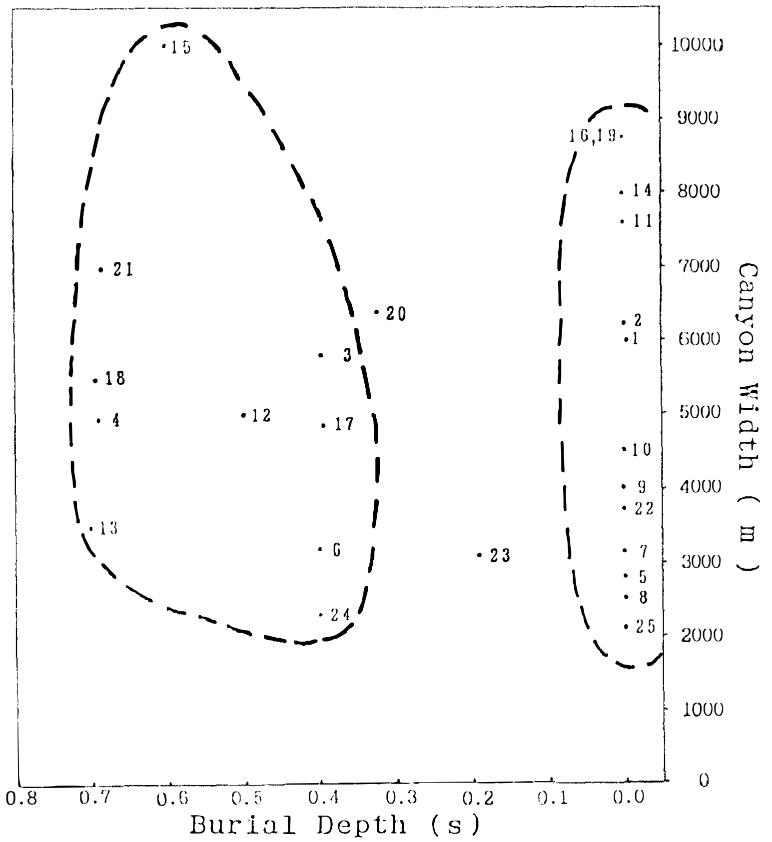

Fig. 12. Relation between the buried depth and the canyon width of the historical canyons in the Bellingshausen Sea. Two groups are identified by burial depths.

Total 25 canyons were measured, of which 13 were located on the surface of the seabed and 12 were buried ones. Relation between buried depth and width of the canyons is shown in Fig. 12. There are observed two groups on the figure, one is the canyons located on the bottom surface and another is 10 canyons out of 12 concentrated between 0.4 and 0.7 s deep in burial depth. If we assume *P*-wave velocity of the bottom sediment to be 2000 m/s, the burial depth of 0.4 and 0.7 s will be 400 and 700 m. The latter group has a width of 5300 m on the average, which indicates that the buried canyons are a little wider than the bottom surface ones with an average width of 5200 m. Since the maximum width is found in the buried canyon group, it can be said that difference is much larger than compared average values. It is a surprise that few buried canyons occur between 0.1 and 0.4 s deep. This discontinuation is probably due to upgrading of the deep-sea fan and burial of the old channels during the deglaciation period. The calm and slow deposition of mud in the deglaciation period did not retain trace of channels on the deep-sea fan.

3.4. Buried canyons in the Riiser-Larsen Sea

Total 24 canyons were measured on the seismic reflection profiles in the Riiser-Larsen Sea, of which 11 were bottom surface canyons, and 13 were buried ones. There

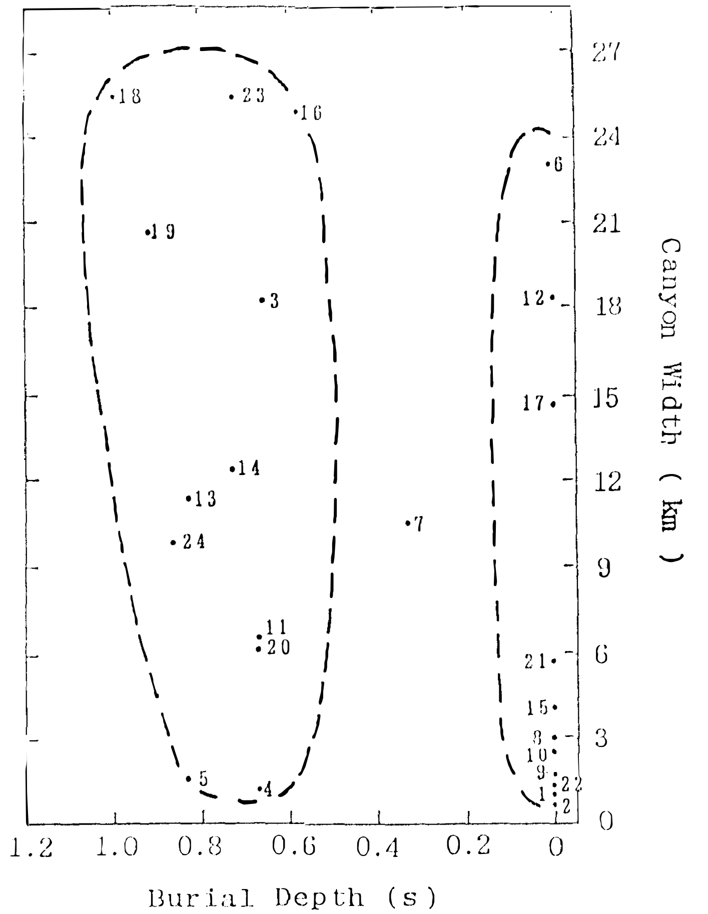

Fig. 13. Relation between the buried depth and the canyon width of the historical canyons in the Riiser-Larsen Sea. Two groups are recognized from burial depths.

are observed two distinct canyon groups; one is the bottom surface canyon and another is the buried canyon observed between 0.6 and 1.0 s deep. Twelve out of 13 occur within this depth, and they are 13.8 km wide on the average which is definitely bigger in scale than the surface canyons having the average value of 6.8 km wide (Fig. 13). The maximum width is found in the buried canyon group.

4. Discussion

The reason why the canyon in the Riiser-Larsen Sea is larger in scale than that of other areas of the Antarctic seas originates in its full development of a canyon-deep sea channel complex. As shown in Fig. 14, the basement age of the Riiser-Larsen Sea is one of the oldest around Antarctica (approximately 145 Ma after MARTIN and HARTNADY, 1986), which causes constant subsidence of baseline of erosion and the resultant formation of the bigger canyon system.

There is another factor in controlling the shape of canyons, that is, supply of sediments from the continent. The continental shelf in the Riiser-Larsen Sea is relatively

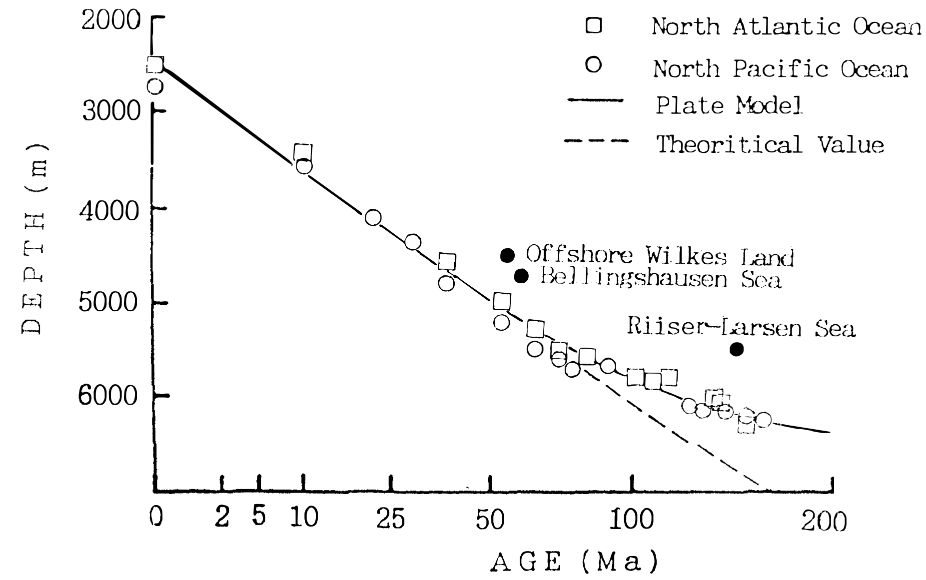

Fig. 14. Relation between the age and the depth of the ocean basins (*MARTIN and HARTNADY, 1986; WEISSEL et al., 1977*).

narrow and rugged at depth of 500 m, and there is observed a marked terrace with a rugged surface on the slope at depth of 750 m (Fig. 4, H) which may indicate the maximum extended position of grounded ice sheet. On the contrary, the continental shelf in the Bellingshausen Sea is very flat and extensively broad with the shelf break at depth around 500 m, and is characterized by its gentle slope without any terraces at depths. This may indicate that isostatic rebound is proceeding fairly well in the Bellingshausen Sea, which had fed large amounts of sediment to submarine canyons and formed well-developed deep-sea fans or apron slopes. Isostatic uplifting in West Antarctica was discussed by STUIVER *et al.* (1981) and SUZUKI *et al.* (1979). It was pointed out that isostatic response to deglaciation was larger than tectonic uplifting (ANDERSON *et al.*, 1979).

DSDP drilling in the Bellingshausen Sea revealed that a period of intensive activity of turbidity currents and debris flows might be attributed to extensive continental glaciation (TUCHOLKE and HOUTZ, 1976). Rate of sedimentation at DSDP Leg 35 sites indicates that very rapid sedimentation up to 10 cm/1000 y started at 6 Ma BP and ended around 3 Ma BP. This corresponds to the maximum expansion of the Antarctic glaciation and the following deglaciation period immediate after the maximum glaciation. According to LARTER and BARKER (1991), the maximum glaciation in Antarctica was either 4.8 or 2.4 Ma BP. The deglaciation period immediate after the maximum glaciation was said to be between 3 and 4 Ma BP (PICKARD *et al.*, 1988).

If we take sedimentation rate of 10 cm/1000 y (from TUCHOLKE and HOUTZ, 1976) for the buried canyon at the depths between 400 and 700 m, an assumed age for the buried canyon will be estimated to be 4 and 7 Ma BP. Therefore, we can get the conclusion that the mechanism responsible for activation of forming buried submarine canyons was glacial conditions and that extended ice sheets controlled timing and delivery of sediments to the continental margin. Our data on canyon width indicated that canyons developed more extensively during the maximum glaciation period sometime between 4 and 7 Ma BP, and that the present canyons have been formed since 2.4 Ma BP.

We will show a model for canyon activation by advancement of grounded ice sheet (Fig. 15). This model explains that the maximum transport of sediment can be possible only when the grounded ice sheet comes close to the shelf edge, thereby providing a potential source for sediment deposition at the canyon head. Turbidity currents and debris flows transported those sediments to the continental rise and abyssal plain, thus

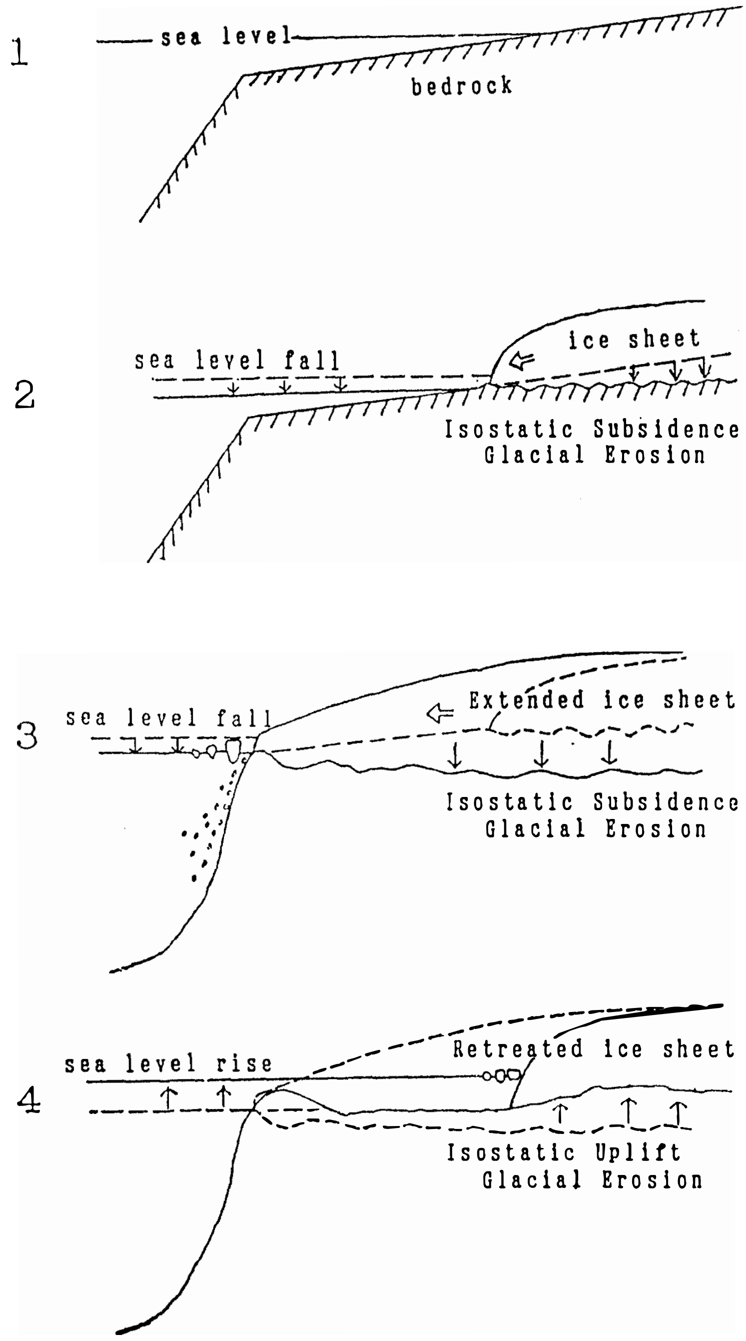

Fig. 15. A model showing activation of canyons during advancement of the Antarctic ice sheet. Estimated age for stages 2 and 3 was between 4 and 7 Ma BP, and 3 and 4 Ma BP for stage 4.

causing rigorous development of the canyon. When the ice sheet retreated inland, isostatic downwarping caused trapping of eroded sediments within the inner continental shelf and preventing sediment supply to canyons, as we see at the present ice shelf in East Antarctica.

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References

ANDERSON, J.B., KURTZ, D.D. and WEAVER, F.M. (1979): Sedimentation on the Antarctic continental slop. Soc. Econ. Paleontol. Mineral., Spec. Publ., **27**, 265–283.

HAQ, B.U., HARDENBOL, J. and VAIL, P.R. (1987): Chronology of fluctuating sea levels since the Triassic. Science, **235**, 1156–1167.

INTERNATIONAL HYDROGRAPHIC ORGANIZATION AND INTER-GOVERNMENT OCEANOGRAPHIC COMMITTEE (1983): General bathymetric chart of the ocean, 1:6000000. Ottawa, Canadian Hydrographic Service.

JOHNSON, G.L., VANNEY, J.R. and HAYES, D. (1982): The Antarctic continental shelf. Antarctic Geoscience, ed. by C. CRADOCK. Madison, Univ. Wisconsin Press, 995–1002.

KAGAMI, H. and IWASAKI, T. (1991): Variation of natural levees of submarine canyons around Antarctica: An indicator of Antarctic contour-current. Proc. NIPR Symp. Polar Meteorol. Glaciol., **4**, 108–118.

KENNETT, J.P. (1982): Marine Geology. New Jersey, Prentice-Hall, 813 p.

KIMURA, K. (1982): Geological and geophysical survey in the Bellingshausen basin, off Antarctica. Nankyoku Shiryô (Antarct. Rec.), **75**, 12–24.

LARTER, R.D. and BARKER, P.F. (1991): Neogene interactions of tectonic and glacial processes at the Pacific margin of the Aatarctic Peninsula. Spec. Publ. Int. Assoc. Sediment., **12**, 165–186.

MARITIME SAFETY AGENCY OF JAPAN, HYDROGRAPHIC DIVISION (1989): Bathymetric chart of Breid Bay.

MARTIN, A.K. and HARTNADY, C.J.H. (1986): Plate tectonic development of the southwest Indian Ocean: A revised reconstruction of East Antarctica and Africa. J. Geophys. Res., **91**, 4767–4786.

MORIWAKI, K. and YOSHIDA, Y. (1989): Bathymetric chart of Lützow-Holmbukta. Spec. Map Ser. Natl Inst. Polar Res., No. 4.

PICKARD, J., ADAMSON, D.A., HARWOOD, D.M., MILLER, G.H., QUILTY, P.G. and DELL, R.K. (1988): Early Pliocene marine sediments, coastline, and climate of East Antarctica. Geology, **16**, 158–161.

SAKI, T., TAMURA, Y. and TOKUHASHI, S. (1987): Preliminary report of geological and geophysical survey off Queen Maud Land, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 23–40.

STUIVER, M., DENTON, G.H., HUGHES, T.J. and FESTOOK, J.L. (1981): History of the marine ice sheet in West Antarctica during the last Glaciation: A working hypothesis. The Last Great Ice

Sheets, ed. by G. H. DENTON and T. J. HUGHES. New York, J. Wiley, 319–436.

SUZUKI, Y., MATSU'URA, M., SATO, R. and KAMINUMA, K. (1979): Nankyoku Tairiku no ryûki—Danseiron-teki setsumei (Uplift of Antarctica: From the elastic rebound theory). Gekkan Chikyu (Chikyu Monthly), **1**, 779–782.

TUCHOLKE, B. E. (1977): Sedimentation processes and acoustic stratigraphy in the Bellingshausen basin. Mar. Geol., **25**, 209–230.

TUCHOLKE, B. E. and HOUTZ, R. E. (1976): Sedimentary framework of the Bellingshausen basin from seismic profile data. Initial Rep. Deep Sea Drill. Proj., **35**, 197–227.

WEBB, P. N. (1990): The Cenozoic history of Antarctica and its global impact. Antarct. Sci., **2**. 3–21.

WEISSEL, J. K., HAYES, D. E. and HERRON, E. M. (1977): Plate tectonic synthesis: The displacements between Australia, New Zealand and Antarctica since the late Cretaceous. Mar. Geol., **25**, 231–277.

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