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VARIATION OF NATURAL LEVEES OF SUBMARINE CANYONS AROUND ANTARCTICA —AN INDICATOR OF ANTARCTIC CONTOUR-CURRENT—

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Abstract: Natural levees developing at the western side of the submarine canyons on the continental rise around the Antarctic continent are for the first time described quantitatively. It is found that they apparently involve in large benthic flow.

The observations presented here suggest that the benthic flow may be caused by a combination of bottom-trapped Rossby waves, the background mean current which most probably consists of Antarctic Bottom Water, and high-frequency tidal flow.

1. Introduction

Recent ocean drillings on Legs 113 of early rifting history in the Weddell Sea, 114 of back-arc basin program in the South Orkney Islands, and 119 of Cenozoic glacial history in Prydz Bay have stimulated interest in sedimentary evolution in respect to advancement and decay of the Antarctic ice sheet. Also, past Deep Sea Drillings on Legs 28 of glacial history in the Ross Sea and 35 of continental rise stratigraphy in the Bellingshausen Sea have contributed to the Antarctic deep-water environmental studies.

The broad picture of high speed inflow on the western sides of ocean basins with a distributed return flow according to STOMMEL and ARONS (1960) has been confirmed by many current measurements. It has also become apparent that there are undercurrents of cold bottom water beneath the western boundary flow. The high energy benthic boundary layer experiment (HEBBLE) revealed a strong bottom current at depths of 4500 to 5000 m on the lower continental rise off Nova Scotia (GRANT *et al.*, 1985). From the evidence, abyssal circulation patterns of the Antarctic Bottom Water were fairly well understood (MCCAVE, 1986). Because the water type mentioned above was not strictly defined, the present authors would like to use "the Antarctic bottom water" hereafter.

These patterns of bottom currents are very similar to the distribution pattern of the excess load of bottom suspended sediment (MCCAVE, 1986). However, there are several places of very high load which are not obviously related to likely increases in bottom flow velocity. HOLLISTER and MCCAVE (1984) introduced the notion that these high loads were caused by intermittently high velocities under regions where high surface eddy kinetic energy was propagated downward, resulting in high abyssal eddy

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kinetic energy. This was called a deep sea benthic storm (WEATHERLY and KELLEY, 1985). For example, the circum-Antarctic region at about 60°S has the highest load ever observed under high surface productivity which reflects the energetic bottom circulation associated with possible penetration of eddy energy from the surface (McCAVE, 1986).

Contourites are sedimentary deposits in the deep ocean which are deposited by benthic storms moving parallel to the contours. The term was proposed by HOLLISTER and HEEZEN (1972) to describe a specific silt-laminated red-brown lutite facies from the continental rise off eastern North America. Recent studies by HEBBLE (McCAVE, 1985) demonstrate concentration of medium silt mode (10–17 micron) at flow speeds from 10 to 18 cm/s during the benthic storm (see KAGAMI and SUK, 1986, for a review).

The overall distribution of silt mode size is undoubtedly controlled by turbidite input (GARDNER, 1989). Processes of sediment gravity transport such as turbidity currents have long been recognized to be associated with glacial activity. Indirect relationships such as worldwide activation of submarine canyon transport during a glacial-eustatic drop in sea level have been noted through an association between glacial deposits and mass flow deposits. The relationship between glacial activity and submarine canyon transport, which will result in the Antarctic bottom water flow as a contour-current to form natural levees of submarine canyons, is the main subject of discussion. The present paper deals with levee pattern and a contour-current.

2. Methods and Materials

The outer margin of the continental shelf of Antarctica is situated at a depth of 500–600 m. It is relatively deep compared with the world average of 200 m, apparently due to originally deep location and to incomplete isostatic rebound. The continental slope is rather steep to a depth of 3800–4000 m and incised by submarine canyons. The continental rise is well developed around the Antarctic continent and many submarine canyons are recognized on and beneath the surface of the continental rise. Submarine canyons have been major conduits through which turbidity currents, debris flows and slumps carried large volumes of continental sediments to form expansive continental rises and abyssal plains.

On the continental rise around Antarctica are many leveed channels or submarine canyons. The river channel of a meandering stream is generally found to surmount a ridge of wedge-like cross section called a levee that rises above the adjacent lowlands known as flood plains. It is puzzling that submarine canyons of the Antarctic are almost straight and that natural levees are mostly observed at the western banks of the canyons. To compare regional variations of the leveed channels around Antarctica, seismic profiles in the Bellingshausen Sea, Amundsen Sea, offshore of Enderby Land, and offshore of Queen Maud Land were investigated (Fig. 1). Seismic lines running in the east-west direction in each area are only examined in order to check the contour-current on the continental slope and rise.

The dimensions of the natural levees of submarine canyons are defined in the following way (Fig. 2). Levee height (H) is measured from the floor of the main

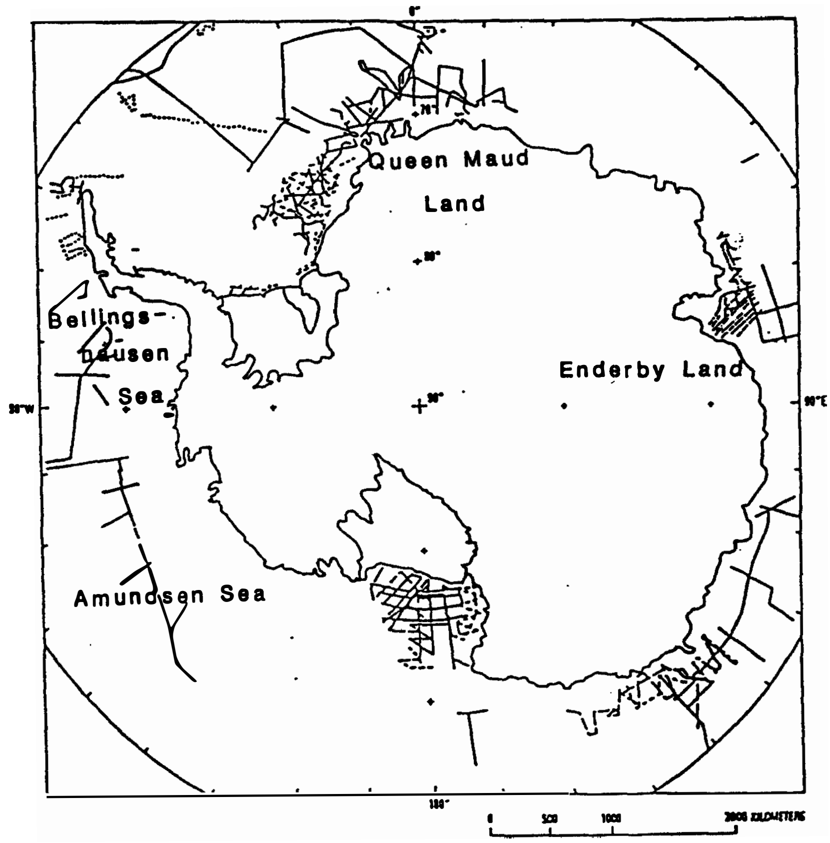

Fig. 1. Locality map of seismic reflection lines in the Southern Ocean.

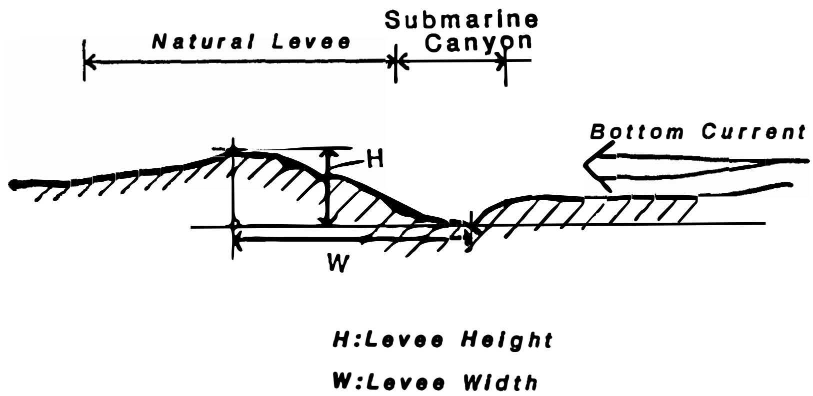

Fig. 2. A transversal profile of the submarine canyon on the continental rise. Bottom current is parallel to the contour. The levee height (H) is measured from main channel floor to the top of the levee ridge (see text).

channel to the top of the levee ridge. Levee width (W) is measured from the erosive channel to the axis passing through the top of the levee ridge. The erosive channel generally develops at the floor of the main channel.

3. Areal Description of Leveed Channel

In the Bellingshausen Sea (TUCHOLKE, 1977), two kinds of valleys are observed: a broad graben-like feature and a steep valley-like feature with winding distributaries. The former is generally associated with a transform fault and is not the submarine canyon. The latter is the submarine canyon formed by turbidity currents.

The transverse profile of the canyon indicates channels that migrated upward and eastward during their depositional history as a result of deposition from channel-bank overflow on their western sides. Levees on the western sides of most channels contain acoustically non-laminated to finely laminated sediments indicating a large amount of muddy materials (Fig. 3).

The effect of the Bellingshausen contour-current on development of leveed channels is demonstrated at DSDP Site 324. The upper 200 m at Site 324 was a non-laminated sedimentary sequence and contained clays with thin well-sorted silt beds. They were thought to be concentrated by the Bellingshausen contour-current from turbidity currents flowing down along the submarine canyon (TUCHOLKE, 1977).

The topography of the Amundsen Sea has not been fully studied, because of its thick rafted sea ice. In the west, the Amundsen Ridge develops at around 70°S, protruding from the continental slope as a submarine spur. The continental rise is rather rough in topography and a small amount of sediment is distributed on it. In contrast, many submarine canyons are recognized in the eastern part of the Amundsen Sea (Fig. 4). This is consistent with the coastal topography, which shows considerable embayment of the coastal line between Thurston Island and Marie Byrd Land, and

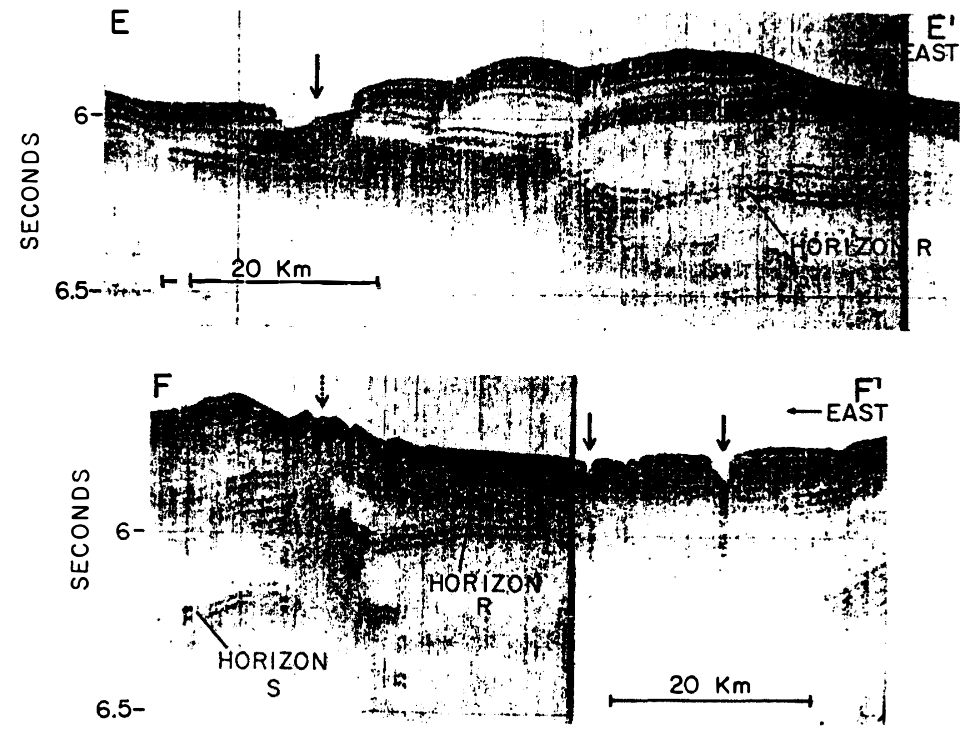

Fig. 3. Seismic reflection profiles from the Bellingshausen Sea (TUCHOLKE, 1977). Arrows show submarine canyons. Natural levees develop at the western side (facing right) of the canyon.

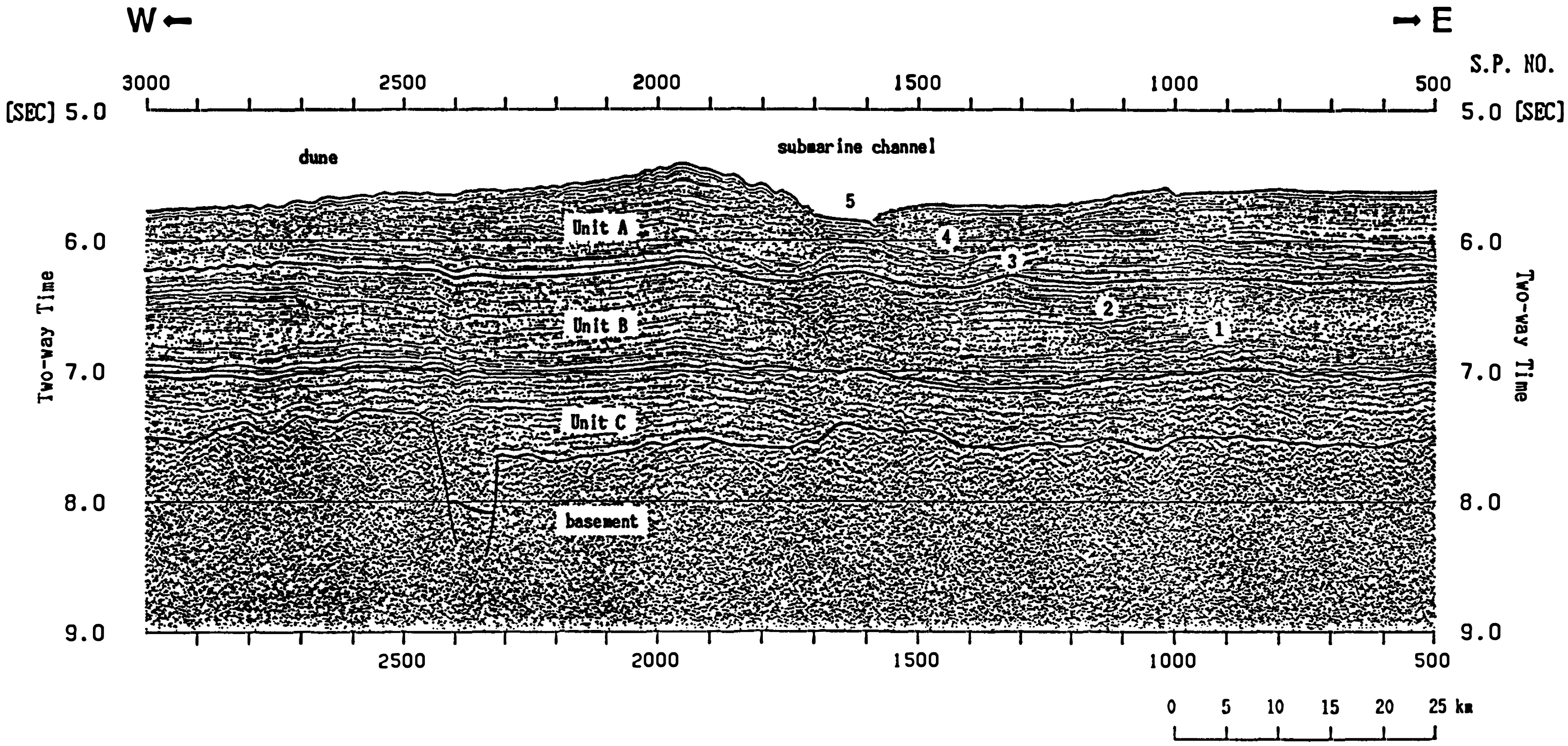

Fig. 4. Seismic reflection profile from the Amundsen Sea (YAMAGUCHI et al., 1988). Natural levee develops to the left (west) of the canyon. Numbers in white circles show the migration direction of leveed channels.

there is a broad continental shelf revealed by the 1000 m contour line.

The seismic section shows well-developed leveed channels (YAMAGUCHI *et al.*, 1988). The levee develops at the western bank of the channel, which indicates a contour-current swept from the east. Westward migrating channels are recognized in the section within 1 second from the bottom surface. This is inconsistent with observations in the Bellingshausen Sea where canyons migrated in the direction away from the levee. From observations it appears that deposition of a levee ridge does not control migration of the channel. There must be another mechanism to shift the channel such as fan development or a staggering channel. From the records, major development of the migrating channel can be identified associated with deposition of sand and gravel at the cannel floor. At least, five stages of development are recognized (Fig. 4).

Topography on the continental rise in the offshore Enderby Land can be divided into two parts: a flat and shallow western part, and a deep eastern part with many channels (MIZUKOSHI *et al.*, 1986). These channels come down from the broad continental shelf which is clearly revealed by the 500 m contour line off Prydz Bay. The levees develop at the western bank of the channel.

Topography in the offshore Queen Maud Land is divided by Gunnerus Ridge (MORIWAKI *et al.*, 1987). The eastern part is Lützow-Holm Bay, where relatively narrow valleys are developed. The western part is the Riiser-Larsen Sea, where a relatively flat continental rise is observed. The channels observed in the Riiser-Larsen Sea are of remarkably large scale (Fig. 5). They indicate faint development of levees at the western banks of channels (SAKI *et al.*, 1987).

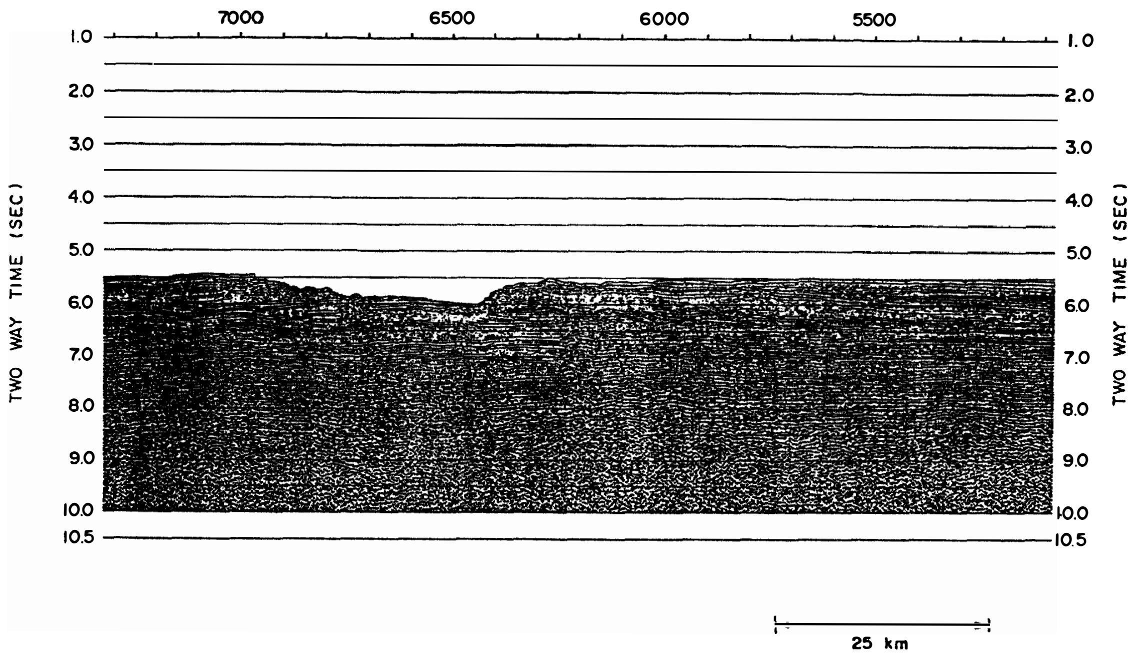

Fig. 5. Seismic reflection profile from offshore of Queen Maud Land (SAKI et al., 1987). A large-scale canyon is observed with slightly higher levee on the left side (west) of the canyon.

4. Relation of Levee Height and Width to Depths

Levee height obtained from four localities around Antarctica is plotted against depths (Fig. 6). On the seismic record, depth can be measured in units of seconds of sound propagation time from the surface of the sea-floor. Depth is the only information on the seismic record that indicates geologic age besides the p-wave velocity in the sediments.

Submarine canyons observed at the present bottom are large in number. This is due to either the present is an era of canyon development, or that the past has had the same number of canyons as observed today but they cannot be identified after burial by muddy sediments with the same reflectivity. The exception is seen when sand and gravel bury the channels, they can be easily identified by their strong reflectivity. Therefore, essential canyons are preserved to be identified.

Submarine canyons at present range from 100 to 800 m in levee height with an average of 350 m. The levee height was less than 300 m beneath the bottom to a depth of 0.6 seconds. Timing of strong bottom scour was reported from the South Australian Basin during Gauss Chron (ALLISON and LEDBETTER, 1982). The levees observed in the depth from 0.6 to 0.9 seconds became the largest scale with height between 700 and 900 m. This example is seen offshore of Queen Maud Land. The levee height of 200–500 m is observed at depth deeper than 0.9 seconds. Sound velocities at these depths must be corrected; therefore, the real height would be much larger.

The levee width observed at present ranges from 1 to 12 km with an average of

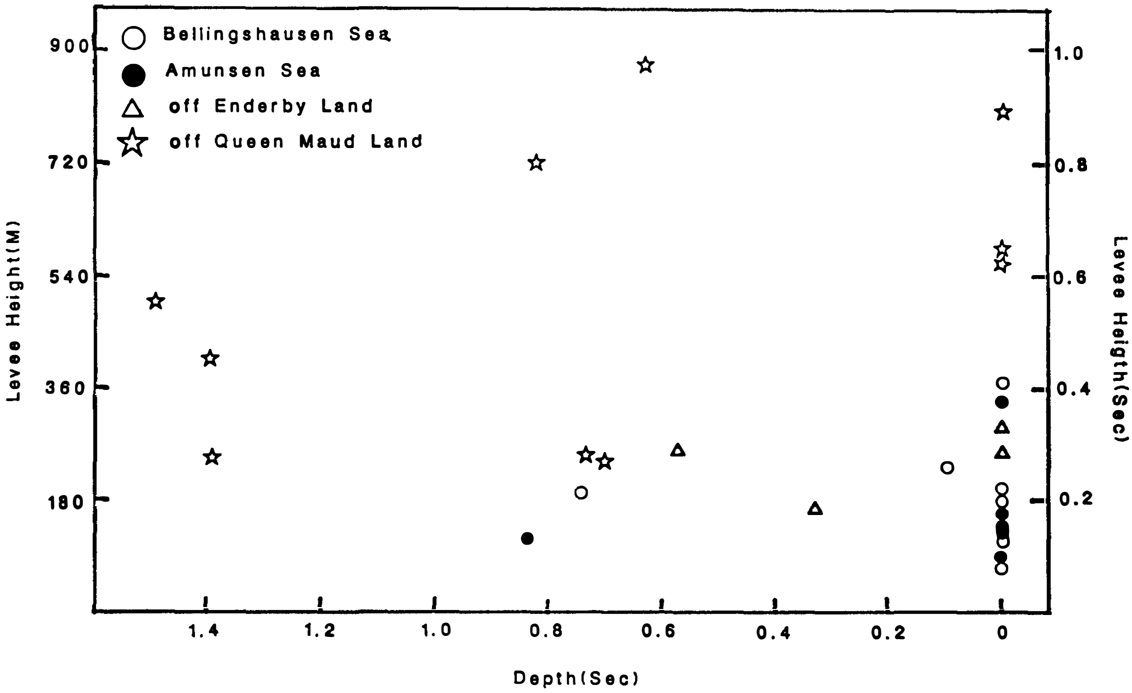

Fig. 6. Relation of levee height to depth. There are many buried canyons found on the seismic profiles. Their depths are measured from the bottom surface to the main channel of the canyon in seconds.

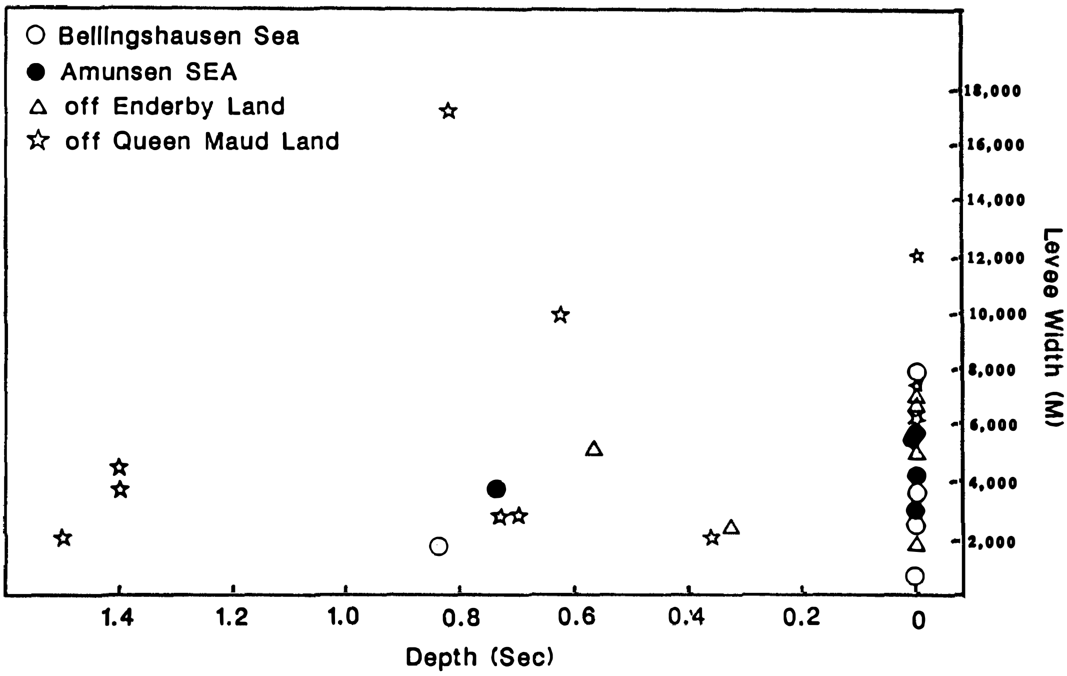

Fig. 7. Relation of levee width to depth. The depth is the same as in Fig. 6.

5 km (Fig. 7). It was only about 3 km in width beneath the bottom to a depth of 0.6 seconds. It had remarkably large scale, with widths of 10 to 17 km in depth between 0.6 and 0.9 seconds, which were observed offshore of Queen Maud Land. Levee widths of 4 to 5 km are also seen in the Amundsen Sea and offshore of Enderby Land in this depth-interval. Therefore, the general trend in this interval is larger than that of the previous and following periods. The levee width deeper than 0.9 seconds was 4 km or less.

5. Relation of Levee Height to Levee Width

The levee height in meters is plotted against levee width in logarithmic meters (Fig. 8). The largest development is seen from the channels offshore of Queen Maud Land. A levee height of 900 m with levee width of 10 km or more is observed offshore of Queen Maud Land. This could be caused by great development of the erosive channel due to local balance between supply and erosion. Sediment supply may be low in this area.

The other case, especially in the Bellingshausen and Amundsen Seas where active sediment supply and strong bottom current were recognized (TUCHOLKE, 1977), is low height compared with width. A levee height of 360 m with levee width of 8 km or less is observed (Fig. 8). This could have been caused by a strong contour-current as TUCHOLKE indicated. From this evidence, it is clear that the relation between levee height and width shows existence of a strong contour-current on the continental rises in the Bellingshausen Sea, Amundsen Sea and probably offshore of Enderby Land. From the relation on the graph, the strongest current can be expected in the Bellingshausen Sea and the weakest offshore of Enderby Land. However, the number

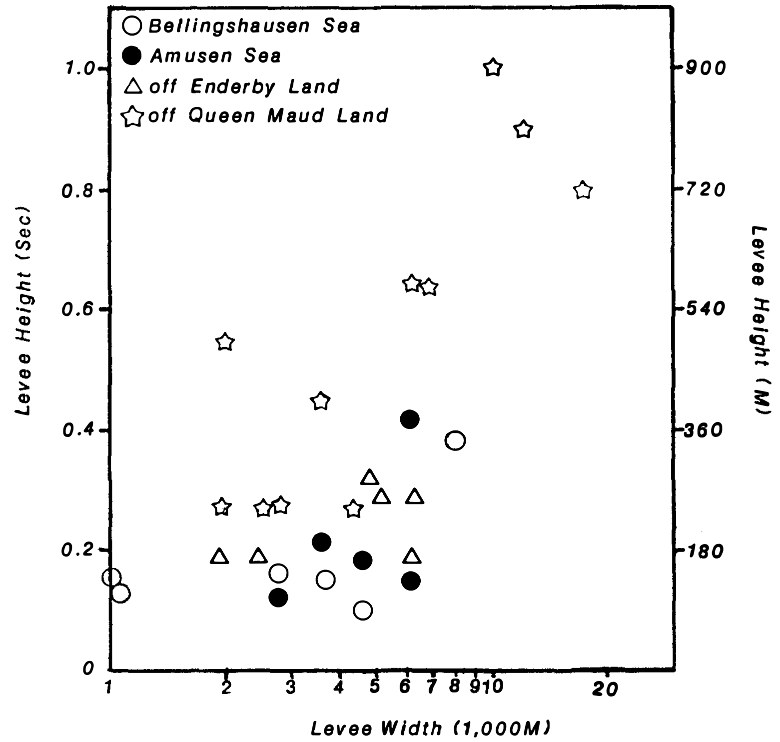

Fig. 8. Relation of levee height in meters and levee width in logarithmic meters.

of samples is limited that it is difficult to draw a definite conclusion.

It is recognized that approximately 85% of natural levees observed at the bottom surface develop on the western sides of submarine canyons. The remaining 15% are obscure and difficult to recognize as levees. This number is evidence to indicate the existence of a deep-sea current on the continental rise.

6. Discussion

Development of natural levees at the western bank of submarine canyons around the Antarctic continent implies that there has been a contour-current parallel to the continental rise. Three possible mechanisms are considered for existence of the contour-current.

ODAMAKI and KURAMOTO (1989) mentioned that the semi-diurnal tide (M_2) in Antarctic waters was highest in amplitude at the Weddell Sea–Antarctic Peninsula and a little bit high offshore of Wilkes Land; and lowest in amplitude in the Ross Sea and offshore of Enderby Land. This means that two semi-diurnal tides with different phases exist around Antarctica; their nodes are thought to exist in the Ross Sea and offshore of Enderby Land. This is consistent with the present data from the Bellingshausen Sea and Amundsen Sea, but not those from offshore of Enderby Land and Queen Maud Land. If we compare tidal data from offshore islands such as Keruguen Island and the Prince Edward Islands (ODAMAKI and KURAMOTO, 1989), the former is much higher in amplitude than the latter, consistent with leveed channel data. These offshore island data apparently relate with continental rise phenomena.

HEEZEN and HOLLISTER (1967) mentioned that sediment dispersal more nearly parallel to the regional contours on the continental rise in the Bellingshausen Sea was effected by an east-west flowing contour-current which probably originated in the Weddell Sea. This Antarctic contour-current apparently entrained sediment from turbidity currents traversing the continental rise, but current speeds measured directly and inferred from bottom photographs were relatively low, probably less than 10 cm/s (TUCHOLKE, 1977). The suggestion that the same current is geostrophic led GORDON (1971) to suggest that the coastal water associated with the strong, persistent west-wind drift or prevailing circum-Antarctic westerlies sank as dense Antarctic Bottom Water.

The third possibility is bottom-trapped topographic Rossby waves. A solution for the bottom-trapped Rossby wave motion (RHINES, 1970) predicts that wave propagation is always to the right of the upslope direction, or westward in the southern ocean. The bottom flow observed at the HEBBLE site was composed of a relatively energetic low-frequency background motion with higher-frequency tidal and inertial fluctuations superposed on it. GRANT *et al.* (1985) attributed the low frequency flow to bottom trapped topographic Rossby waves. An interesting point is that bottom trapped topographic wave motion is bottom intensified and therefore is increasingly important to bottom boundary layer flow.

The observations presented here give a preliminary picture of development of leveed channels on the continental rise around Antarctica where large benthic flow and sediment transport are suspected, and suggest that the westward bottom boundary layer flow may be caused by a combination of low-frequency bottom-trapped topographic waves, a background mean down-slope current (Antarctic bottom water), and tides. It is suggested that in the immediate vicinity of the bottom within the bottom boundary layer, the tidal flow dominates the high-frequency fluctuations and may contribute to develop leveed channels.

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References

ALLISON, E. and LEDBETTER, M. T. (1982): Timing of bottom-water scour recorded by sedimentological parameters in the South Australian Basin. Mar. Geol., **46**, 131–147.

GARDNER, W. D. (1989): Baltimore Canyon as a modern conduit of sediment to the deep sea. Deep-Sea Res., **36**, 323–358.

GORDON, A. L. (1971): Oceanography of Antarctic waters. Antarctic Oceanography I, ed. by J. L. REID. Washington, D. C., Am. Geophys. Union, Antarctic Res. Ser. 15, 169–203.

GRANT, W. D., WILLIAMS, A. J., III and GROSS, T. F. (1985): A description of the bottom boundary layer at the HEBBLE; Low-frequency forcing, bottom stress and temperature structure.

Mar. Geol., **66**, 219–241.

HEEZEN, B. C. and HOLLISTER, C. D. (1967): Physiography and bottom currents in the Bellingshausen Sea. Antarct. J., **2**, 1984.

HOLLISTER, C. D. and MCCAVE, I. N. (1984). Sedimentation under deep-sea storms. Nature, **309**, 220–225.

HOLLISTER, C. D. and HEEZEN, B. C. (1972): Geologic effects of ocean bottom currents. Studies in Physical Oceanography—A tribute to G. Wüst on his 80th Birthday, ed. by A. L. GORDON. New York, Gordon and Breach, 2, 37–66.

KAGAMI, H. and SUK, B. C. (1986): Abyssal bedforms and sediment drifts effected by deep-sea flows —Benthic storm and silt mode concentration. J. Oceanogr. Soc. Jpn., **42**, 308–318.

MCCAVE, I. N. (1985): Sedimentology and stratigraphy of box cores from the HEBBLE site on the Nova Scotian continental rise. Mar. Geol., **66**, 59–89.

MCCAVE, I. N. (1986): Local and global aspects of the bottom nepheloid layers in the world ocean. Neth. J. Sea Res., **20**, 167–181.

MIZUKOSHI, I., SUNOUCHI, H., SAKI, T., SATO, S. and TANAHASHI, M. (1986): Preliminary report of geological and geophysical surveys off Amery Ice shelf, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 48–61.

MORIWAKI, K., MATSUOKA, N. and YOSHIDA, Y. (1987): A preliminary survey by seismic profiling across the Gunnerus Ridge off the Riiser-Larsen Peninsula, Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 41–47.

ODAMAKI, M. and KURAMOTO, S. (1989): Nankyoku Kai no chouseki (Tides in the Antarctic Ocean). Nankyoku no Kagaku, 8. Kaiyogaku (Science in Antarctica, 8. Oceanography), ed. by Natl Inst. Polar Res. Tokyo, Kokon Shoin, 36–62.

RHINES, P. B. (1970). Edge-, bottom- and Rossby waves in a rotating stratified fluid. Geophys. Fluid Dyn., **1**, 273–302.

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

STOMMEL, H. and ARONS, A. B. (1960): On the abyssal circulation of the world ocean II—An idealized model of the circulation pattern and amplitude in ocean basins. Deep-Sea Res., **6**, 217–233.

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

WEATHERLY, G. L. and KELLEY, E. A., Jr. (1985): Storms and flow reversals at the HEBBLE site. Mar. Geol., **66**, 205–218.

YAMAGUCHI, K., TAMURA, Y., MIZUKOSHI, I. and TSURU, T. (1988): Preliminary report of geophysical and geological surveys in the Amundsen Sea, West Antarctica. Proc. NIPR Symp. Antarct. Geosci., **2**, 55–67.

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