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High Resolution Seismic Record of Antarctic Glacial History

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Abstract : While multichannel seismic surveys exist for virtually every ice-free portion of the Antarctic continental margin, there have been few high resolution seismic reflection surveys conducted. These high resolution data aid in the interpretation of MCS records and provide important data for resolving Antarctica's glacial/climatic history. The results of two high resolution seismic surveys, one in the Ross Sea and one on the northern Antarctic Peninsula shelf (including the Bransfield Basin), are presented. This work focuses on the identification of surfaces and sedimentary packages unique to these glacial settings ; such features as glacial troughs, till tongues, and subglacial deltas. Examples of these features occur in both regions, and their stratigraphic occurrence aids in the reconstruction of the glacial history of the study areas.

The Ross Sea is the only area in West Antarctica where drill site information provides constraints to the seismic stratigraphy. Our results indicate that ice sheets grounded on the continental shelf as early as late Oligocene. The Antarctic Peninsula continental shelf also has experienced several episodes of ice sheet grounding, but the timing of glacial events remains poorly constrained.

Key words : seismic survey, glacial history, climate, Ross Sea, Antarctic peninsula

Introduction and Methods

There is still considerable controversy concerning the timing of ice sheet development in Antarctica and about the extent to which ice sheets have fluctuated in size since their initial formation. High resolution seismic reflection surveys can provide direct evidence of glacial erosion and deposition on continental shelves, but this technique has not been widely used in Antarctica, not even in conjunction with drilling on the continental shelf. Most seismic surveys on the continental shelf have used large air gun sources and the resolution of the data simply are not adequate to resolve seismic facies and features associated with glacial erosion and deposition with any degree of confidence (Larter and Barker, 1989 ; Cooper et al., in press). In this paper we present results from two case studies, one in the Ross Sea and the other on the northern Antarctic Peninsula continental shelf. These surveys were aimed at acquiring high resolution seismic records with sufficient stratigraphic resolution to discern glacial features and deep enough penetration to record the entire glacial history of the region. Data were acquired using either one or two 100 in^3 water guns or a bubble-free G.I. (Generator/Injection Gun) air gun. These two sources provided records that are very similar in terms of resolution, however, the G.I. gun provided greater subbottom penetration (between 1.5 and 2.0 seconds two way travel time for the G.I. gun compared to 1.0 second for the water gun). High quality digital and analogue data were acquired using a Litton-Teledyne streamer. To date, only minimal processing of data has been performed.

Ross Sea

The Ross Sea continental shelf has long been recognized as a key region for investigating the long-term glacial history of Antarctica. During DSDP Leg 28 four sites were drilled on the continental margin in order to examine the history of glaciation in the region (Hayes and Frakes, 1975). Unfortunately, recovery was poor at these sites and the interpretation of the recovered strata has remained problematic. For example, massive diamictites, as old as early Miocene age, were recovered at all of the sites, but the subglacial versus glacial marine origin of these diamictites remains controversial, even after detailed sedimentologic analysis (Barrett, 1975 ; Balshaw, 1981). This is a crucial controversy because a subglacial origin for these diamictites implies expansion of a marine ice sheet onto the shelf ; a glacial marine origin for these deposits may imply the presence of much smaller tidewater glaciers in the region. The former implies a polar climate whereas tidewater glaciers can exist in a temperate climatic setting. While the recovery at sites 270 through 273 is too sparse to allow confident paleoclimatic interpretations from lithologic units, these sites provide a rare stratigraphic column with which to conduct sequence stratigraphic studies in Antarctica. The only other sites on the continental shelf of Antarctica are in Prydz Bay, East Antarctica (ODP Leg 119, Barron et al., 1990).

Although the Ross Sea seismic reflection data base is large, these data constitute either multichannel air gun data, which lack the needed resolution for seismic facies analysis, or high resolution data (mostly sparker records) which consist of short and discontinuous lines. Hence, the existing data set (prior to this cruise) was unsuitable for seismic facies and high resolution sequence stratigraphic analyses. During the 1990 austral summer, the R/V *Polar Duke* was used to acquire nearly 6,000 kms of high resolution seismic data on the continental shelf and in McMurdo Sound (Figs. 1 and 2). The planned cruise track relied upon existing data sets to avoid structural features that disrupt the stratigraphic sequences on the shelf, especially in the western Ross Sea. Stratigraphic correlations are facilitated where our tracklines cross existing drill sites on the shelf and in the Sound (Figs. 1 and 2).

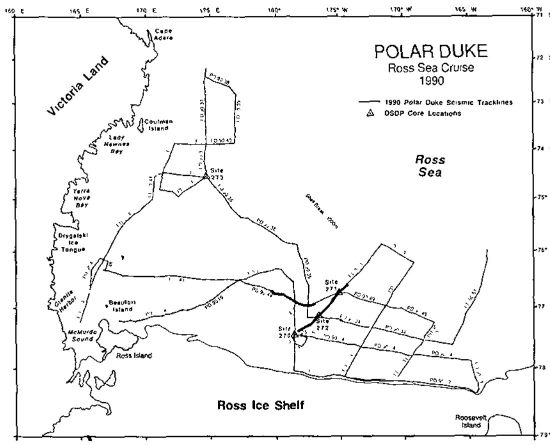

Fig. 1. Location of Polar Duke 90 (PD−90) seismic tracklines and DSDP core locations on the Ross Sea continental shelf. The heavier lines indicate the locations of the profile shown in figures 3 and 4.

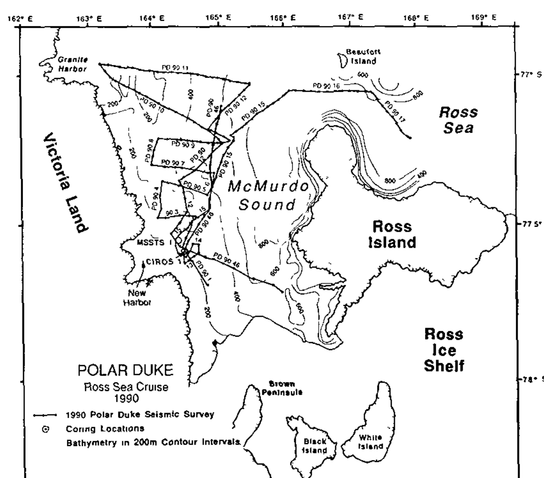

Fig. 2. Polar Duke 90 seismic track lines in McMurdo Sound and the locations of MSSTS−1 AND CIROS−1 drill sites.

Seismic records from the continental shelf show discrete prograding packages bounded by erosional surfaces and acoustically massive, wedge-shaped bodies (Figs. 3 and 4). The massive bodies overlie broad erosional surfaces that are best seen in east-west profiles (Fig. 3). These bodies are similar to till tongues which King and Fader (1986) and King et al. (1987) have described on the Canadian shelf and in the North Sea respectively. The width and depth of the scours associated with the massive tongue-like units is comparable with that of northeast-southwest oriented troughs which highlight the bathymetry of the present shelf. These modern troughs are draped by a massive till unit, and petrographic analyses of this till unit have shown that the troughs were carved by ice streams during the most recent glacial maximum(Anderson et al., 1984 and in press). The massive tongue-like units in figures 3 and 4 are at least 70 to 80 km wide, as compared to modern ice streams which have widths of 100 to 150 km (Alley et al., 1989). The widths of the trough-like scours on the Ross Sea continental shelf also exceeds the widths of incisions carved by fluvial entrenched valley systems ; these are typically 10 to 20 km wide (Berryhill, 1986 ; and Thomas and Anderson, 1989). Thus, a glacial origin is indicated for the erosional surfaces and associated tongue-like units observed in the seismic records. Correlation of seismic records with DSDP site 270 (Fig. 4) shows that the oldest glacial erosional surface and tongue-like unit is late Oligocene in age. At site 270,

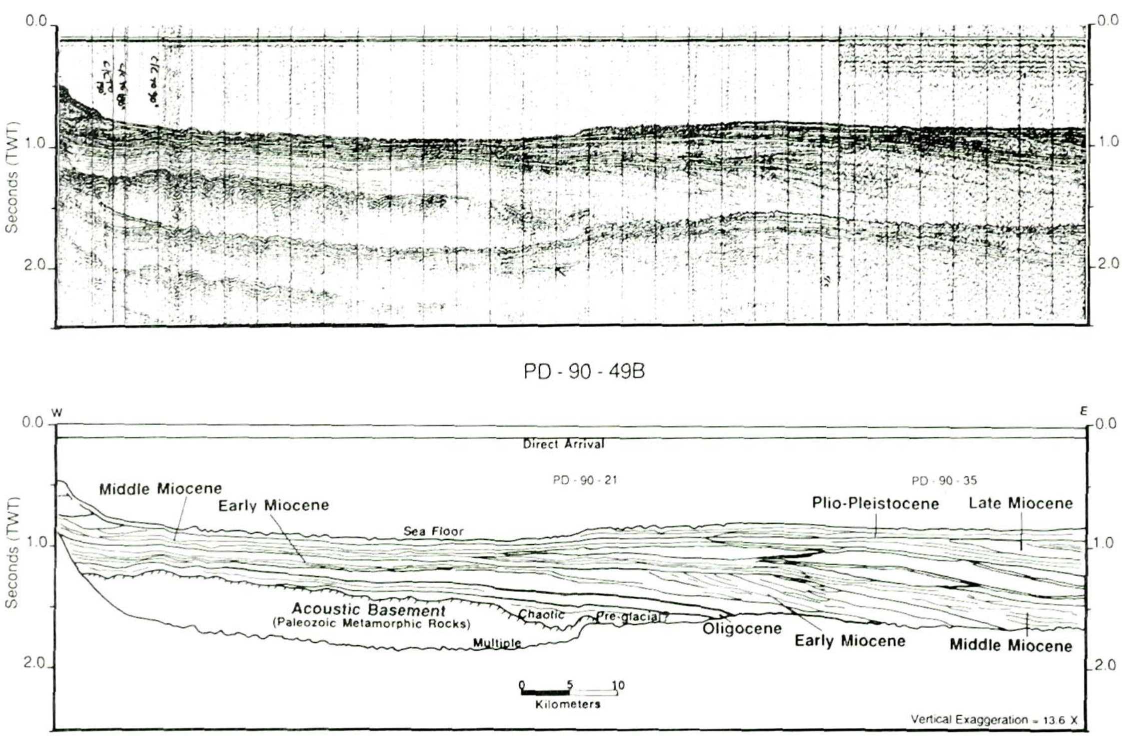

Fig. 3. Seismic Line PD−90−49B from the Ross Sea continental shelf. See Fig. 1 for profile location. Note the massive intervals and the cross cutting relationships of the Neogene strata in this strike section. These are features that are similar to the till tongue stratigraphy described by King and Fader (1986).

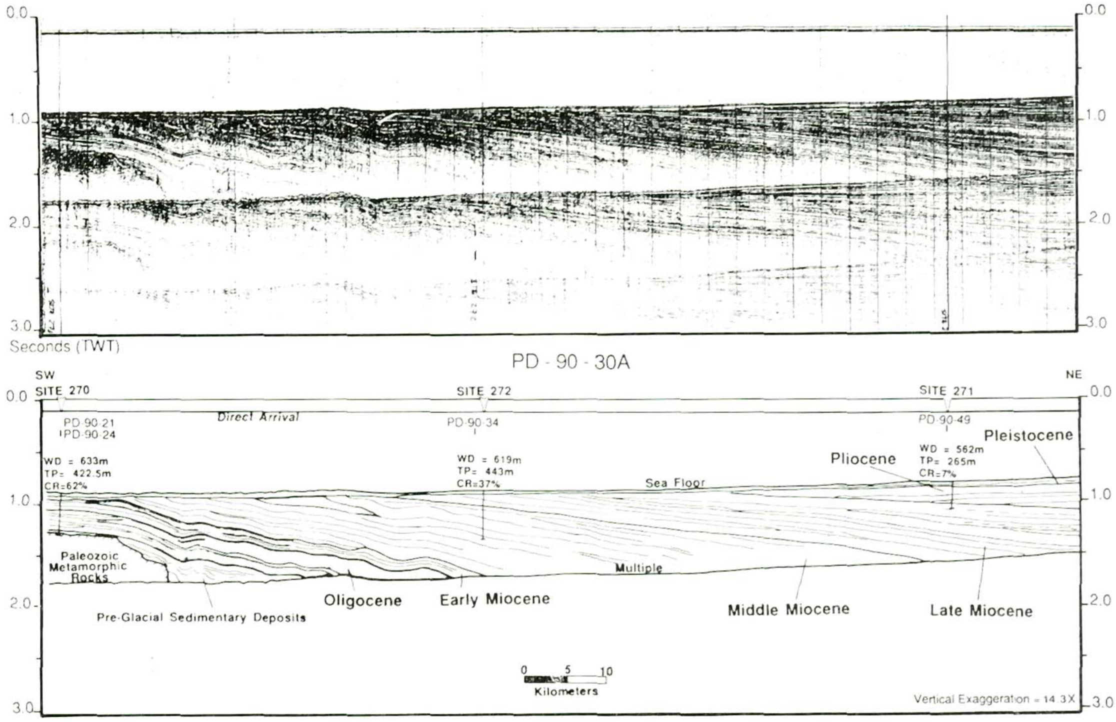

Fig. 4. Seismic profile (PD–90–30A) which extends through DSDP Leg 28 sites 270–272 on the continental shelf. See Fig. 1 for profile and drill site locations.

late Oligocene glacial marine deposits unconformably overlie late Oligocene shallow marine deposits. We suggest that this unconformity is a glacial erosional surface produced by an ice sheet that advanced across what was then a much shallower continental shelf.

Extensive shelf aggradation and progradation followed the late Oligocene grounding event (Fig. 4). Waxing and waning of ice sheets on the continental shelf appears to be intimately related with the aggradation and progradation of the shelf. The ice grounding stratigraphy appears to have been produced by two mechanisms. The till tongue-like stratigraphy, which appears to be the most prevalent, may have been produced by the buoyancy line migration mechanism discussed by King and Fader (1986). In this model tongues of till are deposited on the shelf as wet-based ice sheets wax and wane. The other mechanism involves subglacial delta formation near the grounding line of a marine ice sheet (Alley et al., 1989).

Antarctic Peninsula Region

High resolution seismic surveys were conducted on the northern Antarctic Peninsula continental shelf, including Bransfield Basin and Marguerite Bay, during two cruises of the USCGC *Glacier* and three cruises of the R/V *Polar Duke* (Figs. 5 and 6). No drill sites exist in the region, so the timing of glacial events recorded in seismic records must be inferred by association of seismic stratigraphy with tectonic events of known age and by inferences drawn from land-based geological studies.

The continental margin in this part of Antarctica has evolved from an active margin to a

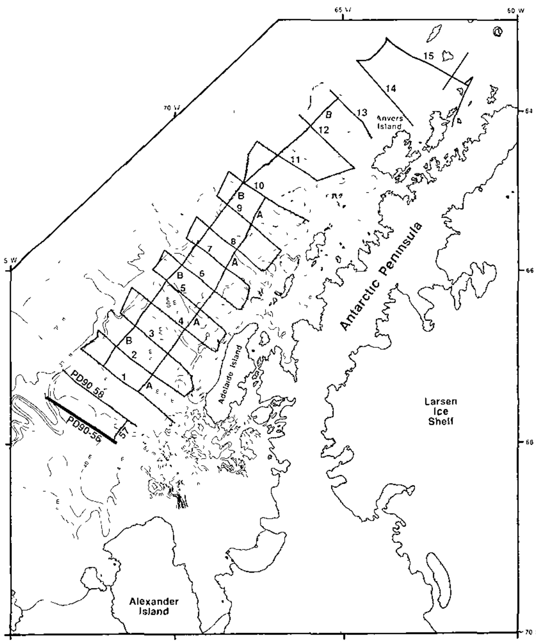

Fig. 5. Polar Duke (PD−88 abd 90) seismic tracklines and bathymetric map for the Antarctic Peninsula region.

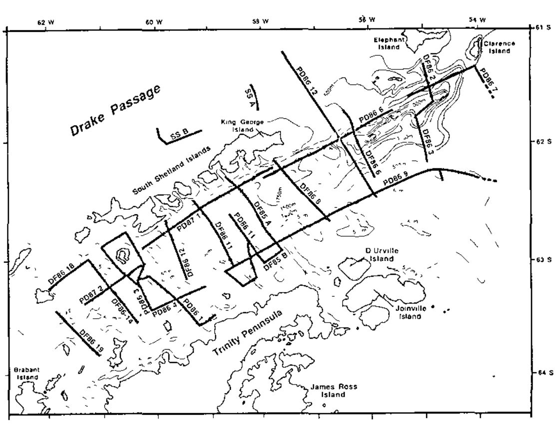

Fig. 6. Glacier (DF−86) and Polar Duke (PD −86 and PD−87) seismic trackline and bathymetric map for Bransfield Basin region.

passive one as the Aluk Ridge gradually was subducted at the Antarctic Plate Boundary. This transition occurred diachronously ; as the timing of ridge subduction proceeded from south to north (oldest to youngest). The shelf exhibits tectonic segmentation, and seismic data show that the extent of tectonic deformation and post-tectonic sedimentation varies correspondingly (Anderson et al., in press).

Seismic records collected from the continental shelf south of Bransfield Basin show four sequences (Fig. 7). The oldest of these, S4, consists of folded and faulted pre-and syntectonic deposits, presumably consisting of volcaniclastic deposits (Jeffers and Anderson, in press). The age of S4 decreases from south to north and is inferred from paleomagnetic data ; it ranges from late Eocene and older south of the Tula Fracture Zone to Modern within the present forearc setting. Sequence S3 represents an accretionary sequence resting sharply on S4, and reflects efficient sediment transport across the shelf following ridge subduction. Sequence S3 displays no evidence of ice sheets having grounded on the continental shelf during the time of its deposition. A major unconformity (glacial erosion surface) separates S3 from the overlying sequence (S2). Abundant glacial erosion surfaces and massive till tongue-like bodies, similar in size and shape to those of the Ross Sea, characterize S2 (Fig. 7). This sequence marks an episode of ice sheet waxing and wanning across the shelf.

The youngest sequence, S1, drapes the outer shelf and thins in an onshore direction (Fig. 7). Its basal surface corresponds to a seafloor unconformity on the inner shelf.

Marguerite Bay is characterized by deep troughs and a virtual absence of sediment, although piston cores from the bay did penetrate till that is overlain by glacial marine sediments (Kennedy and Anderson, 1989). Deep glacial troughs within the bay (Fig. 5) extend onto the continental shelf. The largest of these troughs is the George VI Trough, which was

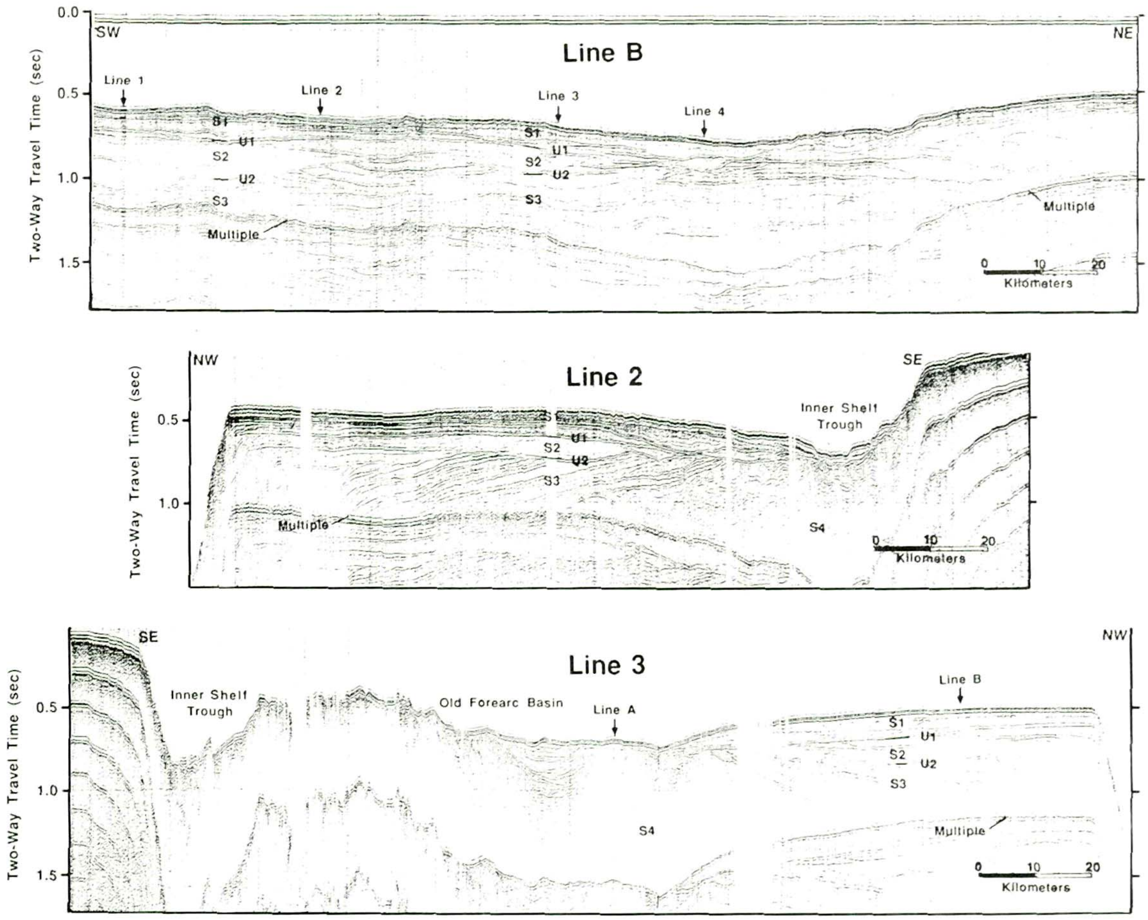

Fig. 7. Representative seismic lines from the Antarctic Peninsula continental shelf showing major sequences and bounding surfaces. See Fig. 5 for profile locations.

carved by the George VI Ice Stream (Kennedy and Anderson, 1989). The products of this erosion now reside on the continental shelf as stacked till deltas seen in Seismic Line PD 90–56 (Fig. 8). This is the only area where till deltas are observed on the northern Antarctic Peninsula shelf, and this may represent the northern extent of large ice streams during the last glacial maximum.

The area north of 62° W is the only part of the Pacific-Antarctic continental margin that is still considered an active margin. Studies of basin evolution and sedimentation within this modern forearc and back-arc setting may provide models for infering the character of Sequence 4 deposits in those protions of the margin (to the south) where subduction has ceased. Seismic records from the Bransfield Basin display two distinct systems tracts that stack to form depositional sequences of the basin (Fig. 9). Organic-rich hemipelagic sediments drape the basin during highstand/interglacial periods. During lowstand/glacial maxima, glaciers erode the shallow platforms and the products of this erosion are transported mainly through troughs and into the basin were they form submarine

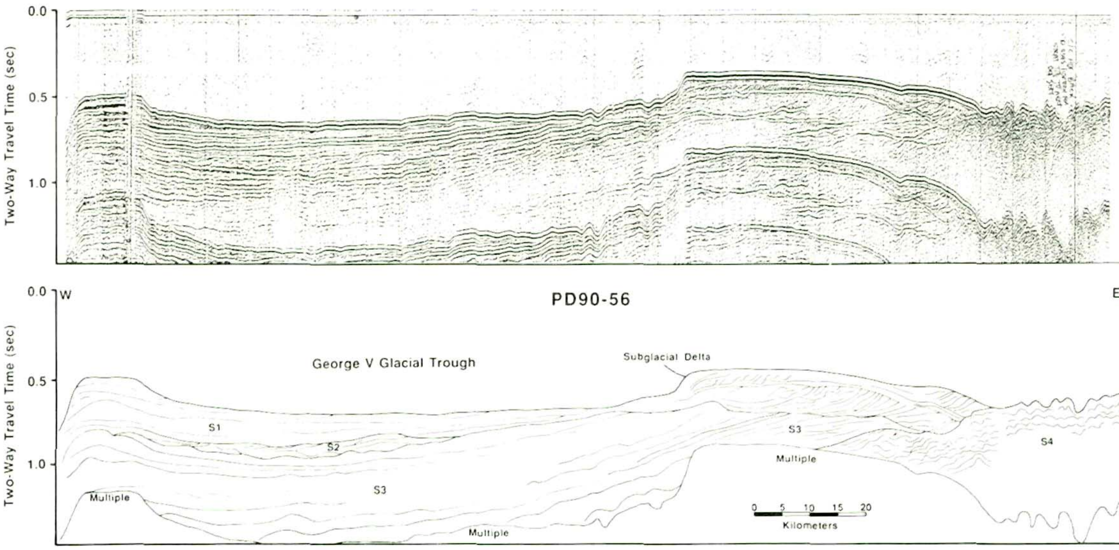

Fig. 8. Seismic line PD 90−56 showing subglacial deltas. See Fig. 5 for profile location.

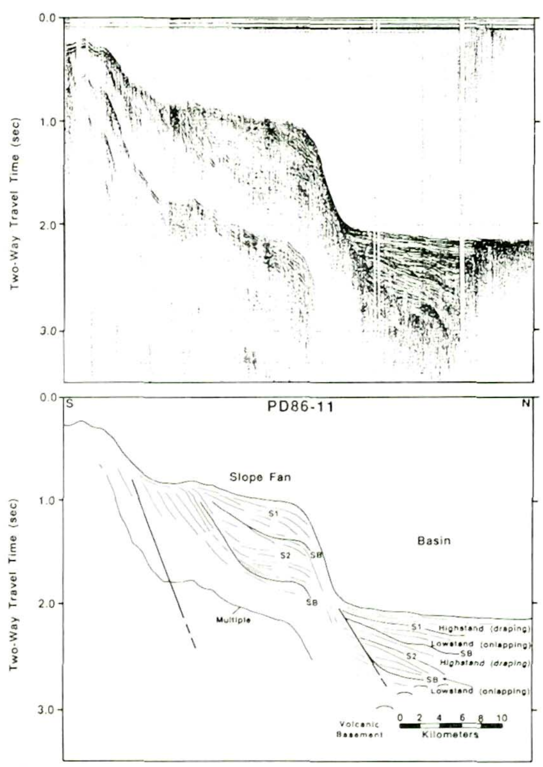

Fig. 9. Representative seismic profile (PD−86 −11) from Bransfield Basin showing the major sequences and sequence boundaries of the basin. See Fig. 6 for profile location.

fans. Subsidence rates and sediment thicknesses suggest that these glacial/interglacial cycles are of ~0.8 Ma duration (Jeffers and Anderson, in press). There is no evidence for ice sheets having grounded at depths greater than 300 meters in the Bransfield Basin region.

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References

Alley, R.B., D. D. Blankenship, S.T. Rooney, and C.R. Bentley. 1989. Sedimentation beneath ice shelves – The view from Ice Stream B : Marine Geology, 85:101–120.

Anderson, J.B., C.F. Brake, and N.C. Myers. 1984. Sedimentation in the Ross Sea Antarctica : Marine Geology, 57:295–333.

Anderson, J.B., L.R. Bartek, and M.A. Thomas. in press. Glacial erosion of the Antarctic shelf, shelf sedimentation, and deep sea fan evolution : a record of Antarctic ice sheet development and history. In : M.R.A. Thompson, J.A. Crame, and J.W. Thompson (eds.), Antarctic Earth Sciences, Cambridge University Press, London.

Balshaw, K.M. 1981. Antarctic glacial chronology reflected in the Oligocene through Pliocene sedimentary section in the Ross Sea : Unpublished Ph.D. Dissertation Rice University, Houston, Texas, 140pp.

Barrett, P.J. 1975. Textural characteristics of Cenozoic preglacial and glacial sediments at site 270, Ross Sea Antarctica. In : D.E. Hayes and L.A. Frakes (eds.), Initial Reports of the Deep Sea Drilling Project, Washington D.C., U.S. Government Printing Office, v.28, p.757–767.

Barron, J., B. Larsen, and J. Baldauf, and Shipboard Scientific Party. 1990. Leg 119 Kerguelen Plateau and Prydz Bay, Antarctica : Proceedings of the Ocean Drilling Program, 119B, Collegs Station, Texas.

Berryhill, H.L.Jr., 1986. The continental shelf off South Texas. In : H.L. Berryhill, Jr. (ed.), Late Quaternary facies and structure, Northern Gulf of Mexico : Studies in Geology No.23, Tulsa, Oklahoma, Amer. Assoc. Pet. Geol., p.11–79.

Cooper, A., H. Stagg, and E. Geist. in press. Seismic stratigraphy and structure of Prydz Bay, Antarctica : implications from ODP Leg 119 Drilling, Proceedings from the Ocean Drilling Program, 119B, College Station, Texas.

Hayes, D.E., and L.A. Frakes. 1975. General synthesis : Deep Sea Drilling Project 28. In : D.E. Hayes and L.A. Frakes (eds.), Initial Reports of the Deep Sea Drilling Project, Washington D.C., U.S. Government Printing Office, v.28, p.919–942.

Hinz, K., and M. Block. 1983. Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica, Proceedings 11th World Petroleum Congress (London), PD 2, Westchester, New York, Wiley & Sons Ltd., p.79–91.

Jeffers, J.D., and J.B. Anderson. in press. Sequence stratigraphy of the Bransfield Basin, Antarctica : implications for tectonic and hydrocarbon potential. In : W. St. John (ed.), Antarctic Symposium Proceedings, American Association of Petroleum Geologists, Special Publication.

Kennedy, D.S., and J.B. Anderson. 1989. Quaternary glacial history of Marguerite Bay, Antarctica : Quaternary Research, 31:255–276.

King, L.H., and G. Fader. 1986. Wisconsinan glaciation of the continental shelf, southeast Atlantic Canada : Geological Survey of Canada Bulletin 363, 72pp.

King, L.H., K. Rokoengen, and T. Gunleiksrud. 1987. Quaternary seismostratigraphy of the Mid Norwegian shelf, 65°-67°30′N – A till tongue stratigraphy : Continental Shelf and Petroleum Technology Research Institute Publication 114, Trondheim, Norway, 58pp.

Larter, R.D., and P.F. Barker. 1989. Seismic stratigraphy of the Antarctic Peninsula margin : a record of Pliocene-Pleistocene ice volume and paleoclimate : Geology, 17 : 731 –734.

Thomas, M.A., and J.B. Anderson. 1989. Glacial eustatic controls on seismic sequences and parasequences of the Trinity/Sabin incised valley, Texas Continental Shelf : Gulf Coast Assoc. Geol. Soc. Trans., 39:563–569.