JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. B4, PAGES 6753–6778, APRIL 10, 1991

Effect of Cenozoic Ice Sheet Fluctuations in Antarctica on the Stratigraphic Signature of the Neogene

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Stratigraphic successions from the Gulf of Mexico-offshore Alabama, northeast Java-Indonesia, Ross Sea-Antarctica, and several other continental margins have been examined. All are characterized by very similar Neogene stratal geometries. In seismic profiles and well log cross sections from these areas, a large, mid-Oligocene (i.e., latest Early Oligocene-earliest Late Oligocene), basinward shift in coastal onlap is followed by a major early Miocene transgression and aggradation, which is in turn followed by early middle Miocene transgressions and late middle and late Miocene progradational episodes. The succession culminates in Plio-Pleistocene high-frequency progradations and transgressions. The interregional character of the Neogene stratal signature and its similarity to the stratal geometry found in seismic data from the Ross Sea continental shelf (Antarctica) suggest that the Neogene stratal signature is a manifestation of glacioeustatic fluctuations. A review of the literature and an analysis of recently acquired and published data indicate that the first major ice sheet grounding event in the Ross Sea occurred during middle to late Oligocene time. The Ross Sea is the repository for ice flowing from a major portion of the continental interior. Thus the glacial record of the Ross Sea should serve as a gage of ice volume changes on the continent that were large enough to influence global eustasy. The ice advance onto the Ross Sea continental shelf during middle to late Oligocene time may have been the result of a decrease in the rate of shelf subsidence as rifting in the Ross Sea slowed or ceased. Advance of the ice sheet resulted in widespread erosion of the continental shelf and shelf overdeepening. It is hypothesized that metastable, marine-based ice sheets have waxed and waned on the Antarctic continental shelf since at least the Oligocene and that the these waxing and waning events were responsible for the development of a global Neogene stratigraphic signature.

Introduction

A number of Antarctic researchers contend that no significant volume of ice existed on Antarctica until evidence of its presence was firmly imprinted on the deep-sea sedimentary record. However, there is evidence from the continent and the continental shelf which suggests that glaciers existed on Antarctica during the Late Paleogene-early Neogene. The question is, how extensive were these ice masses?

It is important to recognize that 95% of the Antarctic continent is covered by ice sheets. Hence the record of Antarctica's early glaciation is largely concealed by ice or has been removed by glacial erosion. A significant portion of the ice draining from both East and West Antarctica flows into the Ross Sea, so the presence of glacial deposits and/or glacial erosional surfaces on the Ross Sea shelf implies that this ice was derived from the interior ice sheets. For this reason, the record of the extent of Neogene ice sheet advances onto the Ross Sea continental shelf serves as a measure of ice volume fluctuations that may have been large enough to influence global eustasy.

Analysis of data from Antarctica indicates that continental-scale ice sheets developed there prior to Neogene time and then fluctuated dramatically. The similarity of Neogene stratal patterns from widely distributed locations to the stratal geometry of the Ross Sea, Antarctica, suggests that a global Neogene stratigraphic signature developed in, response to glacioeustatic fluctuations. The purpose of this paper is (1) to describe the stratigraphic signature of the Neogene, (2) to present key examples from widely distributed locations of the Neogene stratigraphic signature's manifestation in seismic sections, and (3) to present a mechanism for the formation of dramatically fluctuating Antarctic ice sheets.

Paper Number 90JB02528
0148-0227/91/90JB-02528$05.00

Stratigraphic Signature of the Neogene

Neogene stratigraphic successions from a number of continents are characterized by very similar stratal geometries (Figure 1 and Table 1). These stratal geometries can be packaged into globally correlative sequences and systems tracts [*Haq et al.*, 1987]. This is true for both tectonically active and passive margins and siliciclastic or carbonate lithofacies. In areas where the rate of subsidence changes slowly and where there is sufficient sediment supply to prograde into deep water, the Neogene stratal patterns visible on seismic sections and/or well log/outcrop sequence stratigraphic correlation sections are very similar. These stratal patterns are termed the global stratigraphic signature of the Upper Paleogene and Neogene (Figure 2). It is characterized by the following: (1) lower Oligocene landward thickening, (2) upper Oligocene wedge, which laps out at or near the shelf margin and thickens basinward, (3) basal lower Miocene flooding, (4) lower Miocene (Aquitanian) aggradation, commonly ending with lowstand deposits, (5) lower Miocene (Burdigalian) aggradation, commonly ending with major lowstand deposits, (6) middle Miocene (Langhian and lowermost Serravallian) flooding, (7) middle Miocene (Serravallian) major progradation, (8) end of middle Miocene major downward shift of onlap and lowstand deposits, (9) upper Miocene aggradation commonly ending with lowstand deposits, (10) lowermost Pliocene flooding, (11) Pliocene-lower Pleistocene aggradation with multiple lowstand

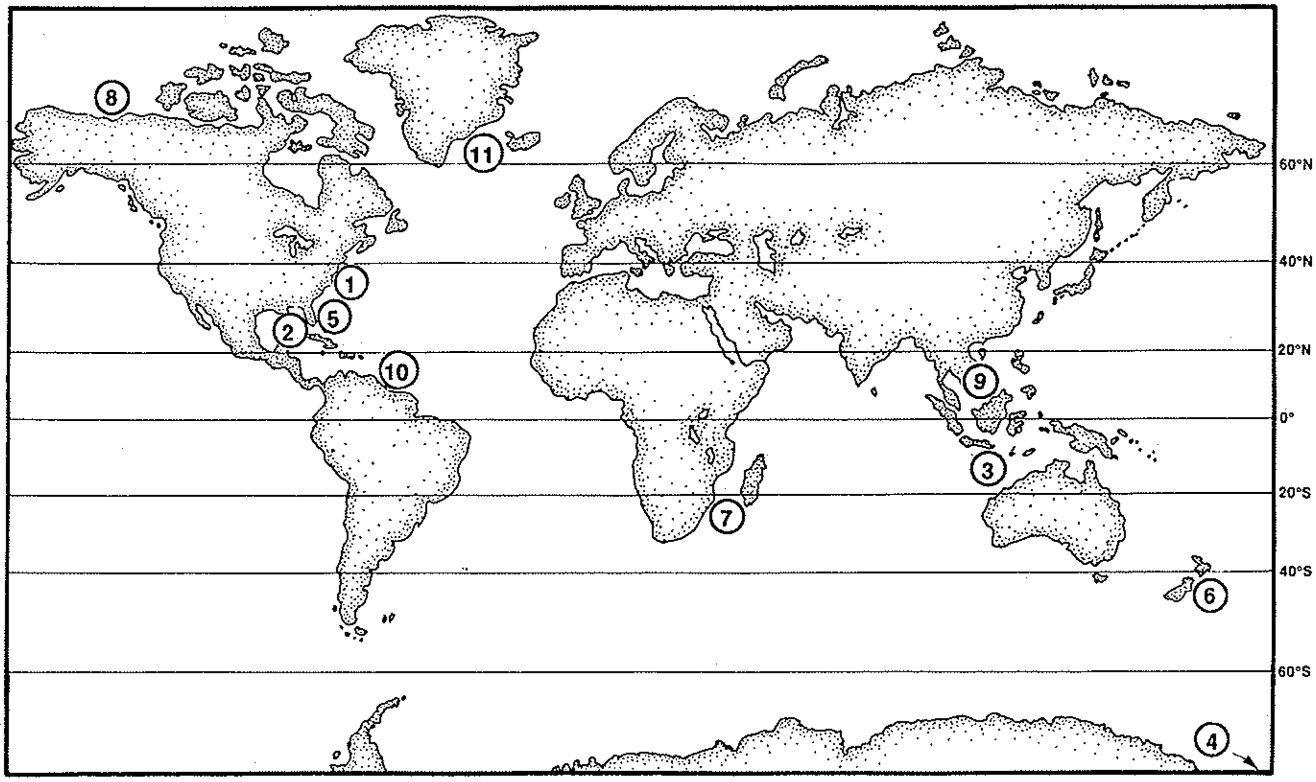


Fig. 1. Map of localities where the geometry of the Neogene strata, as illustrated in seismic profiles, is similar to the idealized stratigraphic signature presented in this paper. Note the wide distribution of these localities.

deposits, and (12) upper Pleistocene high-frequency sequences. We recognize that the examples illustrated in this paper, alone, are not sufficient to unequivocally demonstrate the global extent of these sequences. However, these examples should be sufficient to illustrate the concept. Work is in progress to document, in the public domain, other widely distributed examples of these stratigraphic patterns which have heretofore been recognized in proprietary data sets.

TABLE 1. Listing of Publications and Localities Where the Geometry of the Neogene Strata, as Illustrated in Seismic Profiles, Is Similar to the Idealized Stratigraphic Signature Presented in This Paper

	Area	Reference
1	Baltimore Canyon Trough	*Greenlee et al.* [1988]
2	Offshore Alabama	This paper and *Greenlee and Moore* [1988]
3	Northeast Java (Bali-Flores Sea, Indonesia)	This paper and *Tyrrell and Davis* [1989]
4	Ross Sea, Antarctica	This paper and *Hinz and Block* [1983]
5	Bahama Banks	*Eberli and Ginsberg* [1988]
6	East Coast of New Zealand	*Loutit et al.* [1988]
7	Southeast Coast of Africa	*DeBuyl and Flores* [1986]
8	Southern Beaufort Sea	*Willumsen and Cote* [1982]
9	Central Luconia - Offshore Sarawak, Malaysia	*Epting* [1989]
10	Offshore Guyana	*Jankowsky and Schlapak* [1983]
11	East Coast of Greenland	*Hinz* [1983]

Locations correspond to those posted on Figure 1.

KEY EXAMPLES FROM NORTH AMERICA, THE FAR EAST, AND ANTARCTICA

Seismic sections from the Gulf of Mexico-offshore Alabama, northeast Java-Indonesia, and Ross Sea-Antarctica illustrate the widespread nature of this Neogene stratigraphic signature.

Gulf of Mexico-Offshore Alabama

A grid (Figure 3) of multichannel seismic data, well logs, and biostratigraphic data has been utilized by *Wu* [1989] and *Wu et al.* [1990] in an analysis of the Meso-Cenozoic stratigraphy and salt tectonics in the Gulf of Mexico-offshore Alabama, Mississippi, and western Louisiana. Sequence stratigraphic analysis illustrates the presence of the global Neogene stratigraphic patterns in the Gulf of Mexico-offshore Alabama region. The gross stratigraphy (for summary, see *Winker* [1982], *Buffler and Sawyer* [1985], and *Curtis*, [1987] in the study area is characterized by (1) Upper Triassic-Lower Jurassic red beds and extensive Middle Jurassic evaporites (Callovian) which were deposited during the late rift stage of opening of the Gulf of Mexico, (2) widespread Upper Jurassic carbonate units, (3) thick Upper Jurassic and Upper Cretaceous siliciclastic deposits, (4) extensive Lower Cretaceous carbonate platform deposits and the major condensed section in Middle Cretaceous, and (5) progradational packages of Upper Cretaceous and Tertiary clastic sediments. Tectonically, the study area is situated on a passive continental margin undergoing stable basement subsidence. Growth faulting, salt and overpressured shale movements are typical of the Cenozoic tectonic activity that occurs in much of the Gulf of Mexico (for summary, see *Worrall and Snelson* [1989]). However, the eastern part of the study area lies above the Middle Cretaceous shelf and has therefore been tectonically

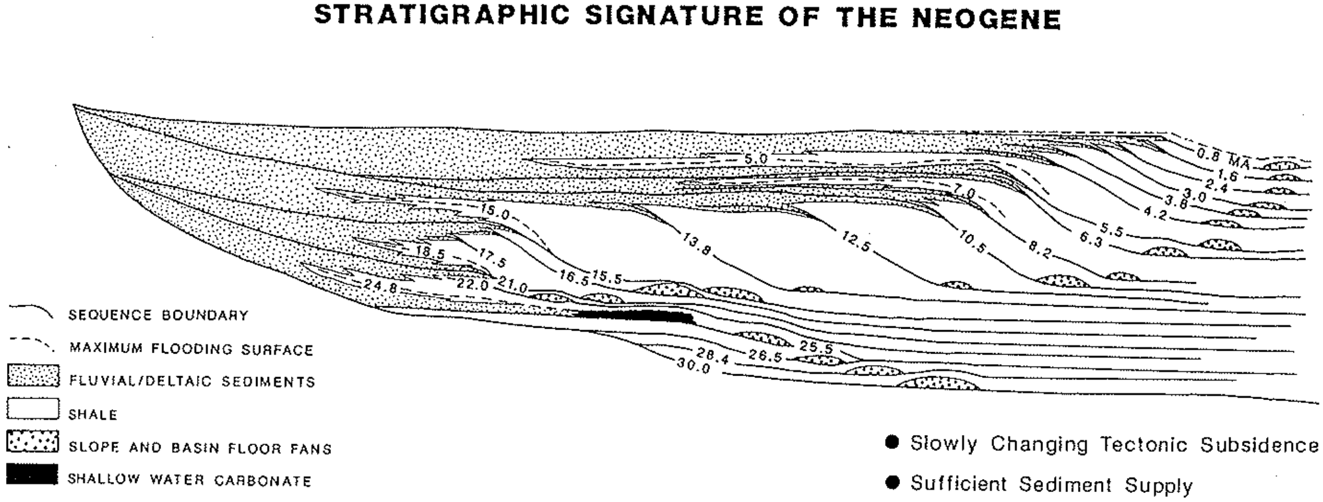


Fig. 2. Cross section of a hypothetical shelf margin illustrating the idealized stratigraphic signature of the Neogene, as observed in seismic profiles, well log correlation sections, and outcrop.

stable, except for an increased in subsidence due to Tertiary sediment loading, since early Cretaceous time [*Greenlee and Moore*, 1988]. Therefore, the region meets the requirements for developing the Neogene stratigraphic signature (slowly changing rates of subsidence and progradation into deep water).

The integrated analysis of stratigraphic sequences using seismic data, well logs, and biostratigraphic information facilitates comparison of the section from this region to the other examples presented in this paper and to the idealized Neogene signature (Figure 2). Ages and depositional environments of the sequences within the well log and seismic profiles were constrained by biostratigraphic data provided by PALEO-DATA Inc. [*Petroleum Information Exploration Systems*, 1989]. A well log cross section (Figure 4; see Figure 3 for location) shows the correlated sequence boundaries. These sequence boundaries are tied to the seismic sequences shown in Figure 5 using check shot velocities and synthetic seismograms. Sequences and system tracts [*Vail*, 1987] are interpreted on the seismic example.

Examination of Figures 4 and 5 reveals that the stratal patterns of the Gulf Coast-offshore Alabama sections are quite similar to the idealized stratigraphic signature of the Neogene (Figure 2). A major Late Oligocene basinward shift between the 30 and 25.5 Ma sequence boundaries is evident throughout the area (Figure 5). The Lower and Middle Miocene sequences (25.5-10.5 Ma) are not well developed within the study area because (1) these sequences were deposited in a landward position during this interval, and (2) sediment supply to the region was low at this time [*Winker*, 1982]. Depocenters were located to the west and landward of the study area during lower and middle Miocene time [*Winker*, 1982]. A general aggradational stratal geometry characterizes the 25.5 Ma to 21 Ma interval. The flooding event at 24.8 Ma is represented by the deposition of a shaley section, the Anahuac Formation which is associated with *Heterostegina* sp., (last occurrence) in the early Miocene. The interval between 21 and 13.8 Ma was also a period of flooding and sediment starvation. There were two significant flooding events during this interval, a 16 Ma event that correlates with *Amphistegina B*, (last occurrence) and a 15 Ma event that correlates with *Cibicides opima* (last occurrence). The long flooding interval was followed by basinward thickening and progradation during the 13.8-10.5 Ma interval (Figure 5). The strata deposited within the 13.8-10.5 Ma interval are widespread, sandy, and generally characterized as regressive. Upper Miocene and Plio-Pleistocene sequences are very well developed in the region due to progradation into the study area. Aggradation of Upper Miocene strata and deposition of Upper Miocene lowstand packages are also well documented in Figure 5. The seismic example also shows lowermost Pliocene flooding followed by Pliocene-lower Pleistocene aggradation and multiple lowstand deposits. Upper Pleistocene high-frequency sequences, as summarized in Figure 2, are clearly seen on the seismic example in Figure 5.

Variations in biostratigraphic interpretations have led to differences in the sequence stratigraphic interpretations [*Wu*, 1989; *Greenlee*, 1988; *Greenlee and Moore*, 1988] for this area. There are discrepancies within the Miocene and and Pliocene-lower Pleistocene sequences of these papers. In the Miocene, the major difference is the position of 10.5 Ma sequence boundary. The data set utilized by *Wu* [1989] suggests that this boundary lies at a much greater depth than indicated by *Greenlee* [1988] and *Greenlee and Moore* [1988]. This causes differences in the interpretations of the sequences lying between the 13.8 and 6.3 Ma sequence boundaries. The discrepancy in the Plio-Pleistocene interpretations lies in the presence of two extra sequence boundaries (5.1 and 4.7 Ma) in the *Greenlee* [1988] and *Greenlee and Moore* [1988] interpretations. These sequences have not been documented elsewhere. Wu examined the published paleotops at the Chevron 6 Main Pass 253 well [*Feeley et al.*, 1990] and proprietary data from the same well and was not able to identify the two sequences reported by *Greenlee* [1988]. A further investigation of the differences in the Plio-Pleistocene interpretations is in progress. However, it is important to note that despite the differences in the interpretations of *Greenlee* [1988], *Greenlee and Moore* [1988], and *Wu* [1989], the general stratal patterns of the Neogene are still very similar.

Northeast Java-Indonesia

A grid of multichannel seismic data, well logs, and biostratigraphic data have been studied by P.A. Emmet (thesis in preparation, 1991) to investigate the evolution of Cenozoic extensional and compressional structures and the interaction of tectonism and sedimentation in the back-arc basin to the northeast of Java, Indonesia. In spite of active tectonism in the area, the stratigraphic signature of the Neogene (Figure 2) is clearly manifested in the seismic records.

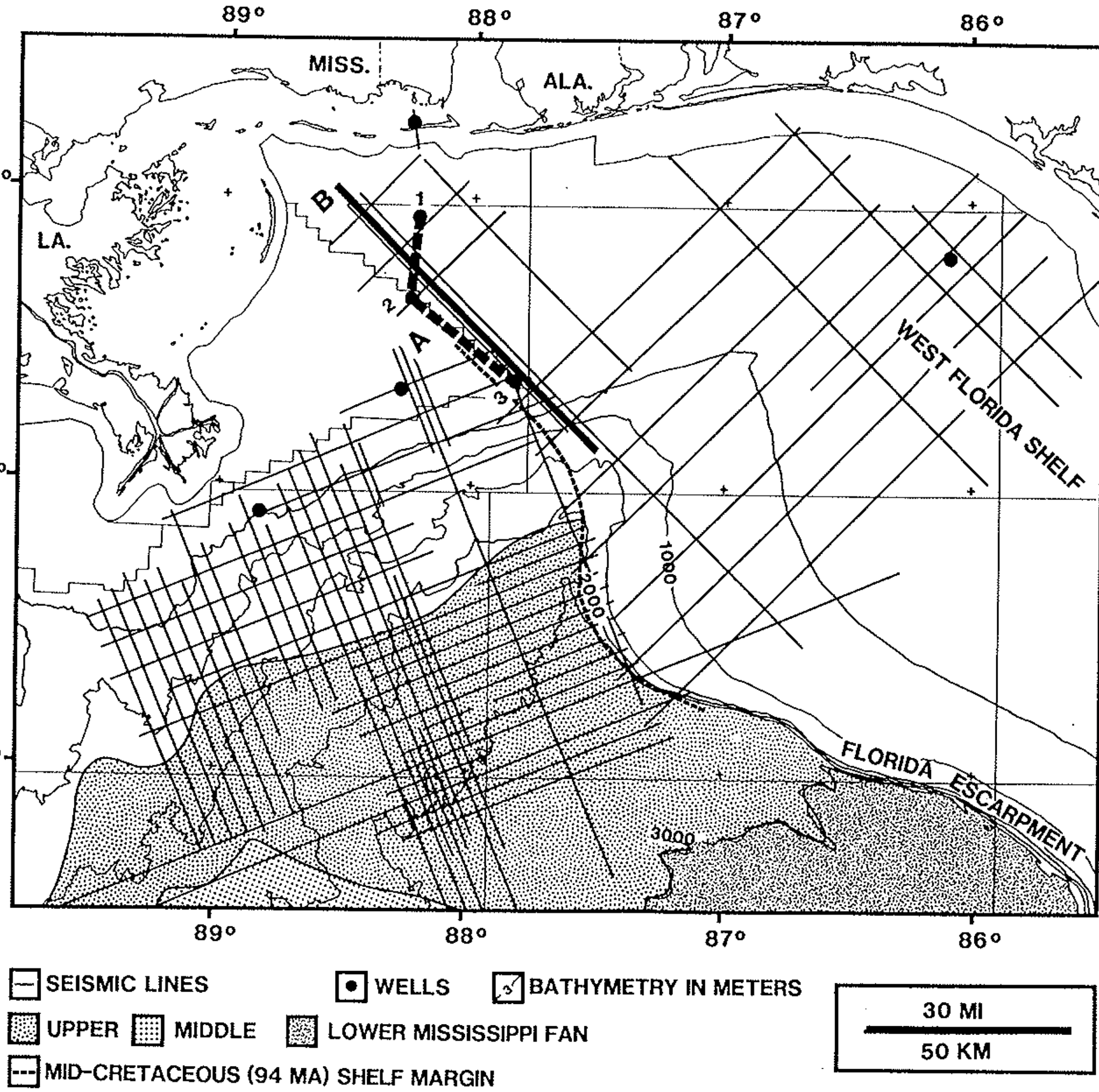


Fig. 3. Map of the Gulf Coast-offshore Alabama illustrating the locations of the well log cross section and seismic profile displayed in Figures 4 and 5.

The study area is an offshore lease block in the Western Flores Sea. Figure 6*a* shows the location of the block with respect to major geographical features, and Figure 6*b* shows the seismic grid and exploration wells within the study area. The area is underlain by a subduction complex of Cretaceous age [*Hamilton*, 1979] which was deformed, mildly metamorphosed, uplifted, and peneplained in the Late Cretaceous to early Tertiary. The development of half graben basins began in the Paleocene and was followed by the regional subsidence which resulted in the evolution of the present back arc basin. Subsidence has been interspersed with episodes of compressional deformation in the Neogene which has inverted some of the half graben basins by reactivating the bounding listric normal faults as thrusts (P.A. Emmet, thesis in preparation, 1991).

An uninterpreted seismic profile (Figure 7*a*) and an interpreted line drawing (Figure 7*b*) illustrate the stratigraphic signature of the upper Paleogene and the Neogene in Indonesia. The seismic profile trends NNE across a drowned Miocene shelf margin (location shown in Figure 6*b*), and the line drawing (Figure 7*b*), shows the stratal termination patterns that define the sequence boundaries and downlap surfaces (maximum flooding surfaces) on this profile. The lower Oligocene section (36.0-30.0 Ma) in this region is dramatically thickened landward of the paleoshelf edge, while the upper Oligocene (30.0-25.5 Ma) is composed of a basinward thickening sedimentary wedge which onlaps out at the paleo shelf edge. A thick transgressive deposit is then topped by the earliest Miocene maximum flooding surface (24.8 Ma). This deposit has the seismic characteristic of an aggrading (keep-up) carbonate. Lower Miocene (Aquitanian) aggradation, without conspicuous progradation (24.8-21.0 Ma) is followed by a thick lowstand prograding wedge below the 18.5 Ma maximum flooding surface. Aggradation with moderate progradation in the Burdigalian (18.5-16.5 Ma) is followed by a modest lowstand prograding wedge (note that in this example the early Burdigalian lowstand deposits are less conspicuous that those of the lowermost Serravallian). Thick transgressive systems tracts are developed below the 16.0 and 15.0 Ma (Langhian and lowermost Serravallian) maximum

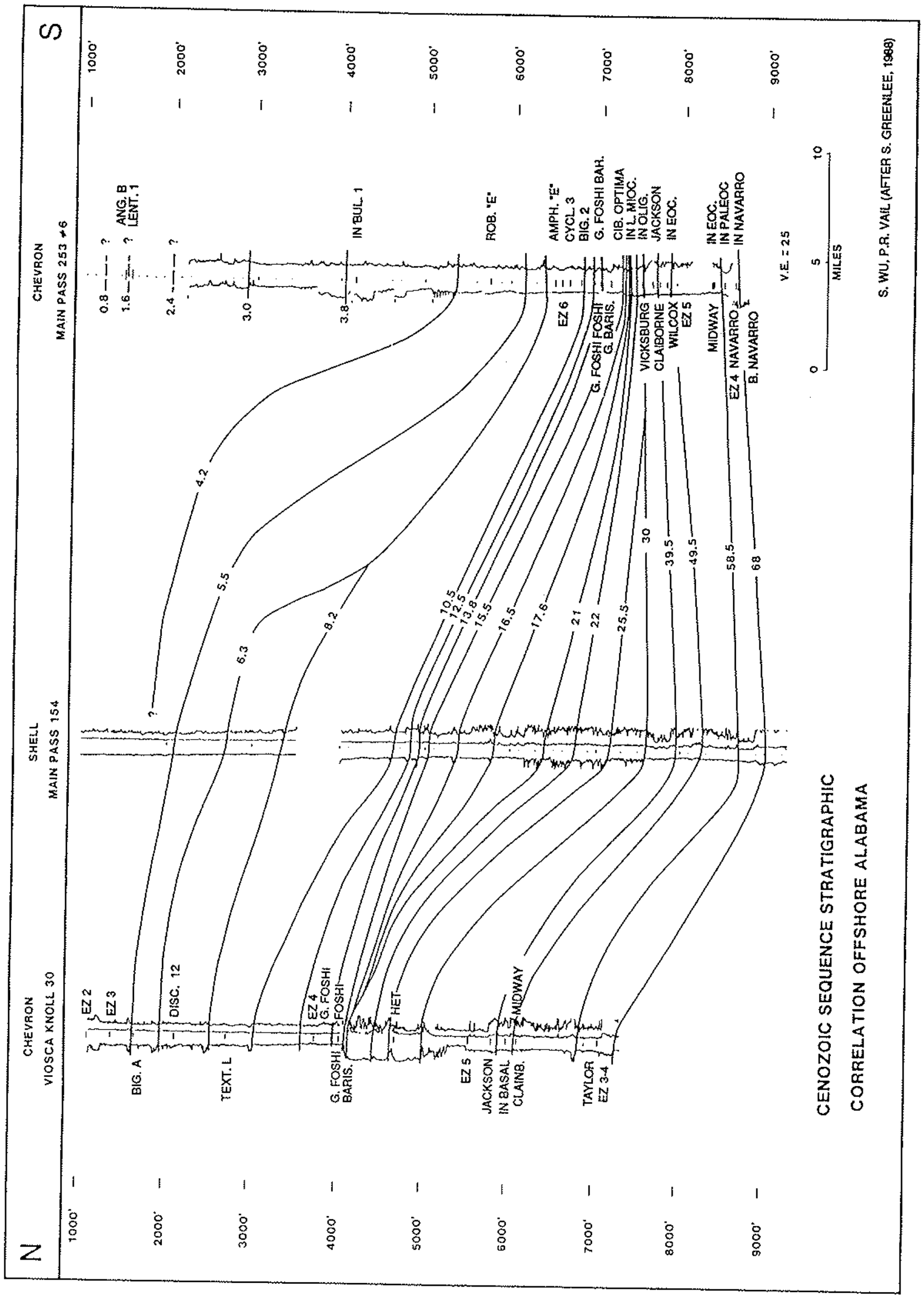


Fig. 4. Well log cross section from the Gulf Coast-offshore Alabama [*Wu*, 1989]. Note that the stratal patterns displayed on the well log section are similar to those seen in the seismic data (Figure 5).

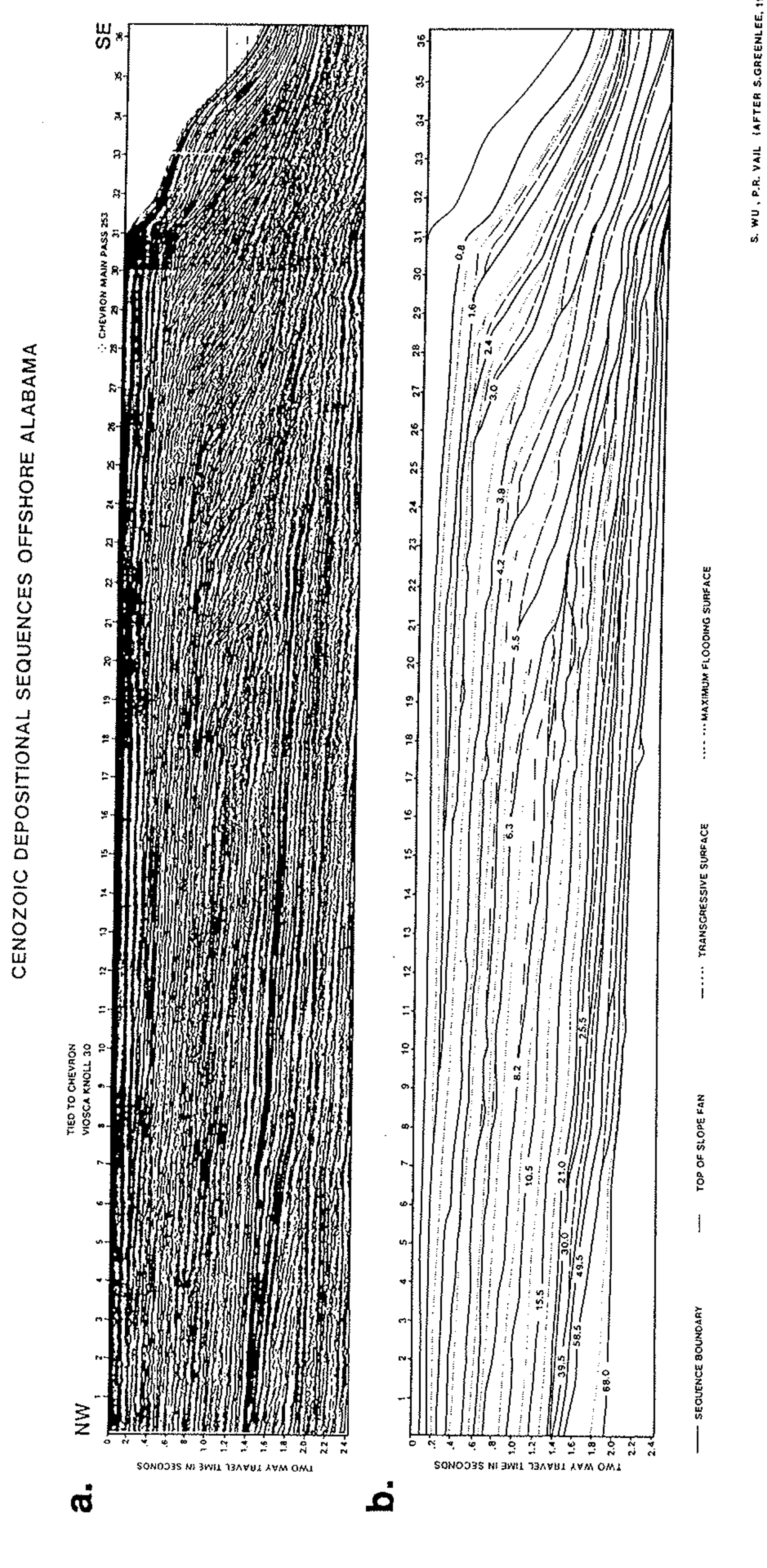


Fig. 5. (*a*) A seismic profile and (*b*) an interpreted line drawing of the data from the Gulf Coast of the United States [*Wu*, 1989]. Note the similarity of the stratal patterns seen in this profile to those of Indonesia (Figure 7), Ross Sea, Antarctica (Figures 14 and 15) and to those depicted in Figure 2 (stratigraphic signature of the Neogene).

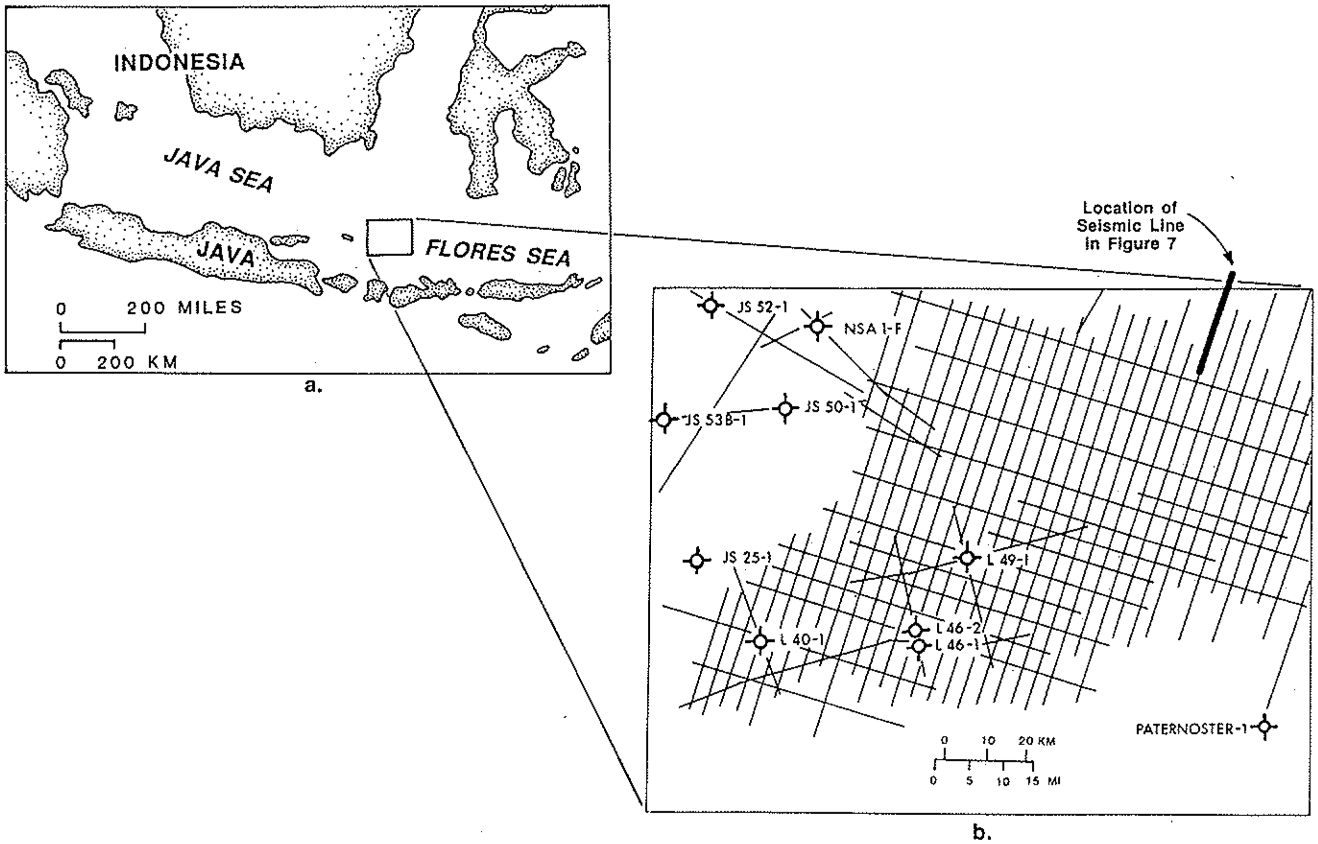


Fig. 6. Location map for the seismic profile shown in Figure 7. (*a*) Study area is the western Flores Sea, Indonesia. (*b*) The grid in the inset illustrates the seismic data base in the area, and the heavy line is the location of the line that is displayed in Figure 7. The crossed-circle symbols (dry hole symbols) are the well control in the area.

flooding surfaces. Spectacular progradation is exhibited in the middle Miocene (Serravallian) highstand deposits from the 13.8 Ma to the 10.5 Ma sequence boundary. A major downward shift in coastal onlap at the end of the middle Miocene is accompanied by truncation below the 10.5 Ma sequence boundary and a lowstand prograding wedge is developed between the 10.5 Ma sequence boundary and the 9.2 Ma maximum flooding surface. At approximately this time the rate of tectonic subsidence increased significantly, eventually drowning the shelf margin. Upper Miocene deposits are characterized by an increase in accommodation and by a change from progradation to aggradational progradation. Lowstand deposits are associated with the 8.2 and 6.3 Ma sequence boundaries. In earliest Pliocene time, eustatic sea level rise combined with tectonic subsidence to drown the shelf margin. This event is marked by the 5.0 Ma maximum flooding surface. The surface is defined by reflections which downlap and climb onto the shelf margin from left to right on the profile. Note that the downlapping reflections above the 5.0 Ma maximum flooding surface lap onto and bury the drowned shelf margin. Drowning of the shelf margin profoundly altered the local stratigraphic signature of the youngest deposits on this profile. However, the signature continued to be generated at the succeeding shelf margin, which stabilized tens of kilometers to the north. The distal conformities of the post-Pliocene sequence boundaries and flooding surfaces, as defined at the succeeding shelf margin, can be correlated back to this area.

Ages assigned to the sequence boundaries and downlap surfaces (Figure 7*b*) are consistent with detailed biostratigraphic control from several wells within the study area. In some cases the resolution of the biostratigraphic control is at the level of planktonic foraminifera and nannofossil zones. The biostratigraphic control used to constrain the interpretation of the Neogene sequence stratigraphy is shown in Table 2. The ages assigned to the sequence boundaries and downlap surfaces in the seismic profile were keyed to the chronostratigraphic chart of *Haq et al.* [1987] in the following manner. Sequence boundaries and maximum flooding surfaces were interpreted independently on the well logs and on the seismic data. The biostratigraphic tops from the wells (Table 2) were converted to time and plotted on the seismic lines that cross the well sites. Sequence boundaries and maximum flooding surfaces interpreted from the well logs were also compared to the stratigraphic interpretations of the seismic data. Differences in interpretations were reconciled by giving priority to the seismic interpretations, which are believed to reflect regional relationships more clearly than the well log data.

Ross Sea, Antarctica

The Ross Sea is a large embayment of the Antarctic coastline that lies at the boundary of the two subcontinents of Antarctica (East and West Antarctica) (Figure 8). The Ross Sea continental shelf consists of a ridge and swale topography (Figure 9). The ridges trend NNE, and the shelf has been overdeepened during glacial-erosional events to an average depth of approximately 500 m [*Houtz and Davey*, 1973]. The shelf also is foredeepened; that is, it is characterized by a gentle slope (≈0.5°) toward the continent rather than away from it. The Ross Embayment is best characterized as a broad

TABLE 2. Biostratigraphic Tops Used to Constrain the Ages Assigned to Sequence Boundaries and Maximum Flooding Surfaces in the Indonesian Seismic Data

Age	Amoco L 40-1	Amoco L 46-1	Amoco L 46-2	Cities JS 53B-1
Plio-Pleistocene	N22/20	N18 (Late)	N18?	N21
	N19			N20/19
	N18			
Upper Miocene	N17/16	N18 (Early)	N17?, NN11	N18?/14?
	N15		N16/15?	
			NN9/6	
Middle Miocene	N13	N14	N14	Upper N13
	N10	N13	N13/11	Lower N13
	N9	N12	N10/9	N12/10
		N10/9 (Late)	NN5	N9
		N9 (Early)/8	N8/7, NN4	
Lower Miocene	N5/4	N5/4	N6/5, NN3/1	N8/7
			N5/4	N6/4?
Upper Oligocene	P22	P22	NP25	Lower Te*

* Te is a zonation of Larger Foraminifera, the top of which is roughly equivalent to middle P22.

Zones preceded by a "P" and "N" are for planktonic foraminifera. Zones preceded by "NN" and "NP" are calcareous nannofossils.

rift (1000 km wide), and the formation of the Ross Embayment has been related to the rifting processes associated with the breakup of Gondwana [*Cooper et al.*, 1987; *Davey*, 1987]. *Davey et al.* [1982] have delineated three major basins within the Ross Embayment: the Eastern Basin, the Central Trough, and the Victoria Land Basin (Figure 9). The Victoria Land Basin and the Central Trough are thought to have formed by continued rifting, while the Eastern Basin is thought to have formed by crustal downwarping due to sediment loading [*Davey*, 1987]. Sedimentary fill within these basins is not well known. However, based upon limited drilling and the available seismic reflection data, it has been surmised that the sedimentary fill of the Victoria Land Basin consists of a thick sequence of Devonian to Recent age rocks, while the fill of the Central Trough and the Eastern Basin is composed of Mesozoic and younger sediments [*Cooper et al.*, 1988*a*, *b*].

The Neogene stratigraphic signature of the Ross Sea continental shelf is best documented in the Eastern Basin. Seismic data that are available in the central and eastern Ross Sea include the *Eltanin* 27, 32, and 52 profiles [*Houtz and Meijer*, 1970; *Houtz and Davey*, 1973], West German and Japanese multichannel seismic surveys (*Hinz and Block* [1983] and *Sato et al.* [1984], respectively), the *Glomar Challenger* seismic profiles over Deep Sea Drilling Project (DSDP) sites 270-272 [*Hayes et al.*, 1975] (Figure 10) and the *Polar Duke* 1990 survey (Figure 11). Seismic profiles collected along the DSDP leg 28 transect in the central and eastern Ross Sea all reveal a series of offlapping reflectors that are truncated near the seafloor [*Houtz and Davey*, 1973; *Hayes et al.*, 1975; *Hinz and Block*, 1983; *Sato et al.*, 1984] (Figures 12 and 13). Velocity analysis of the strata that infill the basins of the Ross Sea via sonobuoy refraction surveys has enabled a number of researchers [*Hayes et al.*, 1975; *Hinz and Block*, 1983; *Sato et al.*, 1984] to correlate their seismic data to the stratigraphy of DSDP sites 270-272.

Hayes et al. [1975] present a preliminary correlation of DSDP sites 270-272 to the seismic data (Figure 12*b*). They correlate the angular unconformity present on the *Glomar Challenger* and *Eltanin* 52 seismic surveys to the marked increase in lithification and to the stratigraphic hiatus (early Pliocene to early Miocene) that occurs at approximately 20 m subbottom at DSDP site 270 (base of unit 1a+b). *Hayes et al.* [1975] state that the core and seismic data from the central Ross Sea indicate a gradual deepening of DSDP site 270 and the central Ross Sea from (1) subaerial exposure under temperate climatic conditions during Oligocene time when breccia, which has been interpreted as a talus deposit (unit 5) was deposited, (2) to littoral conditions when carbonaceous sand (unit 4) and greensand (unit 3) were deposited (middle (i.e., latest Early Oligocene-earliest Late Oligocene) to late Oligocene), (3) to a depth of 500 m under cold conditions when glacial marine sediments (units 2j-2a) were deposited (late Oligocene to Recent) (see Figure 12*b* for stratigraphic position of units). According to *Hayes et al.* [1975], the grounding of an ice sheet in the central Ross Sea did not occur until about 4.5-5.0 m.y. ago (equivalent to the base of unit 1a+b, see Figure 12*b*).

Hinz and Block [1983] interpret the oblique, sigmoid, and complex oblique geometries of seismic reflections from sequences RS (Ross Sea) -1 through RS-5 as a series of fluvial delta lobes that correlate to the Miocene and younger sediments cored at DSDP sites 270-272 (Figure 13*a*). The sedimentary section underlying unconformity U5 is composed of subparallel reflectors of low continuity that gently dip seaward. *Hinz and Block* [1983] state that this section is subdivided by a distinct unconformity (U6) into sequences RS-6 and RS-7. They date U6 as mid- to late Oligocene by correlation to the boundary in DSDP site 270 between basal glacial sediments, which are inferred to be 25 m.y. old (via paleomagnetic stratigraphy [*Allis et al.*, 1975]), and the preglacial greensands, which are estimated to have an age of 26 m.y. [*McDougall*, 1976]. The age of the calcareous greensands was determined by utilizing K-Ar methods to date glauconite from the sand. The 26 m.y. age of the calcareous greensand is regarded as a minimum because another sample from the same interval produced an age of 28.1 $\pm$ 0.4 m.y. [*McDougall*, 1976]. The presence of impurities in the sample that produced the 28 m.y. age may have caused it to yield an older date. However, as *McDougall* [1976] notes, glauconite commonly produces K-Ar ages that are too young due to the ease with which radiogenic argon is lost from it. Therefore the most that can be said about the age of this unconformity (U6) is that it is mid- to Late Oligocene in age. The U6 unconformity is interpreted by *Hinz and Block* [1983] to have been produced by a paleoceanographic event associated with the development of an unrestricted Circum-Antarctic Current.

Figures 13*b* and 13*c* are line drawings by *Sato et al.* [1984] of multichannel seismic data that were also collected in the

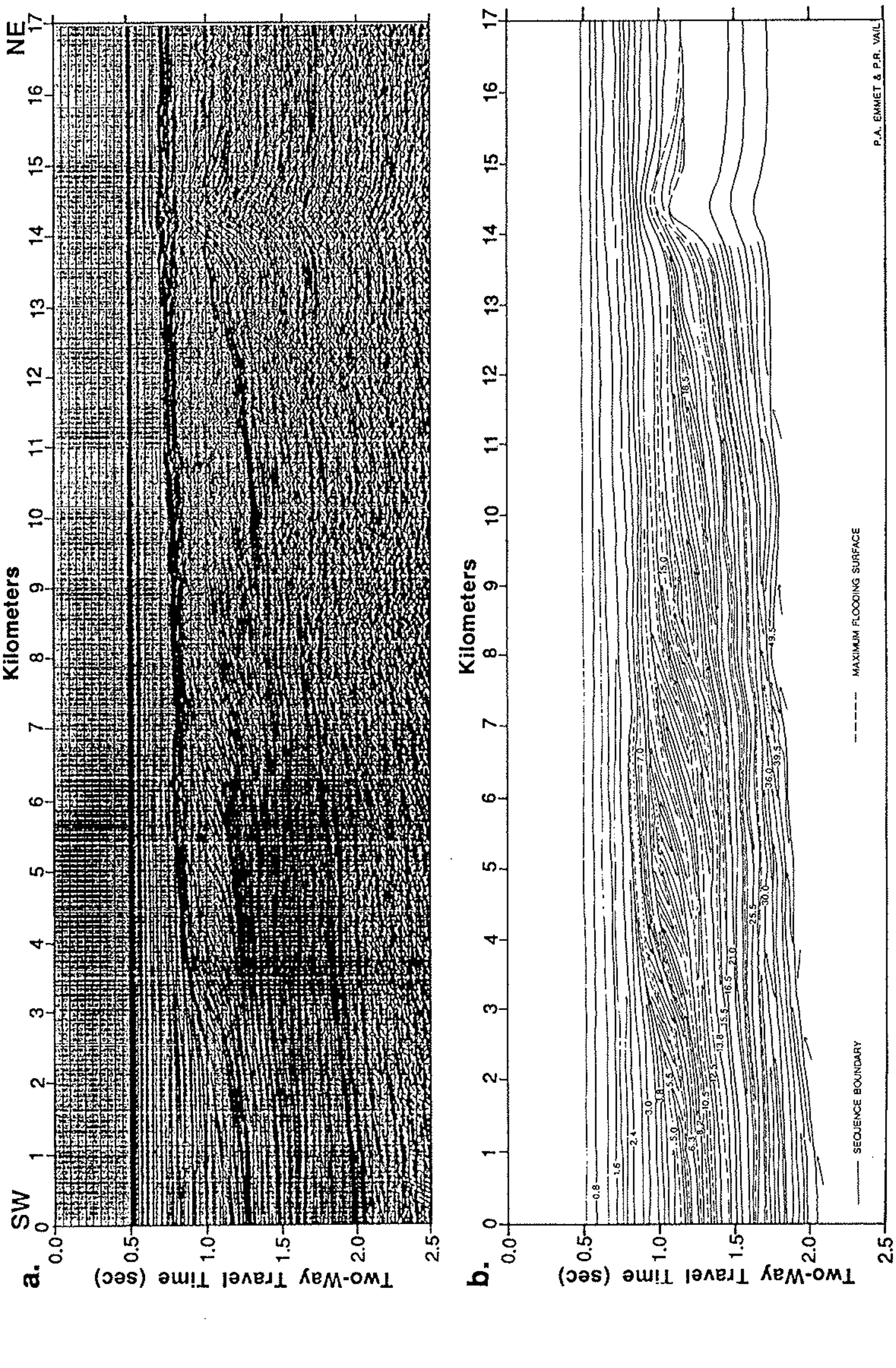


Fig. 7. (*a*) Seismic profile and (*b*) detailed interpretation of data from the western Flores Sea, Indonesia. Note the similarity of the stratal patterns seen in this profile to those of the Gulf Coast-offshore Alabama (Figure 5), and the Ross Sea, Antarctica (Figures 14 and 15), and to those depicted in Figure 2 (stratigraphic signature of the Neogene). The patterns are visible in the Indonesian example in spite of active Cenozoic tectonism.

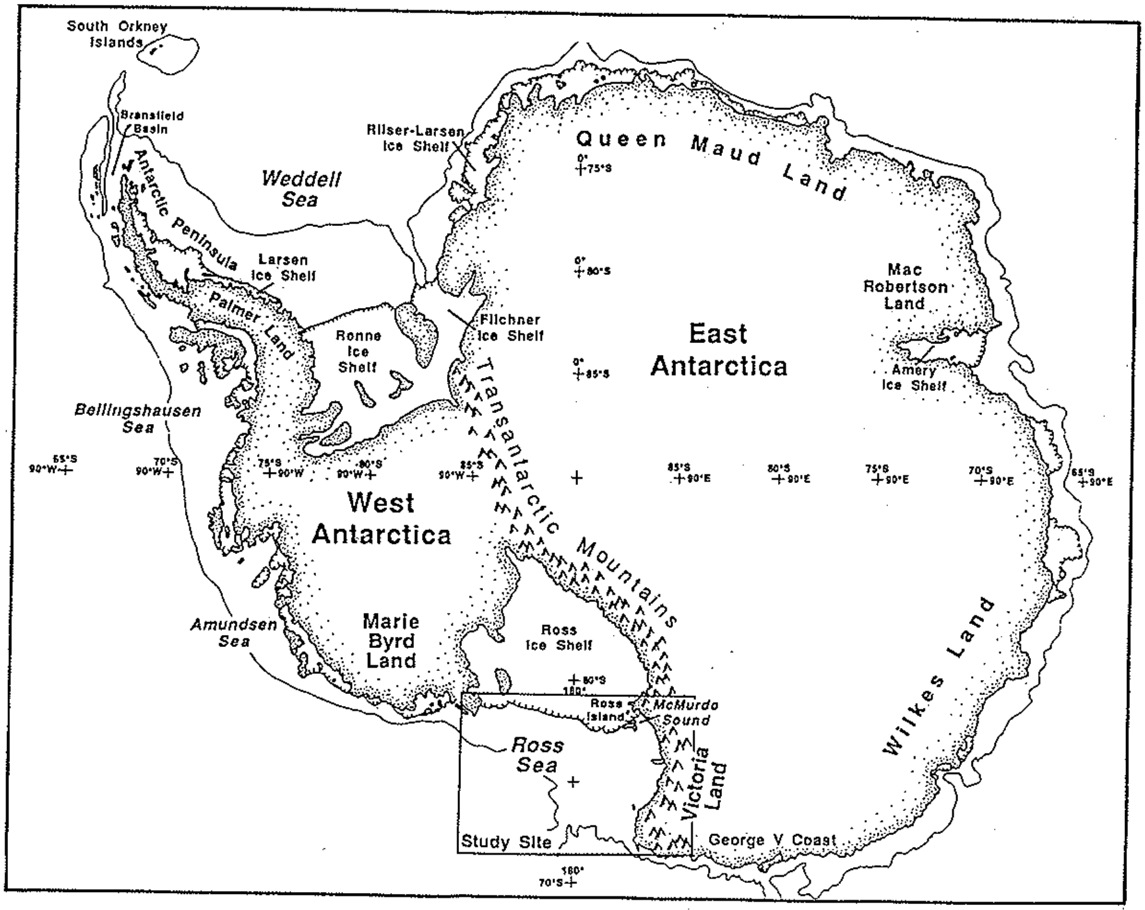


Fig. 8. Map of Antarctica showing the location of the Ross Sea and the other localities that are mentioned in the text .

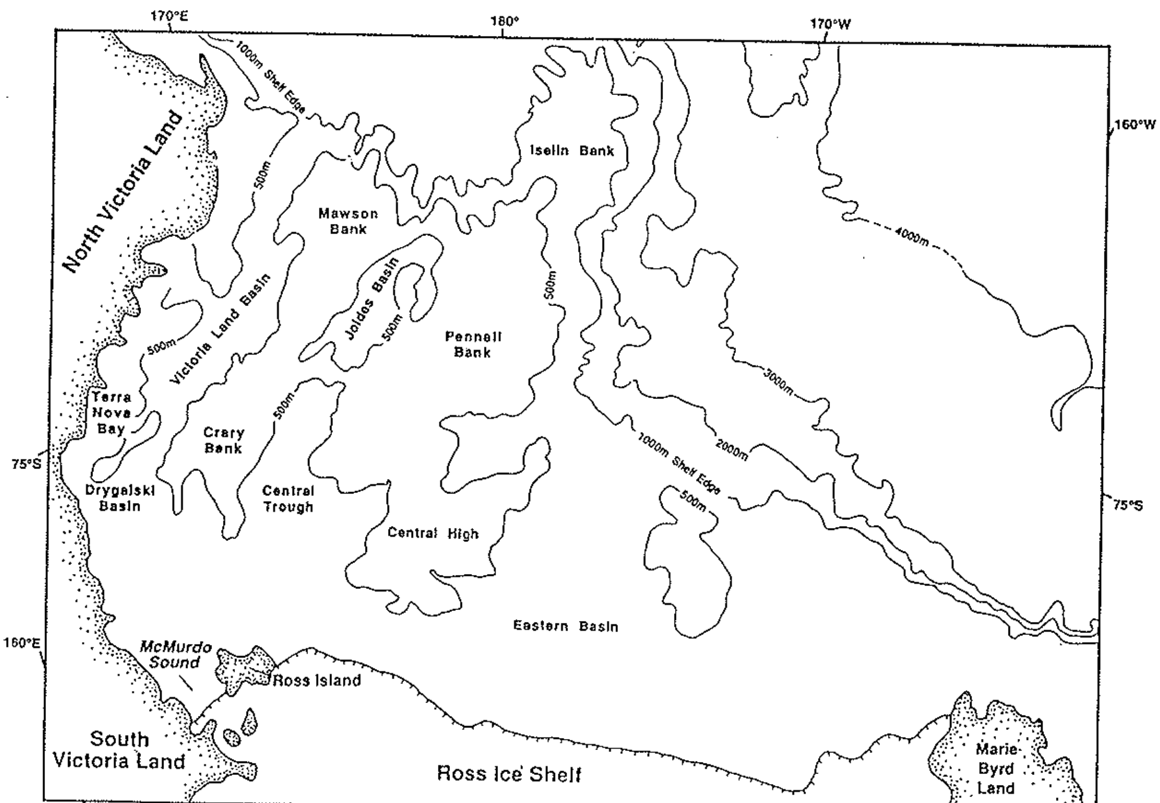


Fig. 9. Map of the Ross Sea showing the bathymetric and structural features of the Ross Sea continental shelf [after *Davey et al.*, 1982; *Cooper et al.*, 1987].

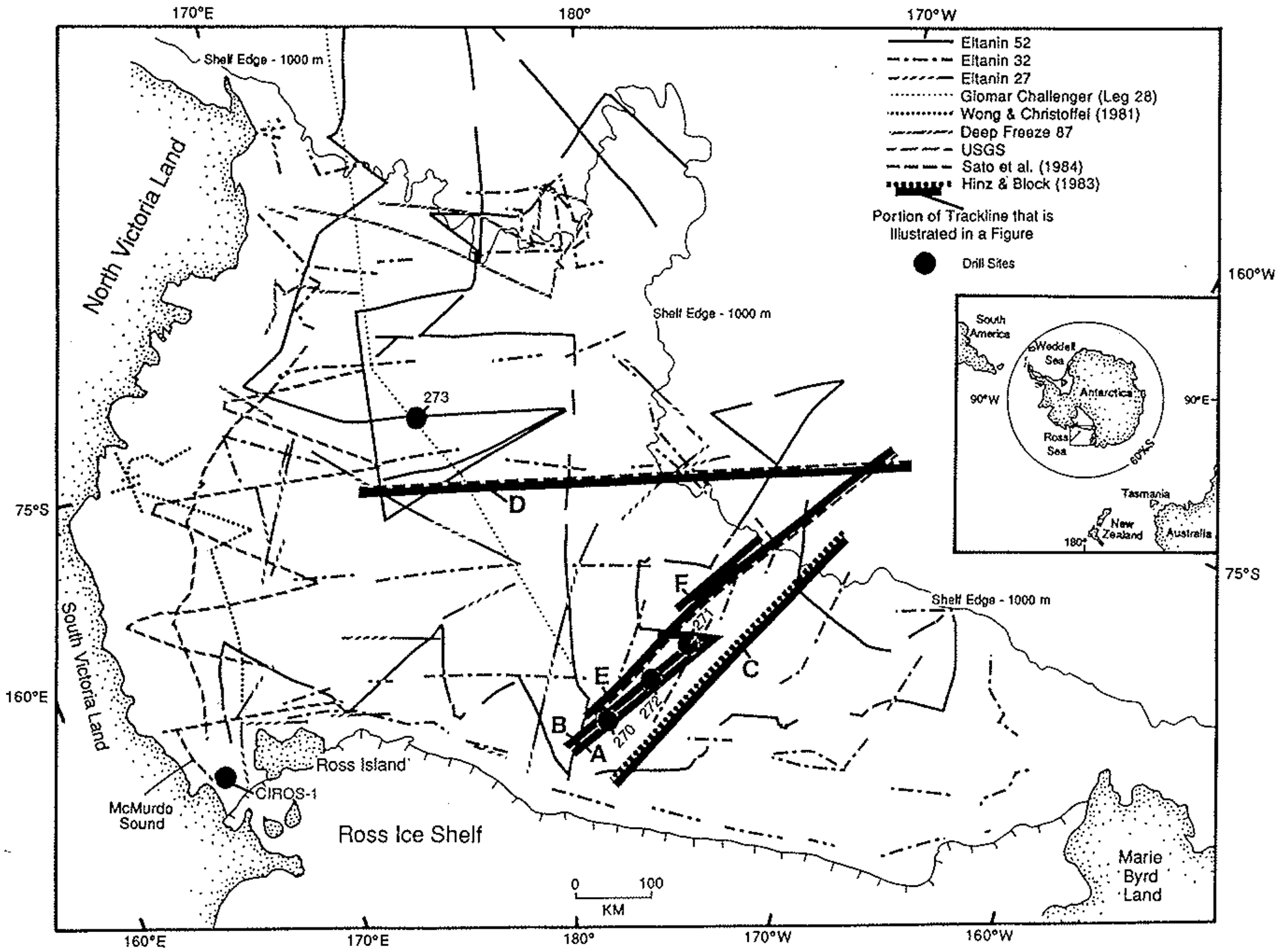


Fig. 10. Map of the Ross Sea showing the location of the drill sites (DSDP 270-273, and CIROS-1) and the seismic data (*Eltanin* 27, 32, 52; *Glomar Challenger* leg 28: *Wong and Christoffel* [1981] and *Northy et al.* [1975]; USGS: *Cooper et al.* [1987] and *Karl et al.* [1987]; *Sato et al.* [1984]; *Hinz and Block* [1983]; and Deep Freeze 87) that were examined in this study. Geographic base map is after *Cooper et al.* [1987] and the seismic track line locations are a compilation from maps published in the papers listed above. *Eltanin* and *Glomar Challenger* track line locations are a compilation of data and maps provided by C. Brenner (Lamont-Doherty Geological Observatory). Drill site locations are from *Hayes et al.* [1975], *Barrett* [1986], and *Robinson et al.* [1987]. The letters next to the track lines correspond to the track lines discussed in the text .

eastern Ross Sea (see Figure 10 for location of these data (lines D and E)). Their track lines are over the leg 28 drill sites and connect the data bases from the eastern and western Ross Sea. *Sato et al.* [1984] recognized sequences of strata with characteristics of prograding clinoforms along lines 17 SMG and 16 SMG. Based upon their own seismic refraction work and comparison with DSDP data and the seismic reflection and refraction work published by *Hinz and Block* [1983], these strata (sequences A1 to E1) were assigned Quaternary to early Middle Miocene ages. *Sato et al.* [1984] have interpreted the strata of sequences A1 to E1 as deposits from a delta that prograded over a subsiding platform. The interpretation by *Sato et al.* [1984] differs from that of *Hinz and Block* [1983] in that they do not make a seismic stratigraphic interpretation of the shift from greensand (F1?) deposition to glacial marine sedimentation. Another difference between the interpretations of *Hinz and Block* [1983] and *Sato et al.* [1984] is that Sato and his colleagues suggest that the early Middle Miocene to Late Oligocene sediments of units F1 and F'1 continuously drape the acoustic basement from the eastern Ross Sea to the western Ross Sea. *Hinz and Block* [1983] produced a map of the reflection time interval between unconformity U6 (mid- to late Oligocene) and acoustic basement [Figure 5 of *Hinz and Block*, 1983] that indicates that the late Oligocene and older strata pinch out against the Central High and therefore do not continuously drape the basement. *Cooper et al.* [1987] concur with the *Hinz and Block* [1983] interpretation, based upon their experiences in the Victoria Land Basin. The continuity issue is important with respect to correlations between the eastern and western Ross Sea and it is still unresolved.

Figure 14 [*Bartek*, 1989] assembles, in composite form, drill core and seismic data from *Hayes et al.* [1975], *Hinz and Block* [1983], and *Sato et al.* [1984]. Figure 14 summarizes the stratigraphic signature of the eastern Ross Sea. The section was constructed by measuring the depth in two-way travel time to various seismic unconformities (U1-U6) (Figure 15) and to the acoustic basement. The unconformities intersect U1 at a number of locations and the positions of these intersections have been plotted on a map by *Hinz and Block* [1983]. These positions were transcribed onto the section (Figure 14). This permitted extrapolation of the unconformities found in the seismic sections presented by

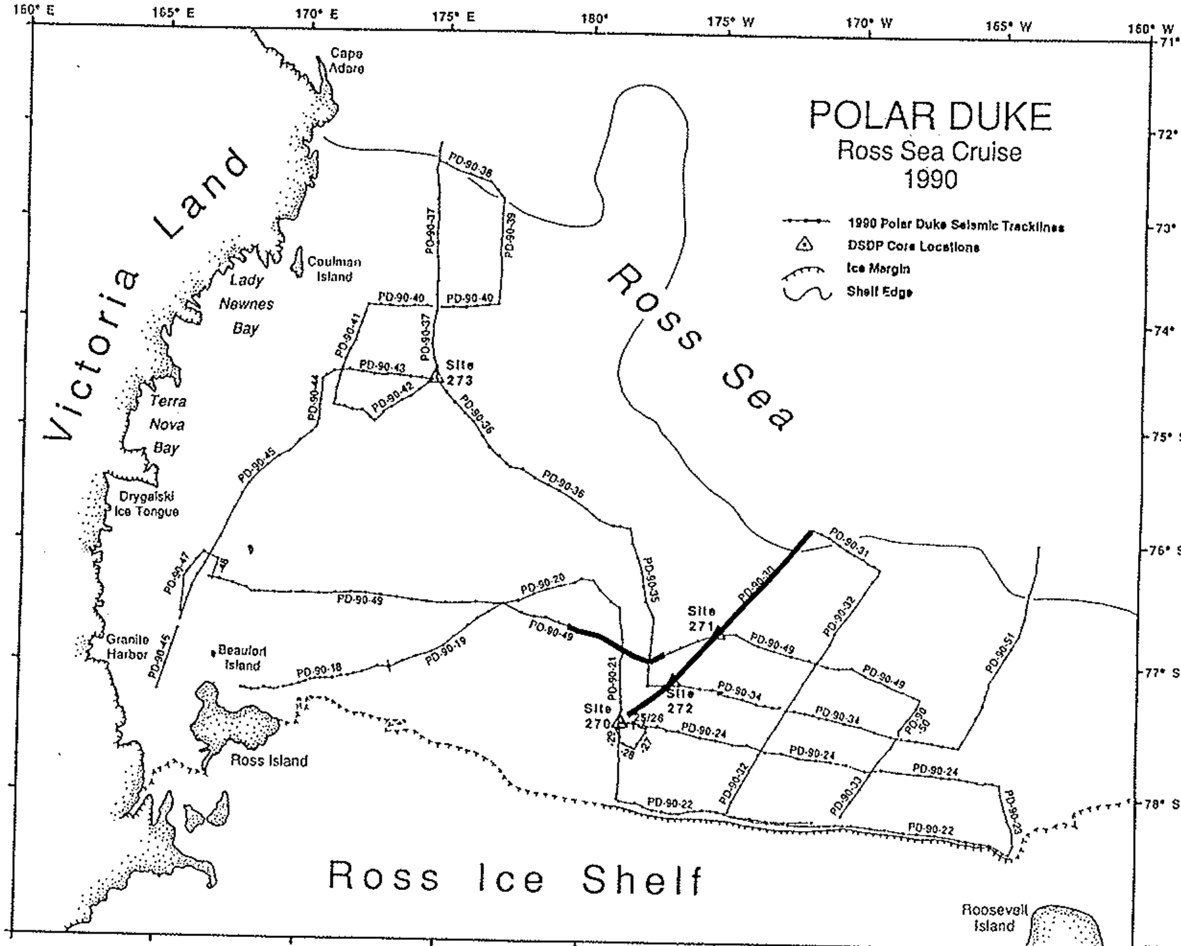


Fig. 11. Location of *Polar Duke* 90 (PD-90) seismic track lines and DSDP core locations in the Ross Sea, Antarctica. The heavier lines along PD-90-30 and PD-90-49 indicate the location of the profiles that are displayed in Figures 16 and 19.

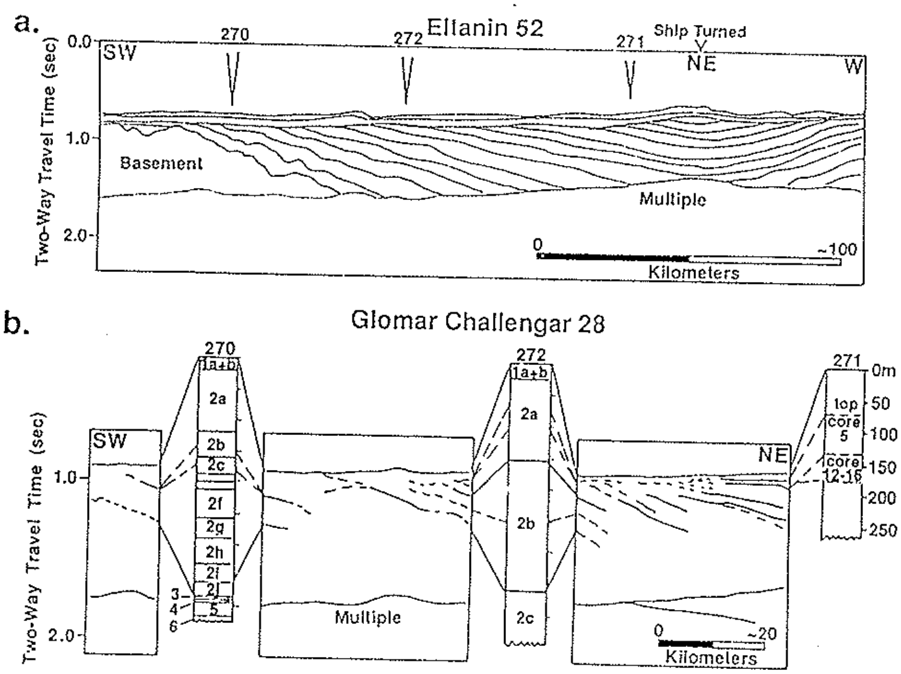


Fig. 12. (*a*) Line A [from *Balshaw*, 1981] and (*b*) line B [from *Hayes et al.*, 1975; *Balshaw*, 1981] are line drawings of the *Eltanin* 52 and *Glomar Challenger* profiles acquired over DSDP sites 270-272. Both profiles reveal a series of offlapping reflectors that are truncated near the surface. The units labeled in the cores of Figure 12*b* are discussed in the text. See Figure 10 for the location of these profiles (lines A and B).

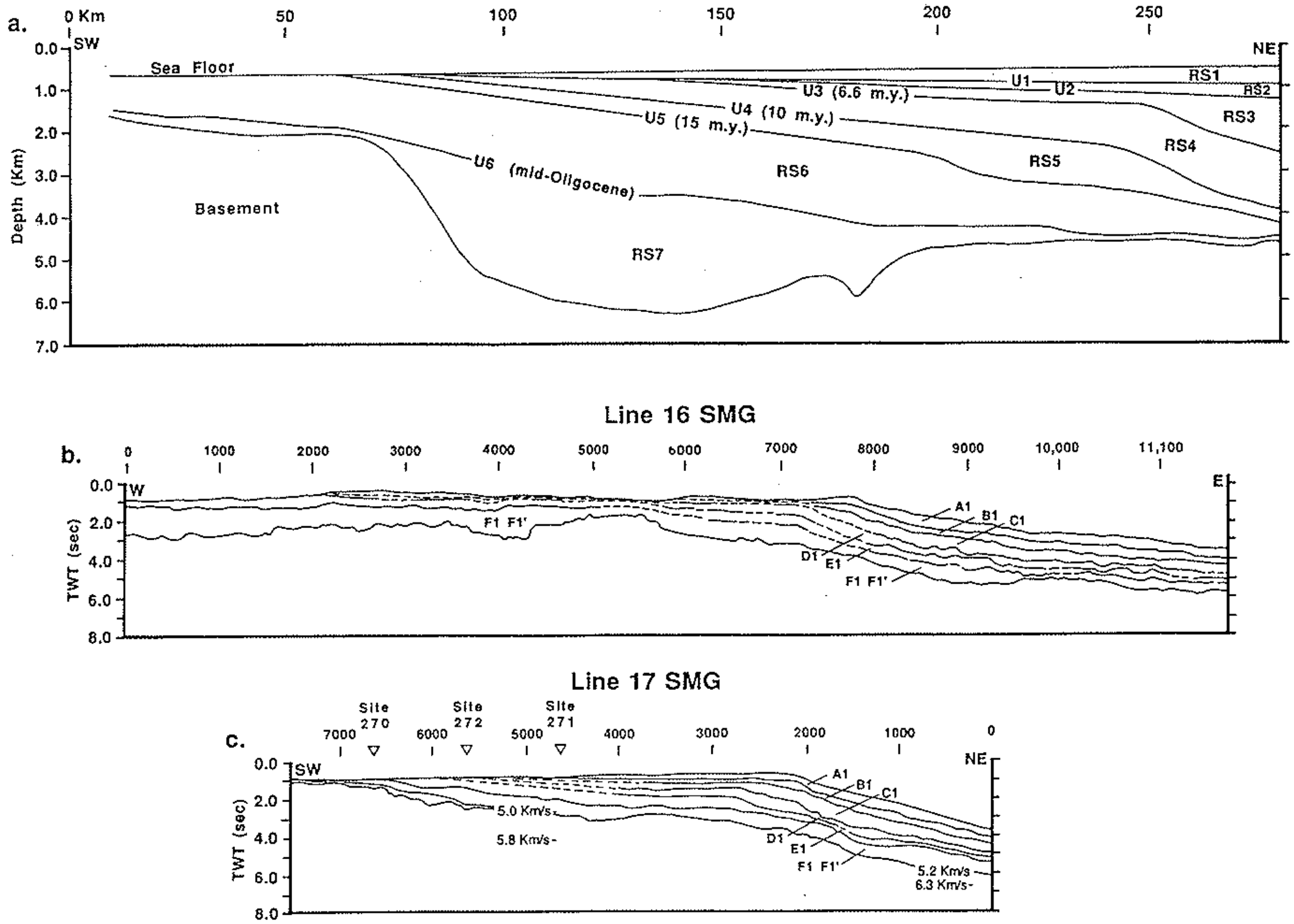


Fig. 13 (*a*) Line C [from *Hinz and Block*, 1983], (*b*) line D, and (*c*) line E [from *Sato et al.*, 1984] are line drawings of profiles on the Ross Sea continental shelf. All three profiles reveal a series of offlapping reflectors that are truncated near the surface. Figures 13*a* and 13*c* are from the eastern Ross Sea and parallel the profiles presented in Figure 12. Figure 13*b* extends from the western Ross Sea to the continental slope of the eastern Ross Sea. The units labeled in the figures are discussed in the text. Ages of surfaces in Figure 13*a* are from *Hinz and Block* [1983]. See Figure 10 for the location of these profiles (lines C, D, and E).

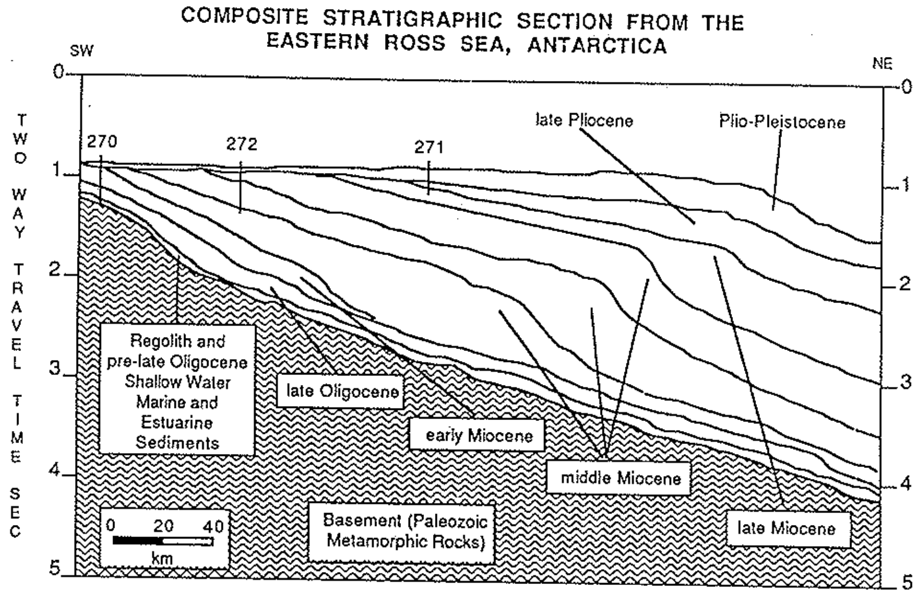
Hinz and Block [1983] to the DSDP sites and facilitated the assignment of ages to the seismic sequences (Figure 14). The drill cores from DSDP sites 270-272 indicate that all of the seismic sequences
are middle to late Oligocene to Recent in age and are composed of a significant proportion of glacially-derived sediment [*Barrett*, 1975]. The stratal geometry of the Neogene sequence from the eastern Ross Sea (Figure 14) is very similar to the geometries of sections from other parts of the world (Figures 1, 4, 5, and 7 and Table 1), pointing to a global mechanism as a causal factor. The sequence begins with a mid-Oligocene unconformity that appears to be regional in extent [*Hinz and Block*, 1983; *Bartek*, 1989]. The mid- Oligocene seaward shift in coastal onlap is followed by an early Miocene flooding and aggradation, which is in turn followed by successive progradational episodes in middle and late Miocene time. The succession culminates with Plio-Pleistocene high-frequency progradations and transgressions (Figures 14 and 16).

Discussion

In the preceding, examples of the Neogene stratigraphic signature from three widely separated localities were presented. The question that arises upon noting the similarity of these stratal patterns is what mechanism caused the nearly synchronous base level changes that drove the shifts in coastal onlap. We believe that the stratal geometry of the Ross Sea was generated by waxing and waning Antarctic ice sheets and that it therefore is a gauge of the ice volume fluctuations that caused the eustatic changes that produced the global stratigraphic signature of the Neogene. The following discussion provides a summary of the evidence that suggests that continental-scale ice sheets had developed on Antarctica by at least late Paleogene time. This discourse is followed by the presentation of a model that links the origin of Neogene stratal geometry of the Ross Sea to the ice volume changes. Finally, we speculate on the relationship between the Ross Sea stratigraphy, Antarctic ice volume variations, and the global stratigraphic signature of the Neogene.

Evidence for Paleogene Development of Antarctic Ice Sheets

The onset of extreme glacial conditions in Antarctica and the ensuing glacial history of the continent have been the objects of controversy for a number of years. Some of the researchers involved in reconstructing the glacial history of Antarctica from the deep-sea record maintain that continental-scale glaciation of Antarctica did not occur until middle to late Miocene time [*Savin et al.*, 1975; *Shackleton and Kennett*,



POSSIBLE CAUSES OF STRATAL GEOMETRY

late Oligocene - Accommodation decreases and an ice sheet advances onto the shelf (possibly as a result of the exponential decrease in thermal subsidence reaching a critical value?)

early Miocene - Accommodation high, ice sheets unable to advance extensively onto shelf (warm climate?)

mid-Miocene - Accommodation decreasing (exponential decrease in rate of thermal subsidence?) and increasing rates of change in accommodation (increase in ice volume due to thermal isolation - Drake Passage opened 22 Ma)

late Pliocene / Pleistocene - rate of change of accommodation very high (i.e., rates of fluctuation are faster than rate of basin subsidence so sequences are cannibalized)

Fig. 14. This cross section [from *Bartek*, 1989] is a composite of the data that have been published by *Hayes et al.* [1975], *Hinz and Block* [1983], and *Sato et al.* [1984]. It shows that the basement has been subsiding in the northeast faster that it has on the southwest and that following an early Miocene transgression, the shelf margin aggraded and then prograded seaward. Notes under the cross section suggest possible causes for the stratal geometry.

1975; *Kennett*, 1977, 1983; *Mercer*, 1983; *Barker et al.*, 1988; *Kennett and Barker*, 1990], and interpretations discussed in the preceding section indicate that ice did not ground on the Ross Sea continental shelf until Pliocene time [*Hayes et al.*, 1975; *Hinz and Block*, 1983; *Sato et al.*, 1984]. However, the possibility that a large ice sheet formed before middle Miocene time and grounded on the continental shelf of Antarctica before Pliocene time must be given strong consideration in light of data that have been acquired in recent years. In fact, a reinterpretation of the older data, in light of the recently acquired data, suggests that eustatic fluctuations related to waxing and waning Antarctic ice sheets during Neogene time played an important role in generating similar stratigraphic patterns at widely dispersed localities with variable tectonic histories. Data that suggest that ice sheets were forming in Antarctica in Paleogene time include (1) the discovery of middle Eocene-Oligocene tills in Ocean Drilling Program (ODP) leg 119 cores on the continental shelf off of Prydz Bay, Antarctica [*Barron et al.*, 1989] (Figure 17), (2) *Birkenmajer's* [1987*a*, *b*], *Birkenmajer et al.'s* (1987), and *Porebski and Gradzinski's* [1987] recent documentation of tills in the South Shetland Islands of West Antarctica which are capped by andesitic lavas that have been K-Ar dated at approximately 49 Ma (Figure 17), (3) *Margolis and Kennett's* [1971] discovery of ice-rafted debris (IRD) in Eocene deep-sea sediments from the southern Pacific, *Breza et al.'s* [1989] and *Barker et al.'s* [1988] discoveries of IRD in lower Oligocene sediment from the Kerguelen Plateau (ODP site 748) and the Weddell Sea (ODP site 693), respectively, and *Tucholke et al.'s* [1976] summary of early circum-Antarctic DSDP cruises which also documents the presence of IRD in Oligocene deep sea deposits, (4) reinterpretations of the oxygen isotope record by *Matthews and Poore* [1980], *Keigwin and Corliss* [1986], *Miller et al.* [1987], and *Prentice and Matthews* [1988] (Figure 17) which suggest that ice volume has effected the $\partial^{18}O$ record since at least the Late Eocene/Oligocene boundary, (5) *LeMasurier and Rex's* [1982] interpretation of an Oligocene ice cap on Marie Byrd Land based upon the presence of extensive Oligocene hyaloclastite deposits (Figure 17), (6) *Stump et al.* [1980] contention of the development of an East Antarctic ice sheet prior to 19 Ma based upon the discovery of two large subglacially erupted volcanos in the Transantarctic Mountains (Figure 17), and (7) The recovery of glacially striated and faceted pebbles from Early Oligocene strata at the CIROS-1 (Cenozoic Investigations of the Ross Sea) drill site in southwestern corner of the Ross Sea [*Robinson et al.*, 1987;

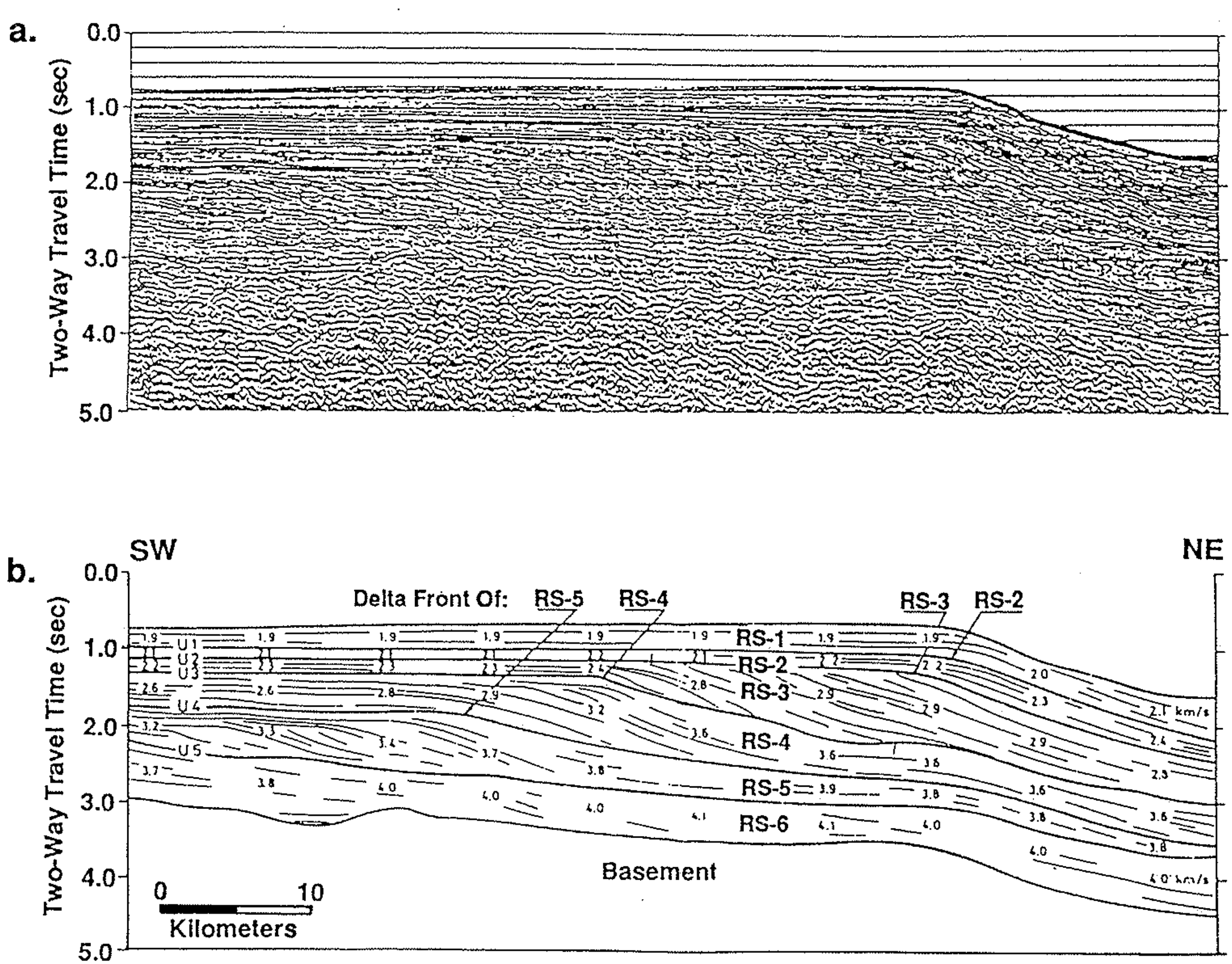


Fig. 15. (*a*) The multichannel reflection seismic data and (*b*) line drawing interpretation of a profile (line F) [from *Hinz and Block*, 1983, Figure 2] that was collected in the Eastern Basin of the Ross Sea. This profile lies parallel to the profiles illustrated in Figures 12, 13*a*, and 13*c* (lines A, B, C, and E of Figure 10). The profile contains a series of offlapping reflectors that are truncated near the surface. Depths to unconformities were measured and plotted on the composite section (Figure 14). Units labeled in the figure are discussed in the text. See Figure 10 for the location of this profile (line F).

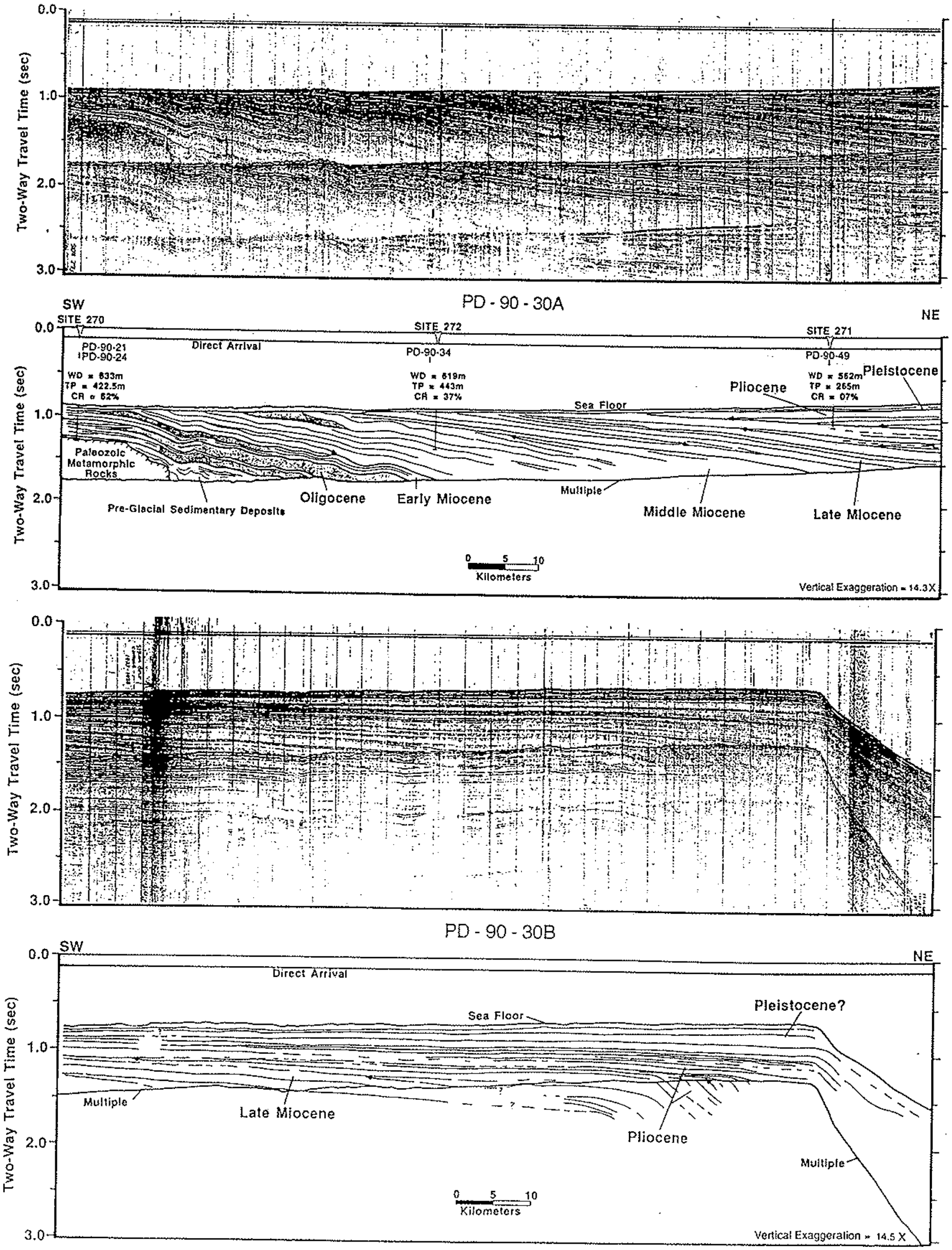


Fig. 16. Seismic line PD-90-30 and a line drawing illustrate the presence of high-frequency shifts in coastal onlap in the Plio-Pleistocene strata from the Ross Sea continental margin. The location of the profile is indicated by the heavier line along PD-90-30 in Figure 11. The locations of tie lines and drill sites are also marked on the line drawing. Annotations at the drill sites correspond to WD, water depth; TP, total penetration; and CR, percentage of core recovered. Arrows on the line drawing denote areas where toplap, onlap, and downlap occur. Surfaces where toplap and onlap occur correlate to broad glacially carved troughs, thus establishing the relationship between glacial waxing and waning and shifts in coastal onlap.

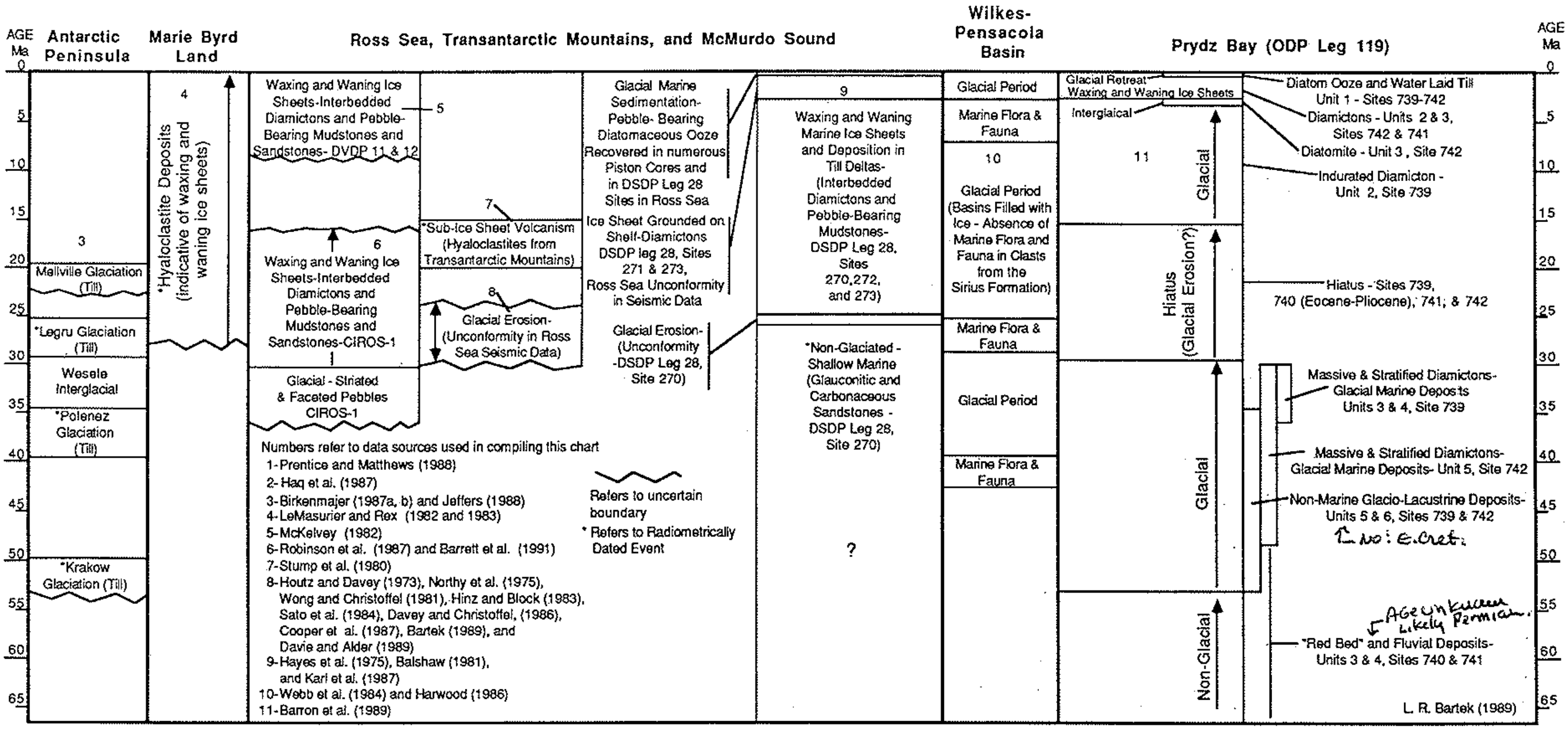


Fig. 17. Compendium of data that are related to Antarctic glacial history. The sea level chart presented in this figure is a slightly modified version of the chart published by *Haq et al.* [1987]. Note the large sea level fall that occurred approximately 30 m.y. ago and the frequency of Cenozoic eustatic fluctuations. The mid-Oligocene sea level fall may be related to the widespread glacial erosional event that has been described in this paper. The *Prentice and Matthews* [1988] sea level chart is based upon oxygen isotope analysis of equatorial planktonic forams. It suggests that there were ice volume effects in Paleogene time.

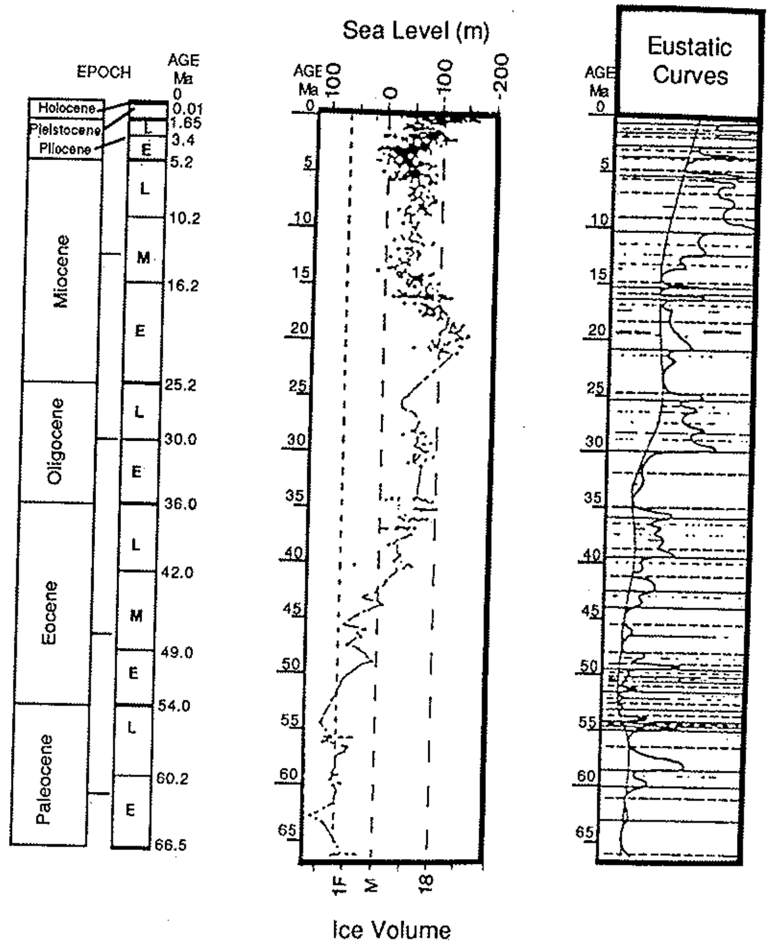


Fig. 17. (continued)

Barrett et al., 1989] and glacially striated pebbles that were derived from Marie Byrd Land in Oligocene to Recent sediments from the central Ross Sea (DSDP sites 270-272) [*Barrett*, 1975].

Numerical modeling of Cretaceous and Eocene climates by *Barron et al.* [1981], *Barron* [1987], and *Sloan and Barron* [1990] corroborates data which suggest that ice sheets were forming in Paleogene time. Modeling results indicate that even if major changes in continental configuration are taken into account, it is difficult to produce an equable, globally above freezing climate (as is usually inferred for the Cretaceous and early Paleogene) at middle and high latitudes with known forcing mechanisms of reasonable magnitude. The models suggest that the winter temperatures in continental interiors may have been as cold -26°C during the Eocene [*Sloan and Barron*, 1990]. Oxygen isotope data from carbonate cements in concretions and IRD from early Cretaceous deposits in Australia support the modeling results. The oxygen isotope data from the Otway and Gippsland basins indicate that the mean annual temperature of the lower Cretaceous at paleolatitudes of 75°-80°S was around -2°±5°C with seasonal extremes of -17°C [*Rich et al.*, 1988; *Gregory et al.*, 1989]. Exotic clasts within the Bulldog Shale in the Eromanga Basin of Australia are interpreted as IRD and, according to *Frakes and Francis* [1988], are indicators of the presence of high-latitude ice near sea level. Thus, there are indications that the climate may have been cool enough to initiate ice sheet growth [*Oerlemans*, 1982] by early Cretaceous time.

An extensive erosional event associated with the grounding of an expanded Antarctic ice sheet on the Ross Sea continental shelf suggests that the ice sheet reached continental-scale by mid-Oligocene time. This event is marked by (1) a dramatic, mid-Oligocene change in the style of sedimentation at CIROS-1 [*Barrett et al.*, 1989] and DSDP site 270 [*Hayes et al.*, 1975] that correlates to a regional unconformity in seismic data [*Hinz and Block*, 1983; *Bartek*, 1989] and (2) a significant deepening (overdeepening) of the shelf [*Leckie and Webb*, 1983]. The presence of basal tills, on the Ross Sea continental shelf, above the mid-Oligocene unconformity [*Balshaw*, 1981], but below the Pliocene unconformity, also indicates that extensive grounding of ice sheets on the continental shelf occurred before Pliocene time.

It is important to note that it has also been argued that Oligocene palynomorphs recovered by *Kemp and Barrett* [1975] from glacial marine sediments in the Ross Sea preclude the possibility of an Oligocene ice cap in Antarctica [*Kennett*, 1977]. However, the recovery of marine fauna and flora [*Webb et al.*, 1984] as well as fossil wood [*Webb and Harwood*, 1987] from the Pliocene Sirius Formation in the Transantarctic Mountains suggests that it is possible that the volume of Antarctic ice sheets has fluctuated dramatically and that it may indeed have been possible to rapidly reforest the once glaciated landscape (Figure 17).

Evidence of Continental-Scale Glaciation in Antarctica During mid-Oligocene Time: The mid-Oligocene Unconformity

Recent seismic studies on the Canadian shelf [*King and Fader*, 1986], in the North Sea [*King et al.*, 1987] and at Ice

Stream B on the West Antarctic Ice Sheet [Alley et al., 1989] provide a framework for seismic studies in Antarctica aimed at deciphering the history of glaciation from the stratigraphic successions preserved on the continental shelf. These investigations provide important information about the nature of seismic facies associated with both sub-ice sheet and glacial marine sequences and therefore facilitate determination of the lateral extent of glacial erosional events. The chronostratigraphic information that is needed to reconstruct the glacial history of Antarctica is provided by drill sites in areas such as the Ross Sea, where successions of subglacial and glacial marine deposits have been penetrated. Velocity analyses of the strata that infill the Central and Eastern basins of the Ross Sea via sonobuoy refraction surveys [*Hayes, et al.*, 1975; *Hinz and Block*, 1983; *Sato et al.*, 1984] facilitate correlation of seismic surfaces to DSDP sites 270-272.

There are two lines of evidence that support the possibility of a grounded ice sheet on the central and eastern Ross Sea continental shelf in Paleogene time: (1) rapid changes in sedimentologic and paleontologic characteristics of sediment across a middle to late Oligocene unconformity, and (2) seismic evidence of erosive surfaces that lie too far below the seafloor to correlate to the Pliocene event. The shift from deposition under shallow water continental shelf conditions, as indicated by the glauconitic greensand deposited in the basal portion of site 270, to deposition under glacial conditions, as indicated by the diamictites that unconformably overlie the greensand, without the presence of a transitional facies or interbedding between the two units, suggests an erosive contact between the greensand and the overlying diamictites (Figure 18). In addition to the dramatic sedimentologic change that has been documented between units 3 and 2-I at site 270 by *Hayes et al.* [1975], *Leckie and Webb* [1983] have documented a shift from benthic foraminiferal assemblages that are commonly associated with a shallow water inner shelf setting, to deepwater assemblages typical of an outer shelf or upper slope environment (150-300 m). The change in foraminiferal assemblages occurs over a stratigraphic thickness of less than 30 m (385-379 m) and there may be a hiatus of 2 m.y. at the contact between the greensand and the basal diamictite [*Allis et al.*, 1975; *Hayes et al.*, 1975; *McDougall*, 1976]. It has been argued that these changes are merely a manifestation of subsidence [*Leckie and Webb*, 1983]. However, the sharp contact between the shallow water greensands and the overlying glacial diamictites, along with the increase in water depth, and the stratigraphic hiatus, may also imply grounding of an ice sheet and coincident removal of up to 250 m of sediment by glacial erosion during mid- to late Oligocene time in the central Ross Sea.

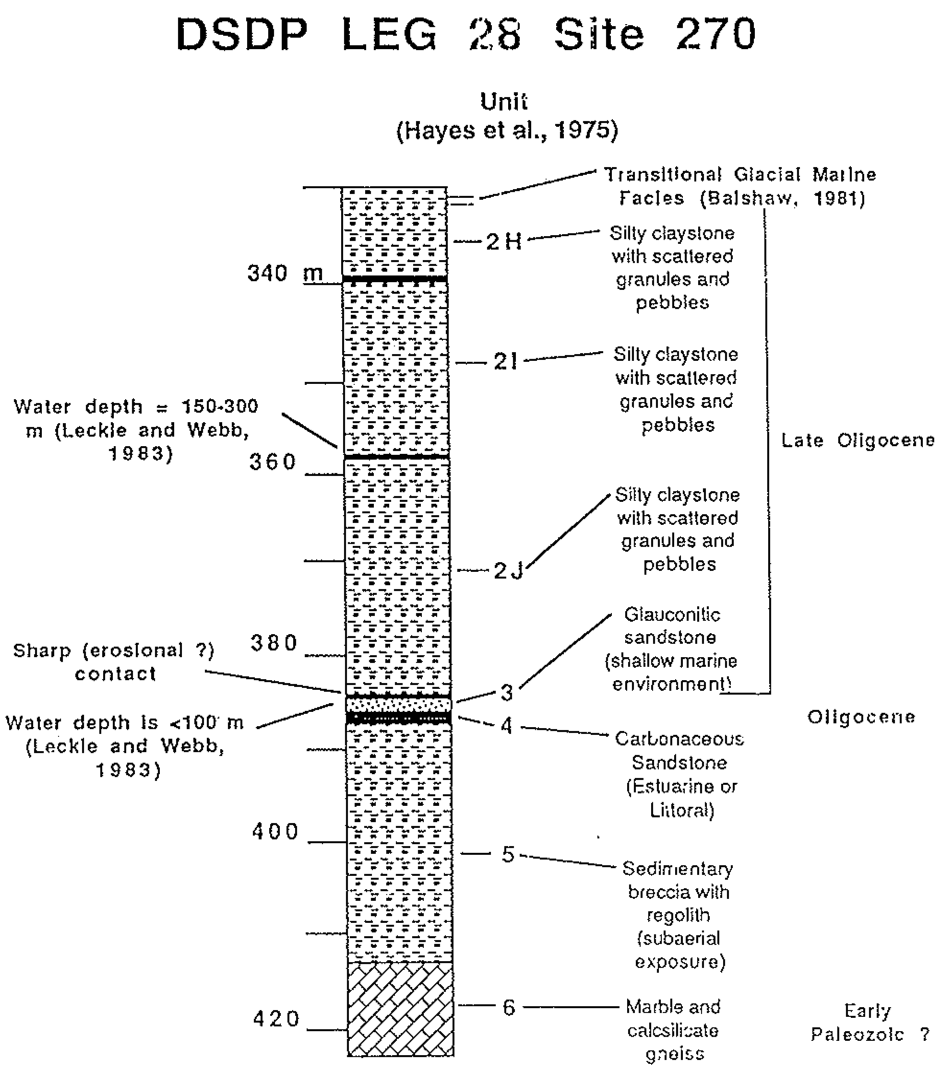


Fig. 18. An expanded view of DSDP site 270 (from 330-422.5 m). It is a compilation of data from *Hayes et al.* [1975], *Balshaw* [1981], and *Leckie and Webb* [1983] and demonstrates the change in sedimentation styles recorded at DSDP site 270.

Other evidence supporting the idea of pre-Pliocene ice sheet grounding events in the central Ross Sea is found in *Balshaw's* [1981] analysis of leg 28 cores from the Ross Sea. Balshaw analyzed the grain size distributions of the massive and stratified diamictites that comprise unit 2 of DSDP sites 270-273. She classified a sample from approximately 331 m subbottom at site 270 as transitional glacial marine (Figure 18). Transitional glacial marine facies are deposited at or near the grounding lines of ice sheets [*Anderson et al.*, 1983] and the presence of such a unit, 331 m subbottom (late Oligocene) at site 270, suggests that an ice sheet was grounded on the continental shelf in the central Ross Sea before Pliocene time.

High-resolution seismic data collected during leg 2 of the R/V *Polar Duke's* expedition in the Ross Sea (Figure 11) also suggest that an ice sheet was grounded on the Ross Sea continental shelf before Pliocene time and at least by late Oligocene time [*Bartek and Anderson*, 1990]. The first occurrence, in late Oligocene strata, of glacial erosional surfaces and till tongues (Figure 19) that are similar to those described by *King and Fader* [1986] and *King et al.* [1987] indicates that the grounding event occurred by late Paleogene time. The width of the scours associated with the till tongues is comparable with the width of modern ice streams. The massive tongue-like units in Figure 19 are at least 70-80 km wide; modern ice streams have widths of the order of 80-100 km [*Alley et al.*, 1989]. The widths of the trough-like scours on the Ross Sea continental shelf also exceed the widths of incisions carved by fluvial entrenched valley systems. Incisions carved by entrenched valley systems are typically 10-20 km wide [*Berryhill*, 1986; *Thomas and Anderson*, 1989].

The lateral extent of the mid- to late Oligocene ice sheet grounding event is indicated by the work of *Hinz and Block* [1983] and *Barrett et al.* [1989]. *Hinz and Block* [1983] correlate an unconformity (U6) to the mid- to late Oligocene boundary between the preglacial greensands and the overlying glacial deposits at site 270, and they mapped it over an extensive portion (≈100,000 km^2) of the Central and Eastern basins of the Ross Sea [Figure 5 of *Hinz and Block*, 1983]. A mid-Oligocene unconformity has also been identified in the western Ross Sea by *Barrett et al.* [1989] at the CIROS-1 site. The lateral extent of this unconformity in the western Ross Sea is still unresolved. The U6 unconformity, as mentioned earlier, is interpreted by *Hinz and Block* [1983] as a product of erosion associated with a paleoceanographic event rather than ice sheet grounding. *Hinz and Block* [1983] suggest that the grounding of ice sheets did not play an important role in producing the numerous unconformities that are present in the central Ross Sea until unconformity U1 time (Pliocene?). However, the recently acquired high-resolution seismic data suggest that the extensive shelf aggradation and progradation that followed the mid- to late Oligocene grounding event (Figure 14) also were intimately associated with the waxing and waning of metastable, marine-based ice sheets on the Ross Sea continental shelf (Figure 19). Fluctuations in grounding line positions at the CIROS-1 site in McMurdo Sound also have been documented by *Barrett et al.* [1989]. According to *Barrett et al.* [1989], these grounding line fluctuations

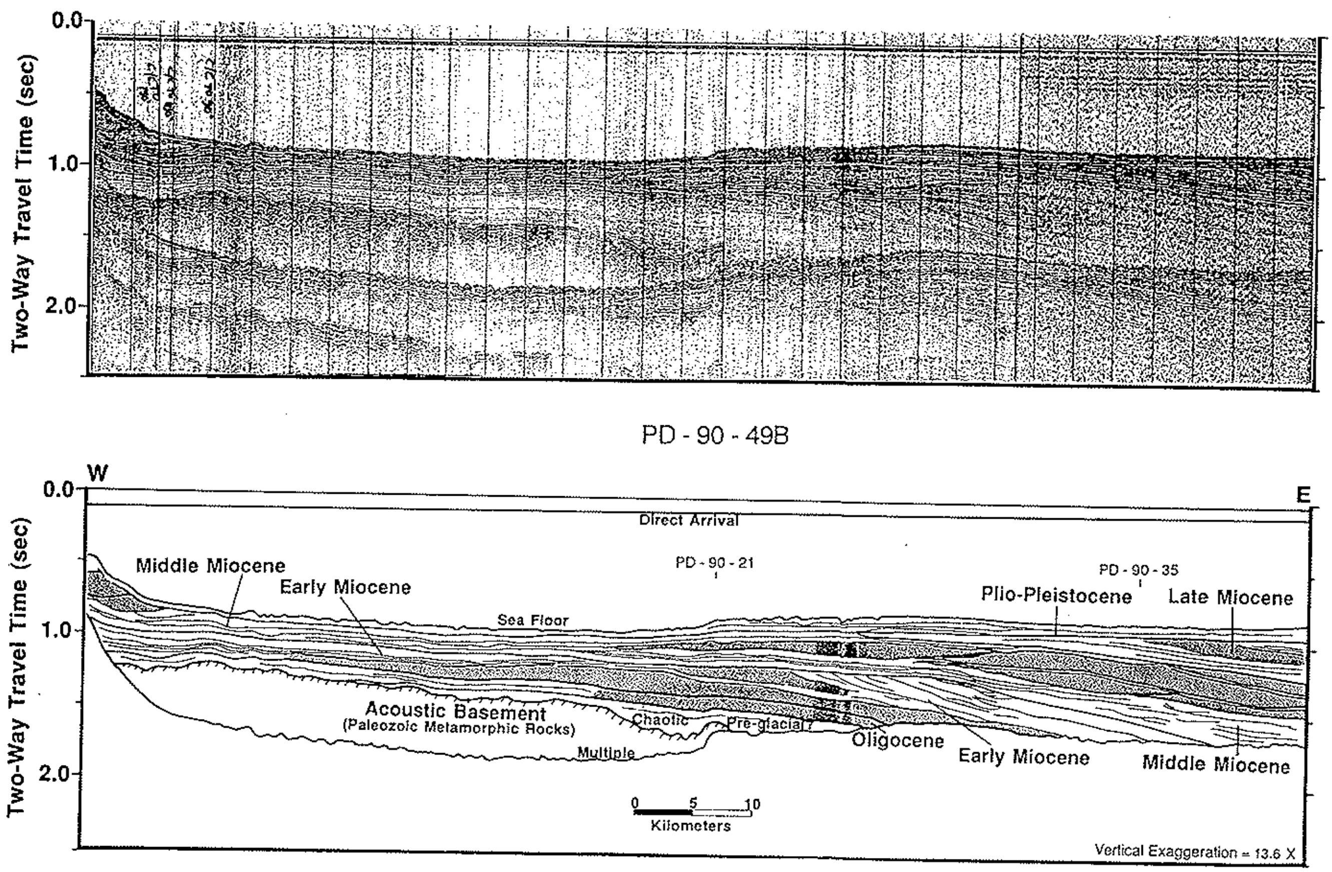


Fig. 19. Portion of seismic line PD-90-49 and line drawing illustrating the presence of subglacial seismic facies in strata as old as mid- to late Oligocene. The location of the profile is indicated by the heavier line along PD-90-49 in Figure 11. Note the massive intervals and the crosscutting relationships 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].

correspond to the late Paleogene and early Neogene eustatic changes that were described by *Haq et al.* [1987].

Marine-Based Ice Sheets, Subglacial Deltas and the Neogene Stratigraphic Signature of the Ross Sea

The ice grounding stratigraphy of the central and eastern Ross Sea 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. Data from the eastern side of the Eastern Basin of the Ross Sea show evidence of the subglacial delta stratigraphy discussed by *Alley et al.* [1989] and indicate that subglacial deltaic deposition is also be an important mechanism producing the ice sheet grounding stratigraphy of Ross Sea.

The stratal geometry seen in seismic sections acquired in the Eastern Basin of the Ross Sea (Figures 13, 14, and 15) is consistent with ice sheet grounding episodes on the Ross Sea continental shelf from mid-Oligocene time to the present. The seismic character (oblique, sigmoid, and complex oblique-sigmoid seismic reflections) of the dip sections also indicates that the shelf margin was migrating seaward during the interval of time that these glacial sediments were deposited [*Hinz and Block*, 1983], and downlap and shifts in onlap in seismic sections imply that there were depositional hiatuses that may represent glacial retreat and advance. The ice grounding stratigraphy of the central and eastern Ross Sea appears to have been produced by two mechanisms. The till tongue-like stratigraphy 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. Investigations of glacial processes that produced the subglacial delta stratigraphy beneath the marine-based West Antarctic Ice Sheet at Ice Stream B by *Alley et al.* [1989] also provide a model that may explain the origin of the prograding seismic sequences comprised of glacially derived sediments (DSDP sites 270-272).

Seismic data and flow calculations suggest to *Alley et al.* [1989] that Ice Stream B is rapidly gliding along on a layer of water-saturated, unconsolidated, deforming till. It is thought that erosion of unlithified subjacent sediments by hard clasts contained in the deforming till (topsets in seismic data) has produced the angular unconformity that is observed in seismic data acquired along Ice Stream B [*Alley et al.*, 1989]. Calculations performed by *Alley et al.* [1989] indicate that erosion rates are high along ice streams and require relatively rapid deposition at the grounding line of an ice stream. *Alley et al.* [1989] indicate that at the grounding line, the highly unconsolidated water-saturated sediment that is transported through the topset (till) loses contact with the ice. This is thought to cause slumping, and development of foresets and bottomsets that are composed of turbidites and debris flows. The stratigraphic succession of foresets and bottomsets composed of glacially derived sediment gravity flow deposits, unconformably overlain by topsets of highly unconsolidated, water-saturated till is termed a subglacial delta (Figure 20*c*) by *Alley et al.* [1989].

Alley et al. [1989] hypothesize that the Ross Sea Unconformity (Unconformity U1 of *Hinz and Block* [1983]) was produced by the migration of ice stream grounding lines and subglacial deltas during the Wisconsinan glacial maximum. They believe that these events may have also occurred before and during the latest Pliocene-Pleistocene, and they suggest that erosion beneath the grounded ice may have

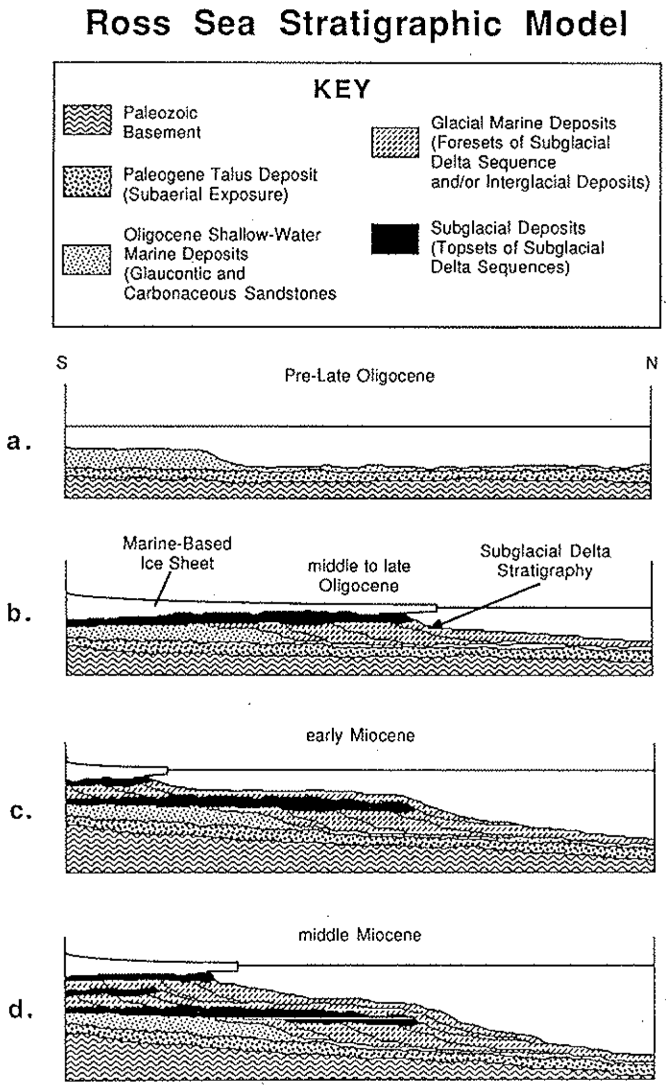


Fig. 20. Figures 20 and 21 are a series of "snapshots" of the waxing and waning of marine-based ice sheets on the Ross Sea continental shelf from late Oligocene to Recent. These schematic cross sections also illustrate the subglacial delta stratal geometry and the dramatic effect that variations in accommodation can have on the stratal geometry of glacial sequences. Accommodation is high in the early Miocene and decreases tremendously by late Pliocene-Pleistocene time. Sequences deposited when accommodation was high are thicker and may have interbedded interglacial deposits (or the foresets of till deltas) preserved (early Miocene-middle Miocene), while those deposited when rates of glacial waxing and waning exceeded basin subsidence rates are characterized by a lack of interbedded interglacial deposits (or the foresets of till deltas) and cannibalization of older sequences (late Miocene-late Pliocene/Pleistocene).

either occurred entirely within the basal tills or may have cut through earlier tills to older glacial marine sediments. *Alley et al.* [1989] also state that "conveyor belt recycling" of till deltas would allow grounding line advance in water that would otherwise be too deep. We suggest that sediment recycling within subglacial deltas would produce subglacial deposits that bear no resemblance to the characteristics that are ascribed to classic tills. Homogenization of clasts from various source areas and incorporation of marine flora and fauna from interbedded glacial marine deposits would make it very difficult to distinguish subglacial deposits and glacial marine deposits in core. An analysis of sediment cores from under the Ross Ice Shelf, adjacent to Ice Stream B at Ross Ice Shelf Project (RISP)

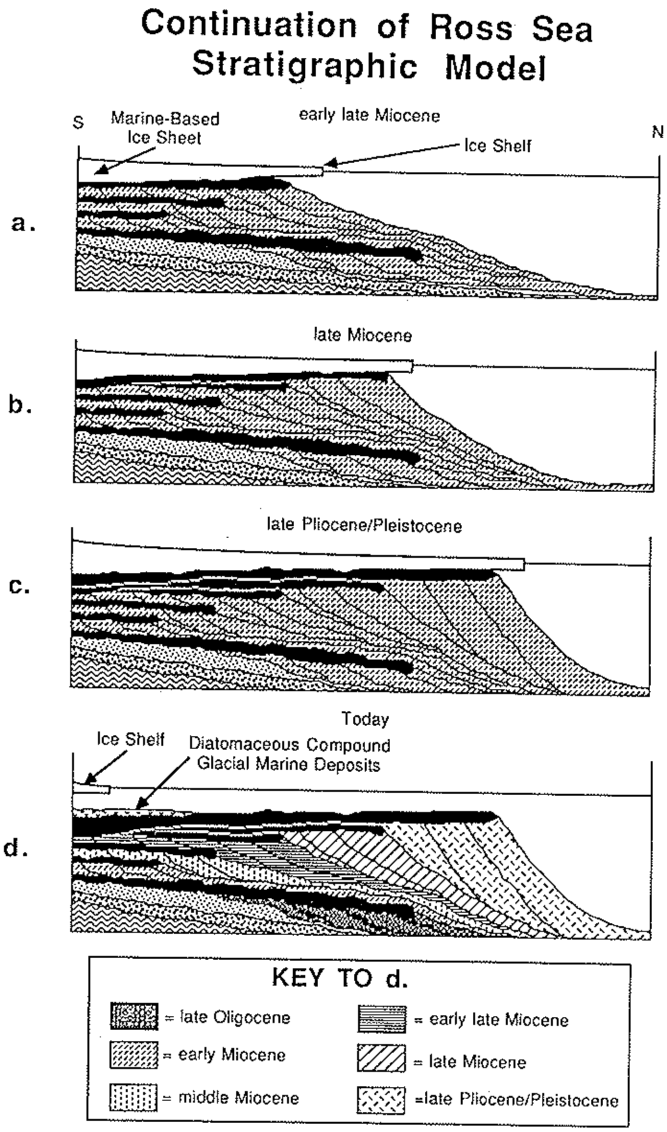


Fig. 21. A series of "snapshots" of the waxing and waning of marine-based ice sheets on the Ross Sea continental shelf from middle Miocene to Recent (continuation of Figure 20).

site J-9, by *Harwood et al.* [1989] indicates that this is indeed the case. The presence of middle lower Miocene and lower middle Miocene diatomite clasts in middle upper Miocene "glacial marine" strata suggests that between the periods when ice sheets were extensively grounded on the continental shelf, there were intervals that were characterized by extensive open marine conditions (implying warmer climatic conditions and state of glaciation less extensive than today) in the interior of West Antarctica during middle lower Miocene and lower middle Miocene time. The deposits that reflect the warmer intervals were later exhumed and redeposited on the shelf [*Harwood et al.*, 1989] by subglacial processes. Thus, the stratal geometry of cored sequences, as revealed in seismic data, may provide the best insight into their origin. We suggest that the pattern of prograding sedimentary sequences (Figures 13, 14 and 16) composed entirely of "glacial marine" sediments (DSDP sites 270-272) was produced by the waxing and waning of marine-based ice sheets on the Ross Sea continental shelf since late Oligocene time (Figures 20 and 21).

The occurrence of a marine-based ice sheet on the Ross Sea continental shelf requires nourishment by ice flowing from an interior ice sheet [*Hughes*, 1973, 1977, 1981], thus negating the argument that this was a local glaciation. Furthermore, changes in the extent of marine ice sheet grounding, as shown by seismic records from the Ross Sea shelf, imply volume changes in the Antarctic ice sheets that potentially were large enough to dominate the Neogene global eustatic record. Alternatively, the sequence stratigraphy of the Ross Sea continental shelf could itself be the product of eustatic changes of a different mechanism. That is, as sea level was lowered, marine ice sheets were able to spread out onto the shallower continental shelf without an increase in ice sheet volume. This requires a tectonic mechanism operating at a rate fast enough to account for the observed frequency of Neogene eustatic events (at least third order, which is approximately 3-15 cm/1000 years [*Haq et al.*, 1987]); we cannot document such a mechanism. Although it is important to note that *Cloetingh et al.* [1985] have suggested that variations in intraplate stresses may generate shifts in coastal onlap and operate at third order rates. However, such a mechanism, still requires a large enough volume of ice on the Antarctic continent to force the marine ice sheet seaward several hundred kilometers during a eustatic low stand.

Speculation on the Relationship Between the Ross Sea Stratigraphy, Antarctic Ice Volume Variations, and the Global Stratigraphic Signature of the Neogene

Marine-based ice sheets waxed and waned on the Ross Sea continental shelf following the widespread erosion and overdeepening of the continental shelf during the mid-Oligocene glacial episode (Figures 20*c*-21*d*). However, an overdeepened shelf profile and relatively high basin subsidence rates on the Ross Sea continental shelf and "warm" climatic conditions [*Harwood et al.*, 1989] may have prevented extensive advances on to the shelf by marine-based ice sheets and resulted in aggradation during early Miocene time (Figures 20*c*, 13, 14, 4, 5, and 7). As basin subsidence rates decreased in early Miocene to Recent time, due to an exponential decline in thermal-tectonic subsidence, marine-based ice sheets were again able to advance onto the Ross Sea continental shelf and the volume of ice in Antarctica increased (Figures 20*c*-21*d*, see Table 1 and Figures 4, 5, and 7 for evidence of synchronous progradation on other margins). The combination of climatic deterioration due to the initiation of deep circum-polar water circulation [*Barker and Burrell*, 1977, 1982; *Kennett*, 1977) and declining basin subsidence rates may have facilitated more extensive grounding events during middle and late Miocene time, and led to more progradation of the shelf margin (Figures 20*d*-21*a* and 21*b*, see Figures 4, 5, and 7 for examples of from other margins) and cannibalization of underlying glacial sequences (Figures 20*d*-21*a* and 21*b*). It has also been suggested that the mid-late Miocene ice buildup on Antarctica was related to coincident upwelling of warm North Atlantic Deep Water (NADW) south of the Antarctic Convergence and subsidence of the Iceland-Faero ridge [*Schnitker*, 1980]. Subsidence of the Iceland-Faero ridge led to inflow of NADW into the Arctic basin and increased outflow of Antarctic Bottom Water (AABW). This resulted in insertion of a tongue of NADW below the Circum-Antarctic Current and resulted in upwelling of relatively warm NADW. The warmer water presumably had a higher evaporation rate and therefore supplied the moisture needed to form an ice sheet during mid-late Miocene time [*Schnitker*, 1980].

Eustatic fluctuations associated with waxing and waning of continental ice sheets in the Northern Hemisphere during late Pliocene/Pleistocene time may have triggered rapid advances and retreats of marine-based ice sheets on the Ross Sea continental shelf during that time interval (Figure 16). Intervals between ice sheet advances and retreats were so short that basin subsidence could not keep up, and many of the underlying sequences were cannibalized (Figure 21*c*, 16, and 19). The last retreat was also quite rapid and only a veneer (0.1-0.5 m thick) of reworked sediment [*Kellogg et al.*, 1979] overlying an unstratified diamicton marks the event. Today, ice-rafted and biogenic debris are being deposited in foredeepened shelf basins, while deep sea currents rework sediment on the outer shelf and on bathymetric highs [*Anderson et al.*, 1984*a*, *b*; *Dunbar et al.*, 1985] (Figure 21*d*). Thus, the boundary conditions (tectonics and ice sheet fluctuations) that produced the stratigraphy of the Ross Sea continental shelf may have caused the eustatic fluctuations that produced the stratigraphic signature of the Neogene (Figure 2).

The data and arguments presented in the preceding paragraphs suggest that the stratal geometries of the Neogene section from the Ross Sea are a product of expansions and contractions of the Antarctic ice sheets. Presumably, the expansions and contractions of the Antarctic ice sheets produced synchronous eustatic fluctuations. These variations in eustasy generated similar stratal geometries in the sedimentary wedges of widely dispersed continental margins. Thus, an improved understanding of the Cenozoic stratigraphic record from the Ross Sea (for as long as it has acted as a barometer of Antarctic ice volume) will help us gain insight into some of the mechanisms that control high-frequency eustatic fluctuations and global stratigraphic patterns. We present our ideas about the origin of the stratigraphic record of the Ross Sea with the hope of stimulating more research in this area. At this time, poor core recovery at the Ross Sea DSDP drill sites limits the resolution of dating. In order to test more rigorously the hypotheses presented in this paper, the timing of ice sheet advances and retreats on the shelf must be better constrained with more core from the Antarctic margin and additional high-resolution seismic surveys.

CONCLUSIONS

Analysis of data sets from around the world indicates that on margins where basin subsidence rates have not changed rapidly and where there is sufficient sediment supply to prograde into deep water, a global Neogene stratigraphic signature is developed. The signature is characterized by a large, late Oligocene seaward shift in coastal onlap, followed by an early Miocene flooding and aggradation. This in turn is followed by successive progradational episodes in middle and late Miocene time and culminates in the Plio-Pleistocene high-frequency progradations and transgressions. Examples from widely dispersed locales with different tectonic histories (Indonesia (Figure 7), the Gulf Coast of the United States (Figures 4 and 5), and the Ross Sea of Antarctica (Figure 14)) illustrate the wide spread nature of this signature. The striking similarity of the stratal patterns from these widely dispersed localities and the rate at which coastal onlap has changed during this interval suggests that eustatic fluctuations, driven by waxing and waning ice sheets in Antarctica, are the source of the Neogene stratigraphic signature.

The link between glacioeustatic fluctuations and the Neogene stratigraphic signature is established in the Ross Sea where changes in the Neogene lithostratigraphy and seismostratigraphy correlate with advances and retreats of marine-based ice sheets. A dramatic shift in the mode of sedimentation during mid-Oligocene time, recorded in CIROS-1 and DSDP leg 28 cores from the Ross Sea and a regional unconformity that correlates to the lithostratigraphic change in the DSDP site 270 core, marks the first ice sheet grounding event on the Ross Sea continental shelf; a possible shift to polar glacial conditions in the Ross Sea region during mid- to late Oligocene time; and the beginning of the Neogene stratigraphic signature.

Documentation of the presence of a mid- to late Oligocene ice sheet and the presence of Eocene, late Oligocene, late Miocene and Pliocene marine microfossils and Pliocene wood [*Webb and Harwood*, 1987] in the Sirius Formation suggest that the ice sheets in Antarctica were not stable. The marine microfossils were derived from interior basins that are now situated below the ice sheet, and their presence in the Sirius Formation suggests that the late Oligocene ice sheet underwent a severe reduction in volume, possibly even disappeared, and then reestablished itself. It appears as though ice sheets (marine) formed on Antarctica during late Eocene/early Oligocene time and have waxed and waned since that time. On the Ross Sea continental shelf, these waxing and waning events produced a stratigraphy that is characterized by a large, late Oligocene seaward shift in coastal onlap, followed by early Miocene flooding and aggradation, which in turn is followed by successive progradational episodes in middle and late Miocene time, and culminates in the Plio-Pleistocene high-frequency progradations and transgressions. The waxing and waning events that produced the Ross Sea stratigraphy were presumably accompanied by eustatic variations which caused globally synchronous shifts in coastal onlap and the development of the global Neogene stratigraphic signature.

Acknowledgments. The authors appreciate constructive reviews and comments by David Feary, Steve Greenlee, Bilal Haq, Peter Webb, and an anonymous reviewer. We also wish to thank Stephanie Staples for her assistance with drafting. Permission to publish the biostratigraphic information from PALEO-DATA Inc. is acknowledged. The authors also thank AAPG for the permission to publish the seismic line displayed in Figure 5 and Amoco Production Company and Pentamina for permission to publish the seismic line displayed in Figure 7. NSF grant 8818523 to John B. Anderson funded the Antarctic portion of this investigation. This study was also partially funded by Total Minatome Corporation and the A.W. Bally research fund at Rice University.

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(Received November 6, 1989;
revised July 5, 1990;
accepted October 29, 1990.)