N91-26578

MARINE RECORD OF LATE QUATERNARY GLACIAL-INTERGLACIAL FLUCTUATIONS IN THE ROSS SEA AND EVIDENCE FOR RAPID, EPISODIC SEA LEVEL CHANGE DUE TO MARINE ICE SHEET COLLAPSE

John B. Anderson
Department of Geology and Geophysics
Rice University
Houston, Texas, 77251

INTRODUCTION

Some of the questions to be addressed by SeaRISE include: 1) what was the configuration of the West Antarctic ice sheet during the last glacial maximum; 2) what is its configuration during a glacial minimum; and 3) has it, or any marine ice sheet, undergone episodic rapid mass wasting? This paper addresses these question in terms of what we know about the history of the marine ice sheet, specifically in Ross Sea, and what further studies are required to resolve these problems. A second question concerns the extent to which disintegration of marine ice sheets may result in rises in sea level that are episodic in nature and extremely rapid, as suggested by several glaciologists (Clark and Lingle, 1977; Thomas and Bentley, 1978; Hughes, 1987). Evidence that rapid, episodic sea-level changes have occurred during the Holocene is also reviewed.

LATE WISCONSIN-HOLOCENE GLACIAL HISTORY OF THE ROSS SEA

Scott (1905) was the first to speculate that Ross Sea once was covered by an extensive ice sheet, which he felt was grounded on the continental shelf as far north as Cape Adare (Fig. 1). He called this expanded ice sheet the "Great Ice Sheet." David and Priestly (1914), who corroborated Scott's ideas, discovered foreign erratics and moraines perched well above present sea level (up to 305 m) at Cape Royds and Ross Island (Fig. 1). From this they concluded that the "Great Ice Sheet" once extended approximately 320 km north of its present position. Later, Priestley (1923) discovered metamorphic and dioritic erratics resting on the basaltic rocks of Cape Adare. He inferred that the East Antarctic Ice Sheet (EAIS) once had flowed over and through the mountains of northern Victoria Land and onto the adjacent continental shelf, filling Robertson Bay (Fig. 1) with at least 300 m of ice. Stuiver et al. (1981) cite widespread occurrences of striated surfaces, erratics, and moraines, now located well above the present ice surface, as evidence for former expansion of the ice sheet in the Ross Sea region. The most widespread deposit is the "Ross Sea Drift," perched 240 m to 610 m above present sea level.

Numerous radiocarbon dates obtained in the Ross Sea region indicate that the late Wisconsin glacial maximum occurred between 21,200 and 17,000 yrs. B.P. (Stuiver et al., 1981). During the glacial maximum, approximately 1,325 m of ice is believed to have been grounded in McMurdo Sound (Stuiver et al., 1981). This ice sheet pushed westward into the Dry Valleys, and grounded in Ross Sea to the edge of the continental shelf (Stuiver et al., 1981). Perched erratics, some resting at elevations of 320 m above present sea level, on Beaufort and Franklin Islands (Fig. 1), provide evidence that an ice sheet once extended onto the continental shelf. Alternatively, these erratics could represent ice-rafted deposits, placed prior to the uplift of the islands, which occurred after the initiation of ice-rafting in Ross Sea (Stuiver et al., 1981). Based on the continental record, the ice front began its retreat around 17,000 yrs. B.P. and reached its present position by 6,190 yrs. B.P. (Stuiver et al., 1981).

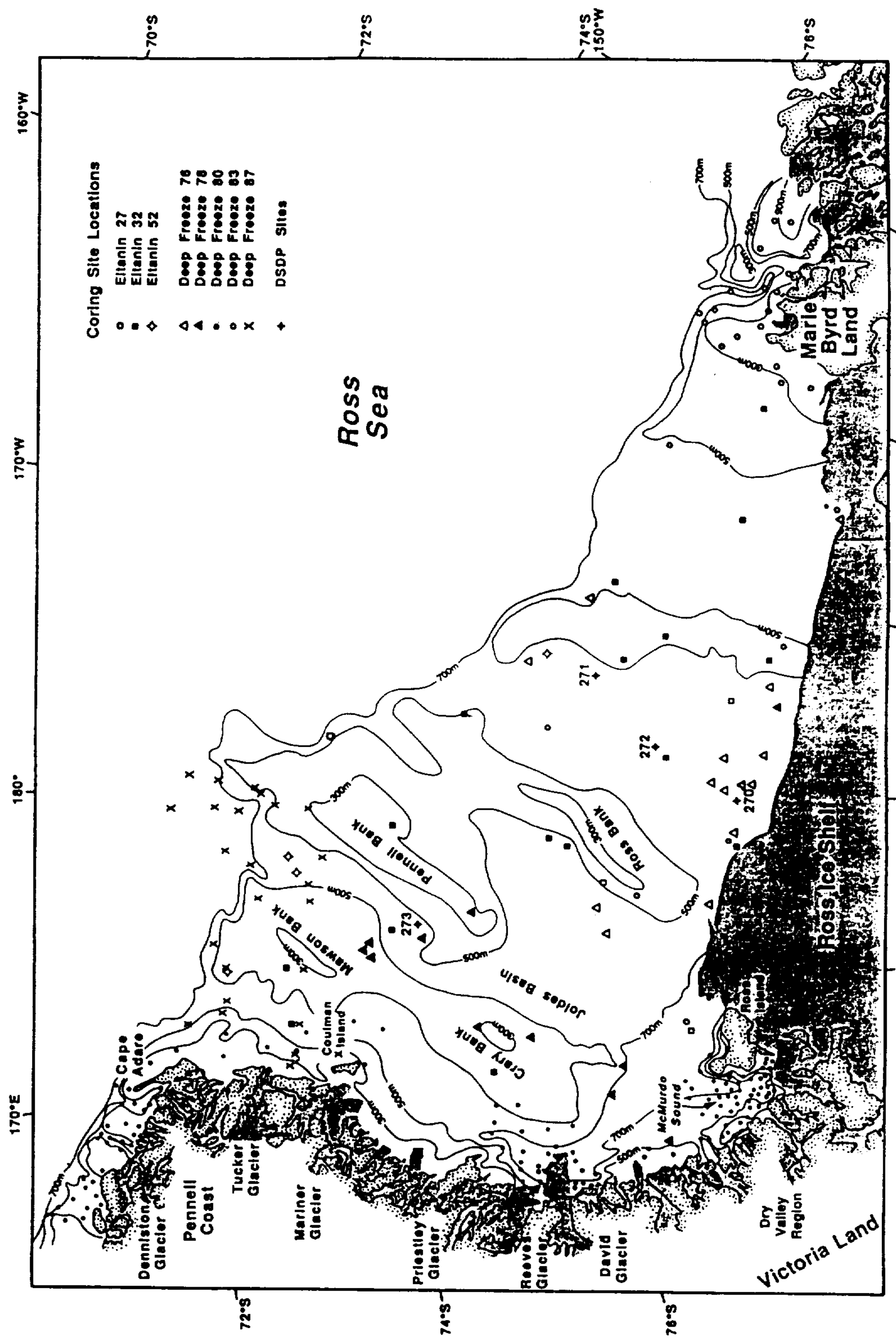

Figure 1. Geography and bathymetry of the Ross Sea. Also shown are locations of piston cores that have been examined in detail.

Arguments for a more extensive ice sheet in Ross Sea during the last glacial maximum have not gone uncontested. As early as 1921, Debenham argued that localized glacial expansions could explain the presence of raised moraines and erratics in the southern Victoria Land region. Mayewski (1975) mapped ancient moraines associated with Scott, Amundsen, Shackleton and Beardmore glaciers and concluded that they were deposited by a much thickened EAIS and that the grounding line of Ross Ice Shelf could have been located very near its present position during these events. Also, Whillans (1976) argued that the West Antarctic Ice Sheet (WAIS) probably varied little in size and dimensions during the last 30,000 years, based on glaciological arguments.

Drewry (1979) reviewed the evidence for ice sheet expansion onto the Ross Sea continental shelf during the last glacial maximum. He concluded that the grounding line of the ice sheet occurred only slightly seaward of its present position 18,000 years ago, but that the ice shelf might have extended over much of the continental shelf. His argument draws from the concept that a eustatic sea-level fall of greater than 120 to 130 m sustained over a period of 5,000 to 10,000 years must occur to fully ground the ice sheet. It is estimated that the maximum sea-level fall around Antarctica, caused by the late Wisconsin build-up of ice in the northern hemisphere, was only on the order of 75 to 100 meters (Lingle and Clark, 1979).

Marine Geological and Geophysical Evidence for an Expanded Ice Sheet

Results of Seismic Investigations

Listed below are some of the questions that high resolution seismic data allow us to address.

1) Are there geomorphological features on the sea floor which mark former grounding lines for the last glacial maximum? If so, how many grounding lines can be identified by this method and what do they imply about geographic, bathymetric and geological controls on the grounding line position?
2) Did the positions of the major ice streams shift significantly during the last few glacial cycles?
3) Are there geomorphological features on the shelf which provide clues to the dynamics and stability of the grounding line (i.e., the subglacial deltas of Alley et al., 1989)?

More miles of seismic reflection tracklines exist for Ross Sea than any other part of Antarctica. Data from earlier surveys consist mainly of sparker profiles, which are short and seldom tie (Fig. 2). More recent seismic surveys concentrate on examining the deep structure and stratigraphy of the region and utilized large air guns as the sound source. The stratigraphic resolution of this method is poor, so these data have limited value in addressing the problems outlined by the SeaRISE workshop participants.

The most recent seismic survey of the Ross Sea continental shelf was conducted during USAP 90 onboard the R/V Polar Duke (Fig. 3). Data acquisition employed a new sound source, a bubble-free air gun. These data provide greater stratigraphic resolution and greater aerial coverage than previously available for the region. Still, the resolution of these data falls short of that needed to address some of those questions related to the SeaRISE program.

A series of north-northeast to south-southeast oriented basins and ridges characterizes the bathymetry of Ross Sea (Fig. 1). These features extend beneath Ross Ice Shelf where they display a more northwest to southeast orientation (Drewry, 1983). Hughes (1977) observed that the linear basins of the Ross Sea shelf roughly correspond to the locations of modern ice streams at the grounding line of Ross Ice Shelf. Based on this observation, he argued that the linear basins of the shelf formed by accelerated glacial erosion beneath ice streams during a previous expansion of the WAIS. However, Vanney et al. (1981) argued that the basin and ridge topography of the Ross Sea shelf also corresponds to the tectonic fabric of the shelf, hence these features may not necessarily

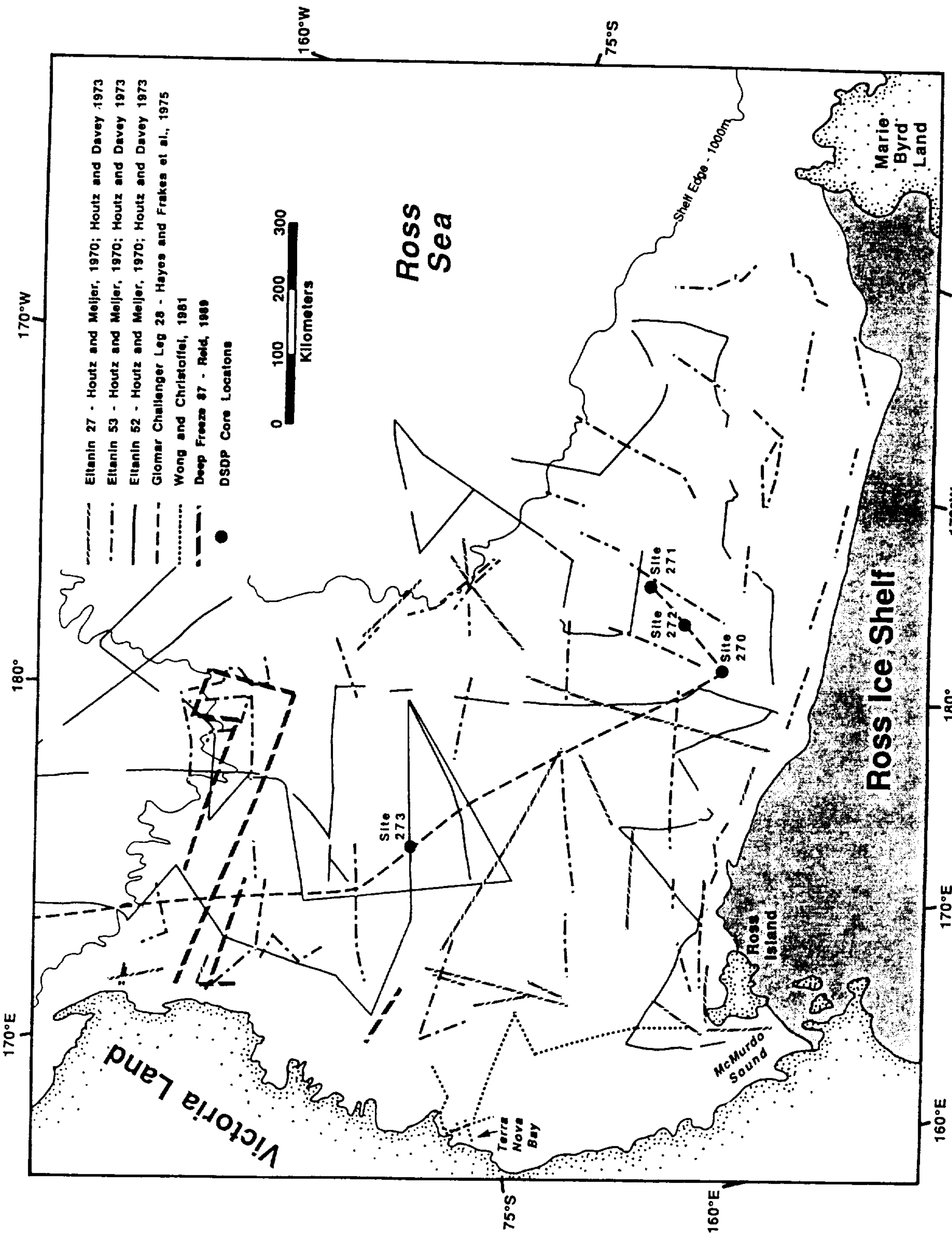

Figure 2. High resolution seismic tracklines for the Ross Sea (prior to 1990).

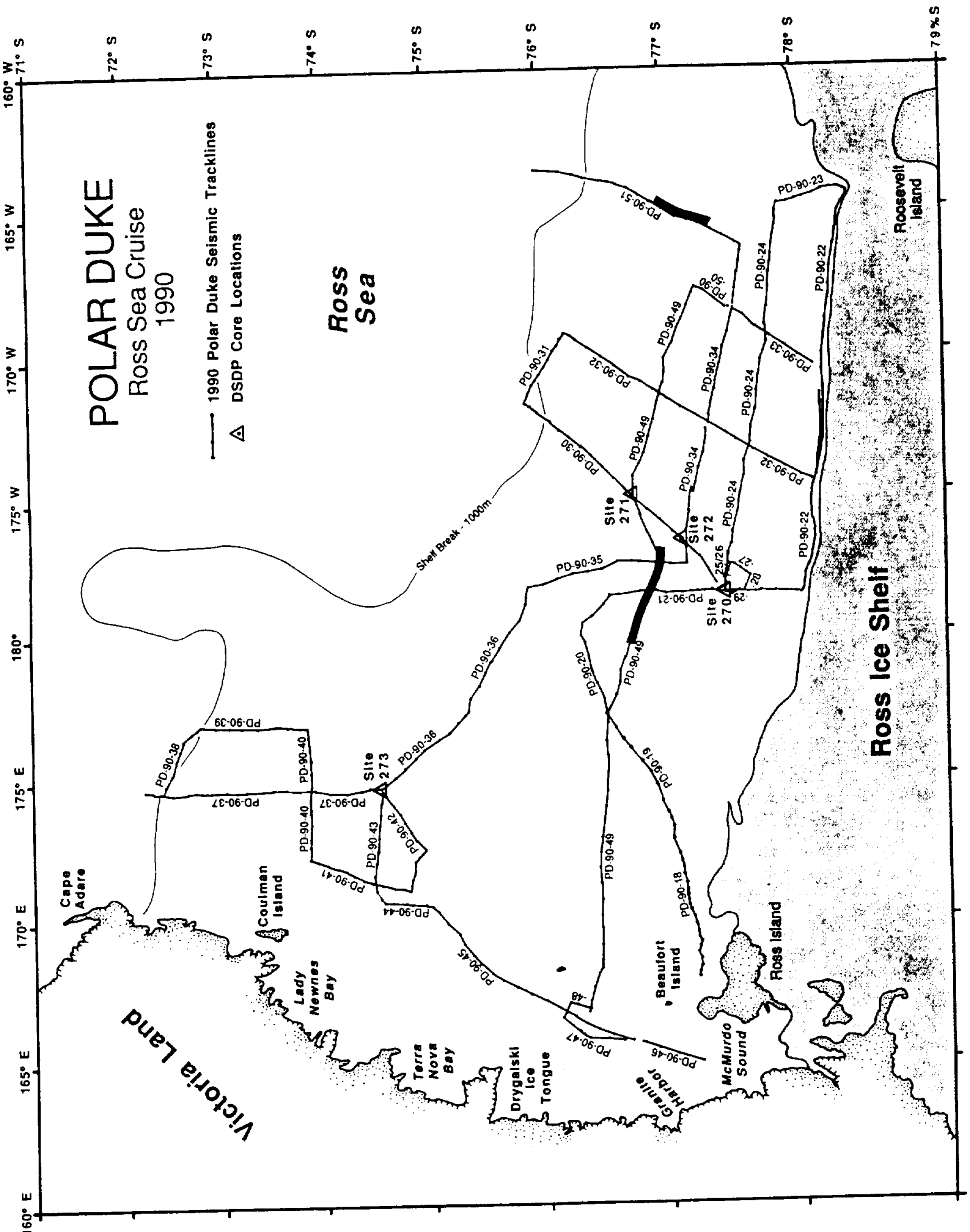

Figure 3. Polar Duke-USAP 90 seismic tracklines. These data were acquired using a new, high resolution seismic source, a bubble-free air gun. Highlighted portions of the tracklines are illustrated in the text.

be of glacial origin. Alternatively, we might infer that there is a geological control on the positions of ice streams.

During USAP 90, several east-west profiles were acquired across the shelf to address whether there is, or has been, a geological control on the position of ice steams in the Ross Sea region (Lines PD90-18, 22, 24, and 49, Fig. 3). These profiles show that large-scale cut-and-fill structures characterize the upper stratigraphic sequence (Fig. 4). The width to depth ratio of these scours mimics that of the modern ridge and basin topography, hence their interpretation as relict glacial troughs. The locations of these features on the shelf has varied through time and tectonic controls on trough positions is observed only in the western Ross Sea. Thus, modern troughs apparently mark the positions of former ice streams, as suggested by Hughes (1977), but the locations of these ice streams have changed with time and are not controlled by geological features on the shelf, at least not on the exposed portions of the shelf.

Early studies of seismic reflection records from the continental shelf led to the discovery of a widespread unconformity, the Ross Sea Unconformity (RSU), inferred to be a glacial erosional surface (Houtz and Davey, 1973; Karl et al., 1987). Efforts to date this unconformity yielded a range of dates (Kellogg et al., 1979, [18000 B.P.]; Savage and Ciesielski, 1983 [0.65 to 13.8 Ma]; Hayes and Frakes, 1975 [3 to 5 Ma]). A more recent examination of these same records led to the conclusion that the RSU represents an amalgamation of several erosional surfaces that cuts across different stratigraphic levels (Bartek, 1989), a conclusion supported by USAP 90 seismic records.

On the inner-most shelf, the RSU is a sea floor unconformity where acoustic basement outcrops all along the coast. There, conspicuous evidence for glacial erosion of the sea floor exists as glacial troughs (Shepard, 1931). These broad, deep submarine valleys, located offshore of outlet glaciers and ice streams, are U-shaped and foredeepened. The largest of these is Drygalski Trough (Fig. 5). This feature exists offshore of David Glacier where ice from East Antarctica flows through the Transantarctic Mountains. Seismic records across the trough provide evidence for several episodes of glacial erosion (Fig. 5).

Seismic reflection profiles also provide evidence of subglacial deposition on the shelf. Wong and Christoffel (1981) mapped one of the more spectacular examples of a morainal bank along the northern rim of Drygalski Trough. It is comprised of steeply dipping (to the north) reflectors which abruptly terminate at the southern flank of the trough (Fig. 5) and rests above the RSU. They interpreted this feature as a "delta moraine," and suggested that it marks the northern limit of Ross Ice Shelf during a previous glacial advance.

USGS profile 413 from the western Ross Sea (Karl et al., 1987) shows a wedge-shaped body of deposits which thickens to the north and has seaward dipping clinoforms at its northern end. Internal reflectors are discontinuous and hyperbolic reflectors characterize the upper surface (Fig. 6a). Similar features, recognized in seismic records acquired during Deep Freeze 87 and USAP 90 (Fig. 4), are identical to acoustically massive wedges described in high resolution seismic records from the southeastern Canadian shelf and interpreted as till tongues (King and Fader, 1986).

USAP 90 seismic profiles on the central and eastern portions of the continental shelf display several mound-like features with foreset beds (Fig. 6b). These features, interpreted tentatively as subglacial deltas (Bartek and Anderson, in press, a), possibly were produced by processes similar to those acting beneath Ice Stream B today (Alley et al., 1989). These features, best seen in seismic lines acquired perpendicular to the paleodrainage divides, rest on glacial erosional surfaces.

High resolution seismic records from the western Ross Sea (Deep Freeze 87) show a change in the character of near surface deposits from north to south within this area (Reid, 1989). The southern part of the area is characterized by intercutting erosional surfaces (former troughs), relatively high relief on individual reflectors, till tongues and morainal banks (Fig. 5).

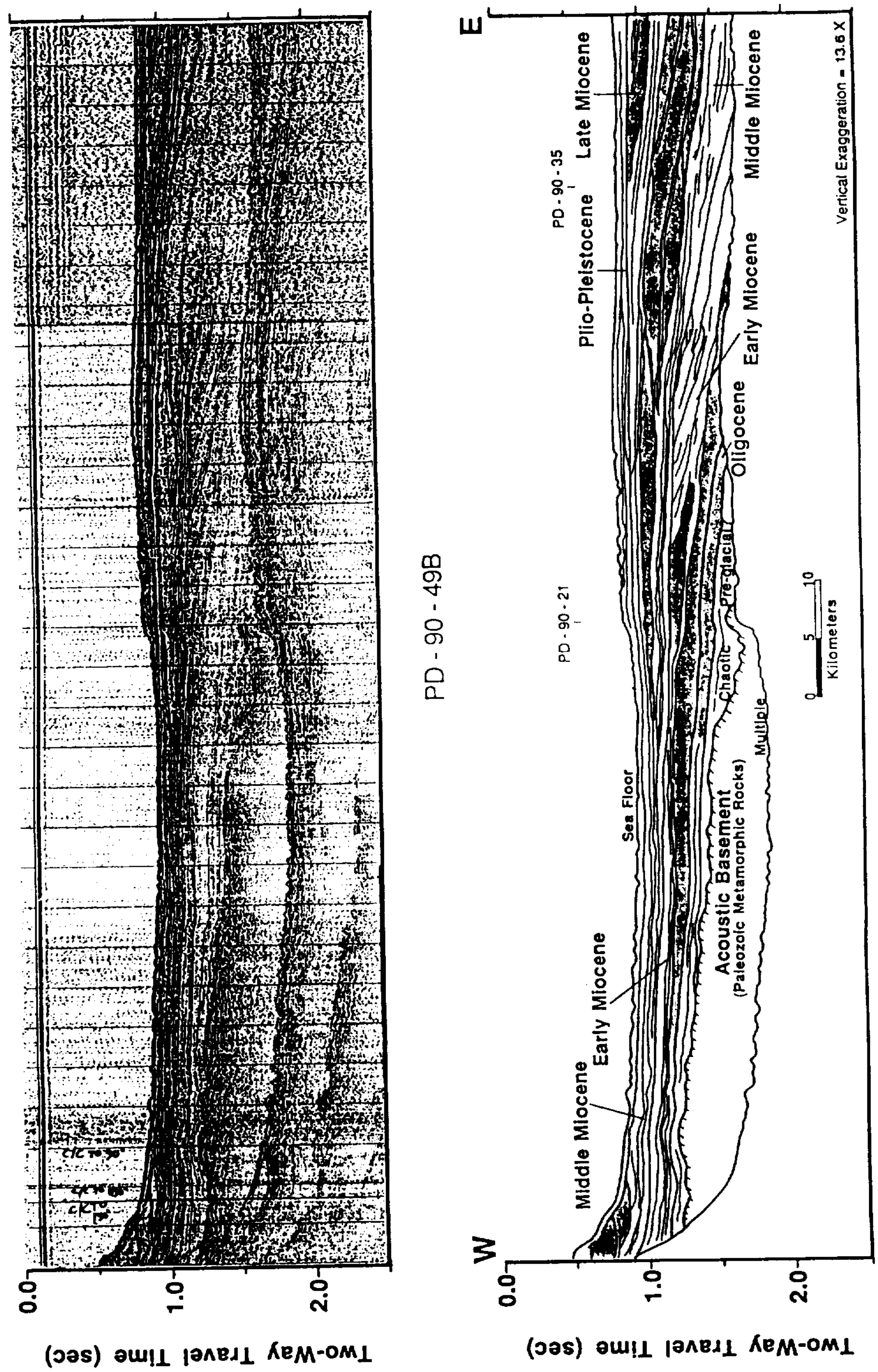

Figure 4. Polar Duke-USAP 90 seismic line PD-90-49B showing broad-scale erosional surfaces, glacial troughs, and massive sediment bodies that are interpreted as "till tongues". See figure 3 for profile location.

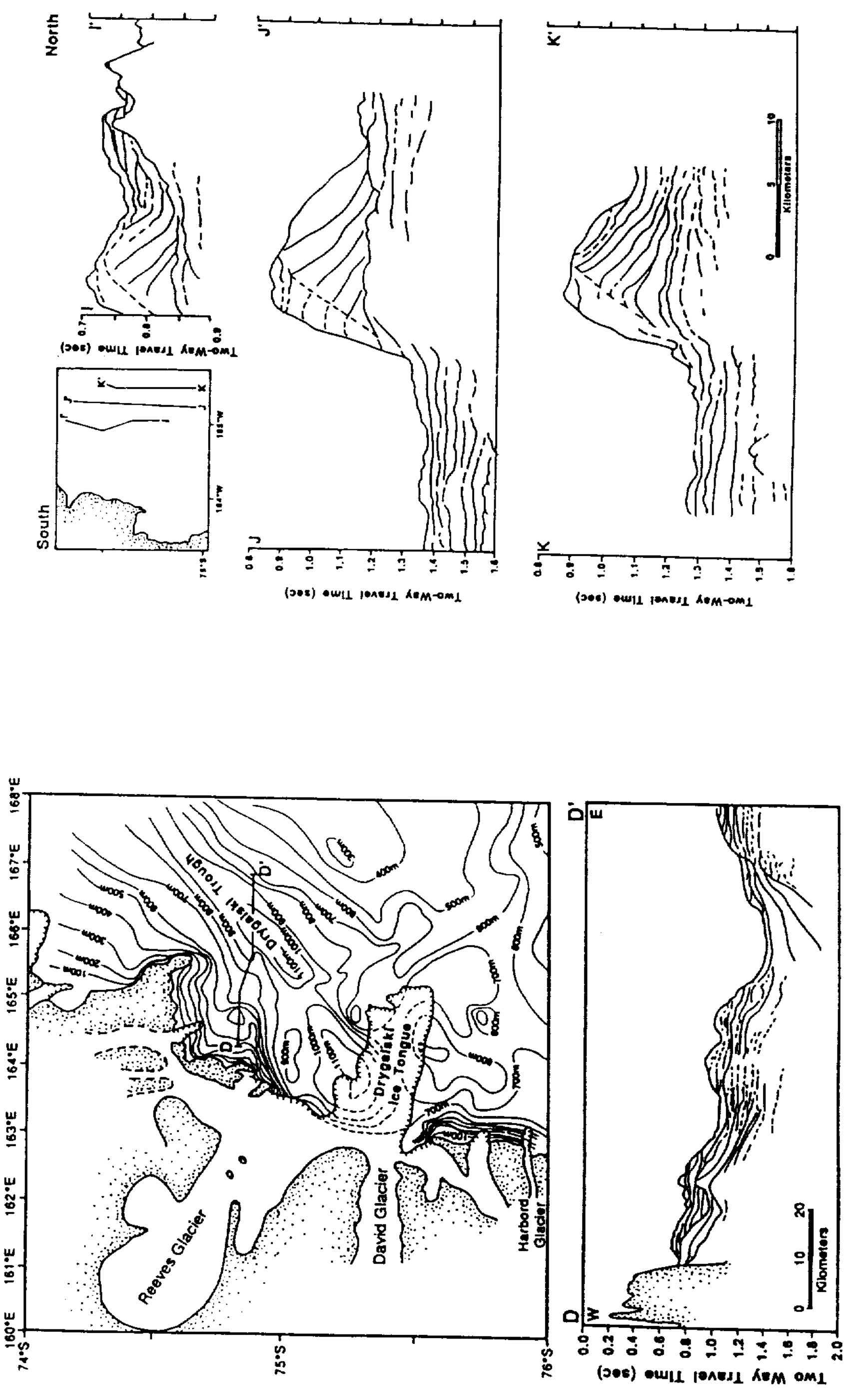

Figure 5. Bathymetric map of Drygalski Trough. Seismic records from this feature provide evidence for several episodes of glacial erosion, as shown in profile D-D". A large "morainal feature that rests above the upper-most unconformity is shown in interpreted seismic lines (I', J', and K') from the northwestern flank of the trough. Seismic lines from Wong and Christoffel, 1981.

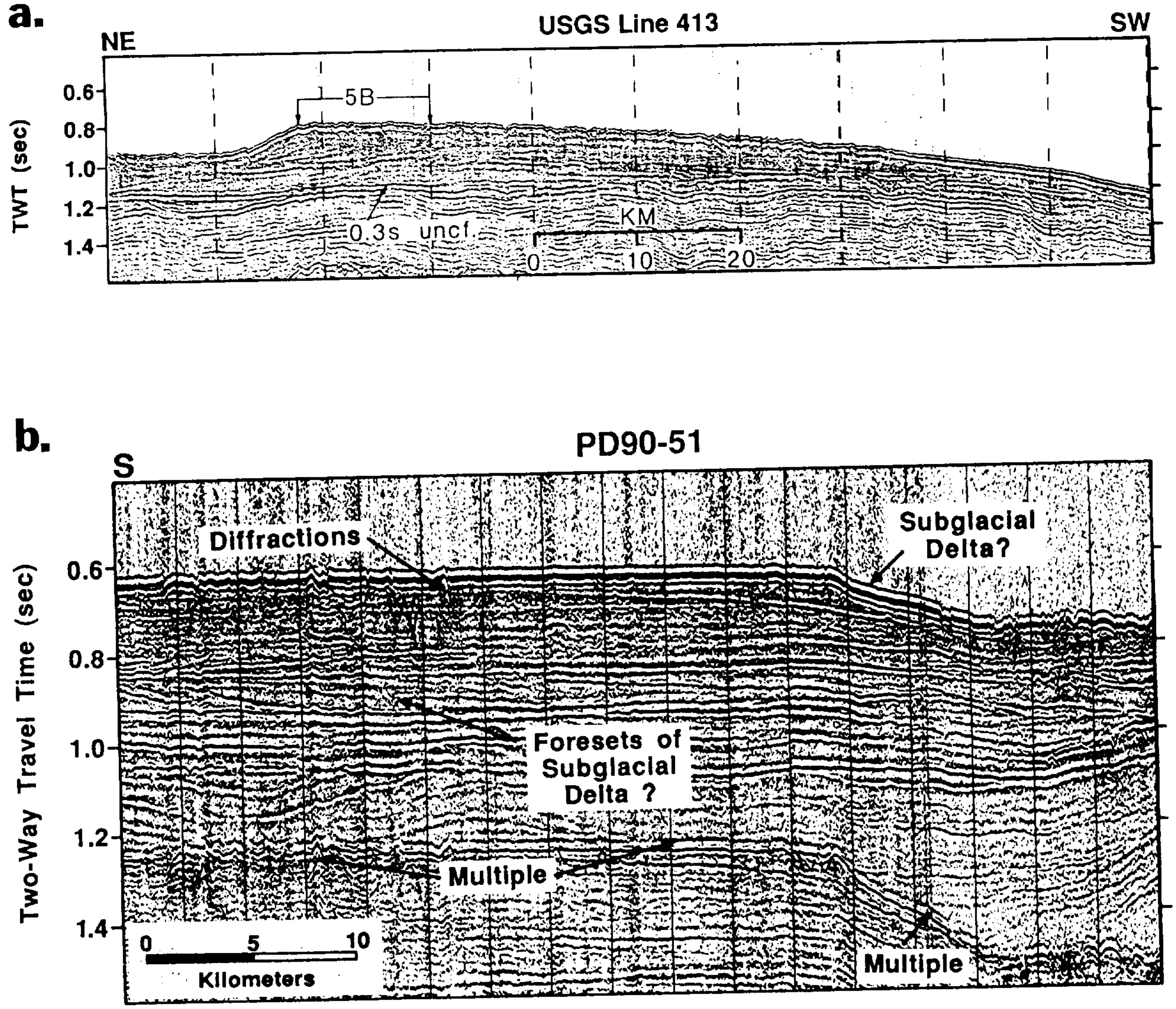

Figure 6. A. USGS seismic profile 413 from the western Ross Sea showing wedge-shaped body (from Karl et al., 1987). This feature is similar to "till tongues" of the southeastern Canadian shelf as described by King and Fader (1986). B. USAP 90 seismic line PD90-51 showing a similar wedge-shaped body, interpreted as a possible subglacial delta. See figure 3 for profile location.

The northern part of the survey area shows generally flat, coherent reflectors separated by acoustically transparent zones. Relief on individual reflectors indicates a sea floor topography that is relatively broad and gentle, and without glacial troughs. Reid (1989) suggests that the boundary between these different seismic provinces marks the northern limit of an ice sheet grounding line during the late Wisconsin.

In summary, high resolution seismic reflection profiles from Ross Sea provide abundant evidence that ice sheets were grounded there on more than one occasion. However, most of these seismic data consist of sparker and air gun records, and the stratigraphic resolution obtained with these seismic sources is not adequate to address some of the questions raised in the SeaRISE workshop.

To address these questions, we must undertake systematic high resolution seismic surveys in which track lines are planned using available information about paleodrainage of the late Wisconsin ice sheet (discussed in the following section). These surveys should employ high frequency sound sources, such as small water guns and/or a Huntec system, in conjunction with side-scan sonar mapping. Holocene sediments on the Ross Sea continental shelf are relatively thin, therefore, subglacial features with greater than approximately 1 m relief will be detectable using side-scan sonar images.

Results of Sedimentologic and Petrographic Studies

Many piston cores have been collected from the Ross Sea continental shelf (Fig. 1). A number of investigators have examined these cores in an attempt to reconstruct the late Quaternary glacial setting (Fillon, 1975; Kellogg and Truesdale, 1979; Kellogg et al., 1979; Anderson et al., 1980, 1984; Domack et al., 1980; Edwards et al., 1987; Reid, 1989) . In general, the late Pleistocene-Holocene stratigraphy of the shelf, revealed by these cores, consists of Holocene glacial marine sediments, reflecting a dominance of marine influence on sedimentation (Chriss and Frakes, 1972), resting on, and typically in sharp contact with, diamictons. These diamictons reflect the earlier influence of glacial processes on sedimentation (Kellogg et al., 1979; Anderson et al., 1980; 1984). A key question concerns the subglacial versus glacial marine origin of these diamictons. Fillon (1975) favored a glacial marine origin for these deposits, whereas Kellogg et al. (1979), Anderson et al. (1980; 1984), and Domack et al. (1980) argued in favor of a subglacial origin.

The evidence provided by Kellogg et al. (1979) for a subglacial origin of diamictons (their unit B) includes: 1) the widespread occurrence of this unit; 2) its compact nature and lack of sorting; and 3) the presence of reworked microfossils. Anderson et al. (1980; 1984) and Domack et al. (1980) re-examined these diamictons and added to the list of glacial criteria textural and mineralogic homogeneity of individual units, pebble fabric (relative to the vertical plane), and pebble shape. These combined criteria imply rapid deposition from basal debris zones, but do not allow us to conclude whether these diamictons were the products of subglacial sedimentation (basal tills) or resulted from deposition beneath an expanded ice shelf. Diamictons produced by sedimentation beneath ice shelves and by sediment mass movement are quite similar to those deposited by grounded ice (Kurtz and Anderson, 1979; Anderson et al., 1980, in press).

Diamictons from the Ross Sea shelf typically have shear strength values that exceed 2.5 kg/cm^2 (Anderson et al., 1980). Overcompaction implies subglacial deposition, but also can result from sediment overburden. Edwards et al. (1987) performed geotechnical tests on these diamictons and concluded that they were overcompacted, but the degree of overcompaction is minor and implies an ice sheet thickness only tens of meters greater than the water depth of the shelf. However, the piston cores Edwards and his colleagues examined penetrated only a short distance into the diamicton. Hence, they measured the physical properties of sediments deposited just prior to when the ice sheet decoupled from the sea floor.

One of the most crucial criteria for determining a subglacial and/or sub-ice shelf origin of diamictons involves petrographic analysis. Since the turn of the century, glacial geologist have utilized petrographic data (mineral and clast content of glacial deposits) to identify tills and determine the source area of these deposits. These studies allowed them to construct glacial paleodrainage maps. Basal tills and sub-ice shelf deposits should consist of fewer varieties of rocks and minerals than iceberg-rafted sediments, whose source area may be quite extensive. The provinance of the tills can be established where the geology of the source area is known. Domack (1982) demonstrated that glacial sediments from the continental shelf off Wilkes Land correlate positively with exposures of continental rocks. Results of diamicton studies on the Weddell Sea continental shelf (Anderson et al., in press), and in Marguerite Bay (Kennedy and Anderson, 1989) parallel the findings off Wilkes Land.

Anderson et al. (1984; submitted) summarize the results of petrographic analyses performed by Balshaw (1981), Myers, (1982), and Reid (1989) on four components of Ross Sea diamictons (rock clasts, coarse sands, heavy minerals, and clay minerals) and the glacial marine sediments that overlie them. Factor analysis was used to group diamictons of similar composition. When plotted on a map, the results of these petrographic analyses fall into seven provinces whose boundaries follow the northeast-southwest bathymetric trend of the shelf and provide the basis for a paleodrainage reconstruction for the late Wisconsinan ice sheet (Fig. 7). Truswell and Drewry (1984) examined reworked palynomorphs in diamictons from the central and eastern Ross Sea shelf and found distribution patterns broadly similar to our petrographic provinces. The paleodrainage map shown in Figure 7 also shows broad parallels with the paleodrainage map of Denton and Hughes (1981), however, the author hastens to emphasize that the actual number of cores examined from the eastern and central portions of the shelf was relatively small, and additional work is needed to better constrain the paleodrainage divides shown in Figure 7.

The most thorough petrographic and sedimentological studies of piston cores have been conducted in the western Ross Sea (Myers, 1982; Reid, 1989) and in McMurdo Sound (Bartek, 1989). Half (20) of the cores collected from the western Ross Sea shelf penetrated diamictons that bear all the characteristics of basal till. The other twenty cores penetrated either glacial marine sediments or sediment gravity flows. The latter deposits appear to thicken to the north and toward the coast and may overly basal tills in these areas. North of Coulman Island (Fig. 1) piston cores penetrated a wide range of glacial marine sediments, including carbonates, but no overcompacted diamictons. This suggests that the late Wisconsinan grounding line at one time existed at the approximate latitude of Coulman Island (Fig. 7, Reid, 1989). Diamictons from the southwestern Ross Sea separate into three petrographic provinces whose boundaries correspond to the northeast-southwest-oriented bathymetric features on the shelf (Fig. 7).

Piston cores from McMurdo Sound penetrated glacial marine sediments, diatomaceous muds, and a variety of sediment gravity flow deposits; the latter group consists of sediments derived from both Ross Island and the Dry Valleys (Bartek, 1989; Bartek and Anderson, in press, b). Basal tills were not collected, although absence of a lag deposit associated with unconformities penetrated in piston cores indicates that glacial ice caused erosion, instead of marine currents. Thus, piston cores from McMurdo Sound indicate a recent period of erosion followed by sedimentation of glacial marine sediments, with a large biogenic component (diatom frustules), and sediment gravity flow deposits. Anderson et al. (1984) suggest that the absence of tills in McMurdo Sound may imply that grounded, stagnant ice existed there during the late Wisconsin.

Retreat of Ice Sheet from Continental Shelf

Reid (1989) studied piston cores collected north and south of Coulman Island for purposes of reconstructing the glacial setting during and after the glacial maximum. He obtained radiocarbon dates between >35,510 B.P. and 17,390 +/- 500 B.P. for glacial marine deposits recovered in piston cores north of the island. Examination of these deposits and correlation with

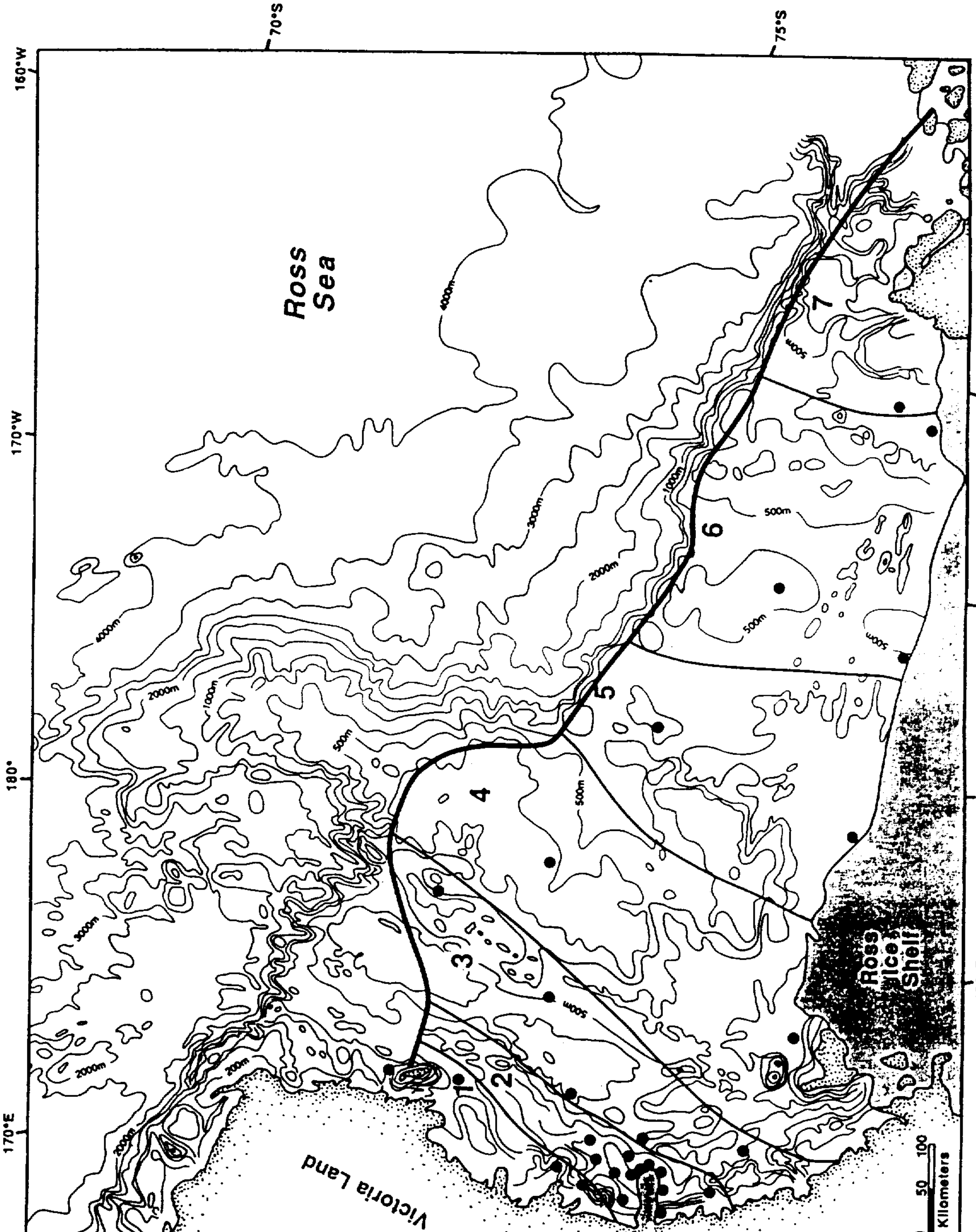

Figure 7. Petrographic provinces for Late Wisconsanan basal tills of Ross Sea and reconstructed ice sheet grounding line.

cores acquired south of the island led to the conclusion that sediment deposition occurred seaward of a grounded ice sheet and that icebergs, not subglacial ice, delivered the sand and pebble-sized glacial debris to these sites. From this, he deduced that either an ice shelf was not present at the outer shelf, or the ice shelf retreated from this area rapidly. The presence of warm deep water currents impinging onto the shelf, similar to the situation today (Jacobs et al., 1985), may account for the absence of an ice shelf at the outer shelf.

The vast majority of piston cores from the central and eastern Ross Sea contain diamictons directly overlain by diatomaceous muds and oozes. A sharp contact separates these units, indicating that the change from subglacial sedimentation to hemipelagic sedimentation occurred rapidly. Grain size analysis of surface sediments reveals a strong pattern of lateral size grading in which sediments decrease in grain size and become more diatomaceous to the south. This may be due to an increase in water depth and a decrease in marine current energy in that direction, and reflects the present dominance of marine processes on sedimentation (Anderson et al., 1984; Dunbar et al., 1985).

Ledford-Hoffman et al. (1986) obtained Pb^{210} sedimentation rates for diatomaceous sediments overlying diamictons in the southwestern Ross Sea, south of 75° S. These rates vary from less than 1 mm/y to 2.7 mm/y, and the thickness of these deposits varies from less than 10 cm to over two meters. If pelagic sedimentation began soon after the ice sheet withdrew from this portion of the shelf, and if these rates have remained relatively constant, the ice sheet retreated only a few thousand years B.P. These combined results suggest that the grounding line retreated rather slowly from north to south, or that it stabilized for some time at a position somewhere between Coulman Island and 75° S.

Leventer and Dunbar (in press) studied the more recent glacial and sea ice history of the McMurdo Sound region. They recognize a pattern in which the extent and/or duration of coastal polynyas increased during the Little Ice Age. They attribute this pattern to colder air temperatures and more persistent winds.

In summary, tills recovered in piston cores from the Ross Sea continental shelf indicate widespread grounding of the ice sheet during the last glacial maximum. Core coverage in the eastern and central Ross Sea is too sparse to allow detailed reconstruction of grounding line positions and paleodrainage on the shelf during the last glacial maximum. Core coverage is better in the western Ross Sea and the glacial setting during the late Wisconsin is better known, but the history of ice sheet retreat from the shelf remains problematic. What is needed is the acquisition of core transects extending from the front of Ross Ice Shelf to the edge of the continental shelf. An additional transect should extend east-west across the shelf to allow the reconstruction of paleodrainage in the region. These cores, if acquired in conjunction with high resolution seismic records (3.5 KHz and small water gun or Huntec) should assure stratigraphic integrity; USAP 90 seismic records from the region show several unconformities in the upper sediment column. In addition, side-scan sonar profiles may provide a direct record of subglacial features and can be used to avoid sampling areas subject to intense iceberg scour.

Detailed radiometric work may help to constrain the timing of ice sheet retreat from the shelf; this requires age control on the glacial marine sediments directly overlying tills. Reliable radiometric dates have been obtained for diatomaceous sediments of the Wilkes Land continental shelf (Domack et al., 1989) and for Prydz Bay (Domack and Jull, in press) using the tandem accelerator method.

DEFINING THE CONDITIONS DURING AN EXTREME GLACIAL MINIMUM

One question that remains unresolved in the late Quaternary glacial history of Ross Sea concerns the extent of grounded and floating ice over the continental shelf during a glacial minimum. This is an important problem; it bears on whether the ice sheet and ice shelf could experience further retreat before reaching a stable configuration, as suggested by Hughes (1973).

The global isotopic and sea-level record provides little information with regard to this question. The oxygen isotope record for the world ocean provides evidence that global temperatures and/or ice volume during Pleistocene interglacials were close to, and potentially less than, those of the present (Imbrie et al., 1984). Sea-level curves for the late Pleistocene indicate that sea level approximately 120,000 yrs. B.P. was a few meters higher than that of the present day (Kendall and Lerche, 1988).

The geological approach to this problem involves drilling through the ice shelf and searching for evidence that open marine conditions existed there during previous interglacials. This is not a "fool-proof" method; the ice sheet undoubtedly has removed older Pleistocene deposits during the late Wisconsin advance. The sediments recovered at RISP J 9 include abundant diatoms, implying open marine conditions. However, the age of these sediments remains the subject of considerable debate. One group of scientists contends that there was no recovery of Plio-Pleistocene sediments (Harwood et al., 1989) while the other group argues that Pleistocene diatoms were sampled and their presence implies open marine conditions at this site, perhaps as recently as 18,000 to 20,000 yrs. B.P. (Kellogg and Kellogg, 1986). It remains unclear whether paleontological resolution is at a stage where Pleistocene deposits will be recognized if they are recovered. Clearly, more work must be undertaken to resolve this problem.

NATURE OF THE HOLOCENE SEA LEVEL RISE

In his summary of Holocene sea-level curves, Kidson (1982) describes two schools of thought which concern the nature of sea-level rise since the late Wisconsinan glacial maximum. One, which he calls the Shepard school, includes those who favor a more or less continuous rise in sea level since about 18,000 B.P.. The other, the Fairbridge school, includes those workers who favor a more episodic post glacial rise in sea level. To some degree this controversy stems from a lack of prior knowledge of hydro-isostatic and geoidal influences, which results in non-uniform changes in sea-level in different parts of the world (Peltier, 1980). Some early attempts to establish sea level curves using data gathered from different portions of the globe (i.e. Fairbridge, 1961) resulted in step-like curves (Fig. 8) that may simply be an artifact of these effects (Kidson, 1982). On the other hand, some curves for specific regions, such as those from the New Zealand and Australian shelves (Carter et al., 1986) and the Gulf of Mexico shelf (Fig. 9), provide evidence of episodic rises in sea level.

In part, the episodic sea-level school of thought has suffered from the lack of a mechanism that could explain the rapid rises indicated by some curves. For example, data from the Gulf of Mexico (Rehkemper, 1969; Nelson and Bray, 1970; Frazier, 1974, Fig. 9) indicate rapid rises in sea level of as much as 3 to 5 cm/yr. Mass wasting of marine ice sheets is the most plausible mechanism for such rapid changes.

Geochemical and Stratigraphic Proxies for Examining Deglaciation Mechanisms

The stratigraphy of continental shelves and the geochemical record of deep-sea sediments provide two indirect methods for investigating the nature of deglaciation and sea-level rise, as opposed to directly measuring the decrease in ice volume in the polar regions. Detailed $\partial^{18}O$ stratigraphy from deep sea cores suggest the late Wisconsinan-Holocene deglaciation proceeded in steps or "terminations" (as many as three have been proposed; Ruddiman and Duplessy, 1985) which may reflect periods of rapid introduction of ^{16}O enriched water to the oceans and/or cooling of the oceans (Chappell and Shackleton, 1986). The use of the $\partial^{18}O$ signature as a proxy for ice volume is not accepted unreservedly because the temperature effect alone could account for the terminations observed (Ruddiman, 1987). These terminations represent changes of 0.5 $\partial^{18}O$ and

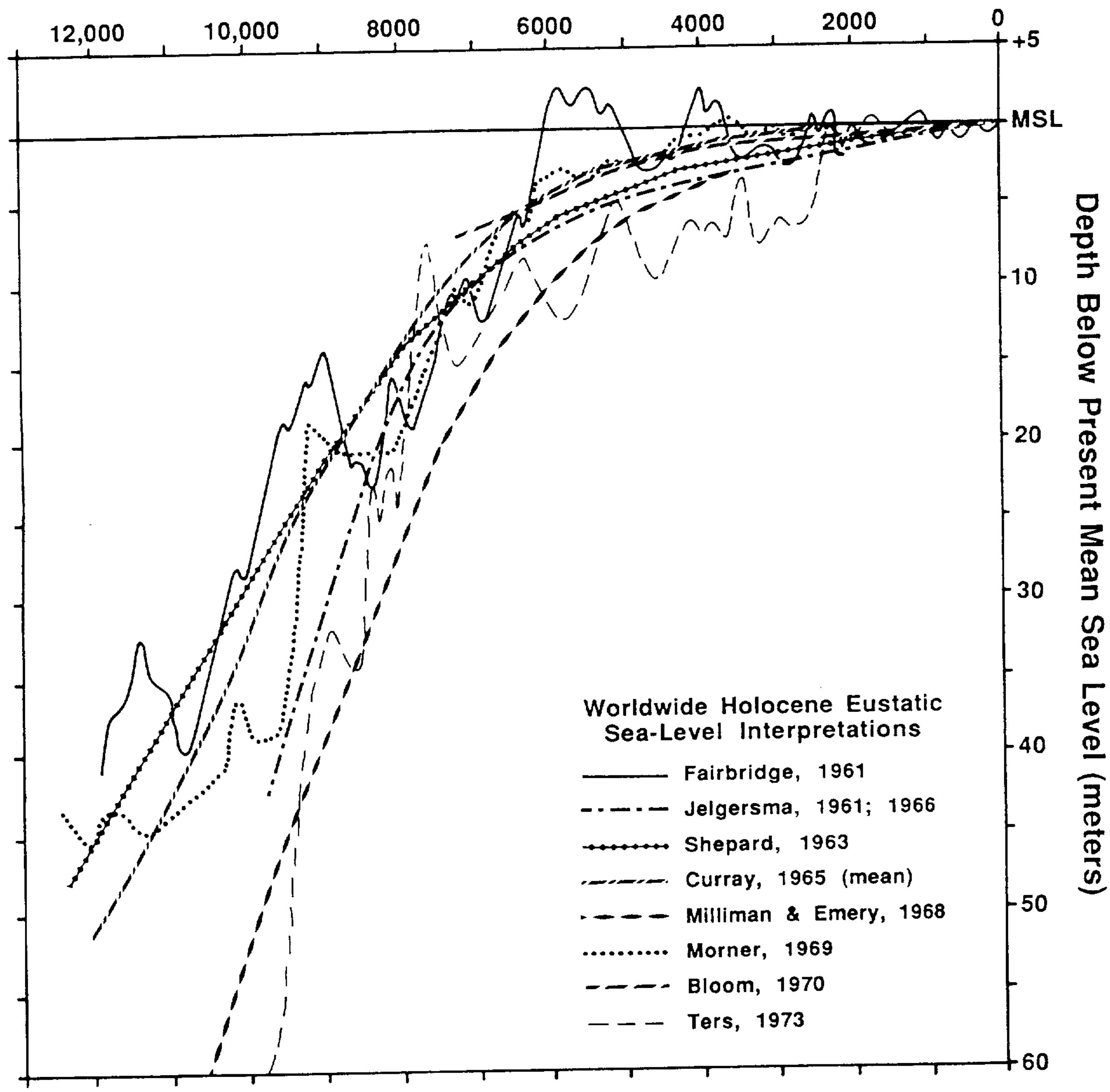

Figure 8. Compilation of Holocene sea level curves from various global locations. Curve shapes reflect the two major schools of thought regarding the nature of the latest transgression: smooth and continuous versus stepped and discontinuous (from Belknap and Kraft, 1977).

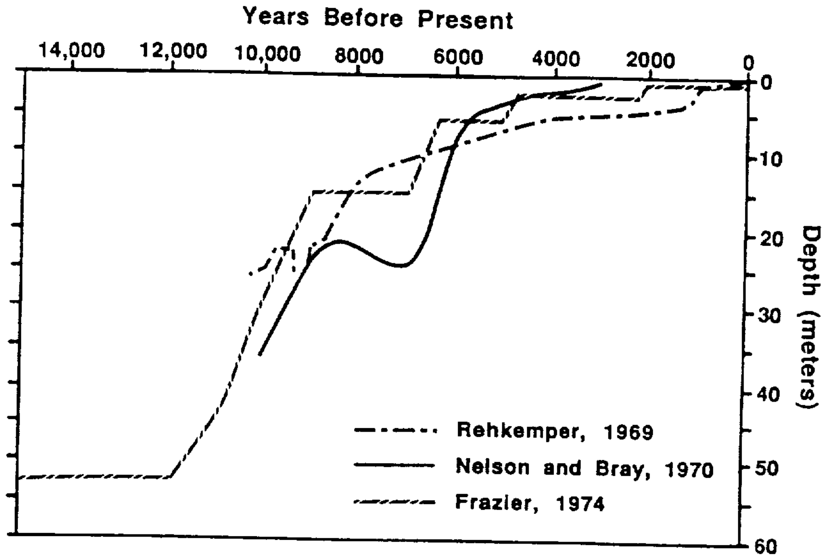

Figure 9. Holocene sea level curves for the Gulf of Mexico region, which interpreted the transgression as proceeding in a series of rises and stillstands.

could translate to a sea-level rise on the order of 35 m (the total glacial to interglacial response is 1.5 $\partial^{18}O$ for ≈ 100 m of sea-level rise). In comparison, the theoretical sea level response of a single marine ice sheet decoupling event is on the order of 5 to 10 m, which corresponds to .05 to .10 $\partial^{18}O$, a magnitude of change that is near or below instrument resolution. Therefore, the $\partial^{18}O$ record is not at this time a practical method for either documenting or disproving the occurrence of high-frequency, low-amplitude sea-level changes. Given this, the stratigraphic record on continental shelves provides the best hope for obtaining the high resolution sea level record needed to address the questions raised by SeaRISE.

Conventionally, sea level curves have been inferred from the age and altitude relationship of sequential shoreline features. A problem with this approach is that transgressive stratigraphy is not due solely to rising sea-level, but can also result from decreased sedimentation rate or increased subsidence rate. To constrain the variables of sedimentation and subsidence rates one should compare the sea-level records from a variety of coastal settings.

Another method for obtaining sea level-curves involves analysis of faunal and floral assemblage changes in carbonate sequences for evidence of changing water depth. This method has recently been used in coastal exposures of Barbados with good success (Fairbanks, 1990). If this method is to be applied to address the questions of SeaRISE, water depth resolution must be improved to a few meters.

Research describing the effects of hydro-isostasy and geoidal influences has led to the consideration of late Wisconsinan-Holocene sea-level curves as regional phenomena (Peltier, 1980; Kidson, 1982), thereby discounting the use of regional sea-level curves as a eustatic indicator. However, the duration of an ice-sheet decoupling/sea-level rise event may be only several hundred years (Clark and Lingle, 1979; Thomas and Bentley, 1978), whereas the viscous response time of hydro-isostasy is several thousand years (Peltier, 1980). Furthermore, Carter et al. (1986) suggest that in middle to low latitude regions correlation by altitude alone is possible, because hydro- and glacio-isostatic effects will be negligible there. This is especially true during the period from 18,000 to 6,000 yrs. B.P.; for according to viscous mantle response models (Peltier, 1980; Clark et al., 1986), most of the differential sea-level behavior occurs only after deglaciation is complete. It is probable then, that high-frequency, low-amplitude sea-level rises due to marine ice-sheet decoupling may be superimposed on the gradual changes in sea level associated with climatic warming and isostatic adjustment. The question is, how do we obtain sea-level curves that are accurate enough to show whether such changes have occurred?

Thomas (1990) and Anderson and Thomas (in press) contend that there is a pattern of episodic sea-level rise worldwide that transcends the six zones of sea-level response (due to viscous mantle behavior) as defined by Peltier (1980). They cite examples of sea-level curves from around the globe that provide evidence for rapid, episodic rises and argue that a pattern for global correlation of such events is emerging. For example, Tooley (1978) found evidence for a 5 m rise that occurred between 7,800 and 7,600 yr B.P., which he attributed to collapse of the Laurentide ice sheet. Carter et al. (1986) documented periods of rapidly rising sea level throughout the last transgression based on studies conducted in Australia and New Zealand. Also, an episodic relative sea-level rise constitutes the favored model for the late Wisconsinan-Holocene transgression in the Gulf of Mexico region (Frazier, 1974; Penland et al., 1990). The problem is that the methods used to derive these curves generally are not capable of resolving low amplitude changes of the scale caused by rapid mass wasting of marine ice sheets. Furthermore, most of the curves shown in Figure 8 rely on radiometric ages of either shell material dredged from banks or peats collected in cores. The assumption that these are shoreline deposits is, more often than not, poorly supported. Thomas (1990) demonstrates that these curves are in error in the case of the Gulf of Mexico (Fig. 9) .

A key obstacle to acquiring high resolution sea-level curves from clastic shelves stems from the fact that Holocene deposits on continental shelves are characteristically thin (generally less than 1 m) and almost always reworked by marine organisms and/or marine processes (Curray, 1960). Thick, undisturbed Holocene strata are required to develop reliable sea-level curves. Belknap and Kraft (1981) contend that a very good record of the late Wisconsinan-Holocene transgression is preserved within incised valley-fill deposits, which escape the effects of shoreface erosion. Thus, these sequences are thick (generally tens of meters) and complete. Because they are thick, these sequences provide the only opportunity for obtaining the high resolution seismic records needed to document shoreline changes.

Ongoing research on the north Texas shelf is aimed specifically at examining the stratigraphic record for rapid, episodic sea-level events (Thomas and Anderson, 1988, Thomas, 1990; Anderson and Thomas, in press). This study focuses on the Trinity/Sabine valley system. High resolution seismic data from the incised valley system, integrated with lithologic data from piston cores, vibracores, and oil industry geotechnical boring descriptions, allow the mapping of estuarine and coastal systems that occupy the valley (Fig. 10). Sea-level stillstands are inferred from paired upper-bay marsh and tidal-inlet estuarine systems (Fig. 11). So far, three such systems, at -14 m, -20 m, and -29 m, have been defined seismically. Large sand bodies, associated with the tidal complexes, most likely were coeval shoreline deposits; however, the shoreline sands (used to recreate sea-level history in the Gulf of Mexico; Curray, 1960; Nelson and Bray, 1970; and Frazier, 1974) were reworked and moved landward. Rapid rises in sea level are manifested in the form of back-stepping parasequences (Fig. 11) which reflect times when fluvial/estuarine/marine systems transgressed tens of kilometers up valley along virtually flat surfaces. It was during these rapid rises that coastal barriers were overstepped to create offshore sand bodies.

The next step in this investigation will be to acquire cores from units that will provide radiometric dates for these sea-level events. But before these events can be accepted as global in scale, they must be correlated with records from similar studies in other parts of the world. An added bonus from such studies is that they provide a record of the impact that rapid sea-level changes have had on coasts and estuaries. Perhaps accurate dating of decoupling events in the Arctic or Antarctic will permit direct correlation of cause and effect. SeaRISE may provide such data.

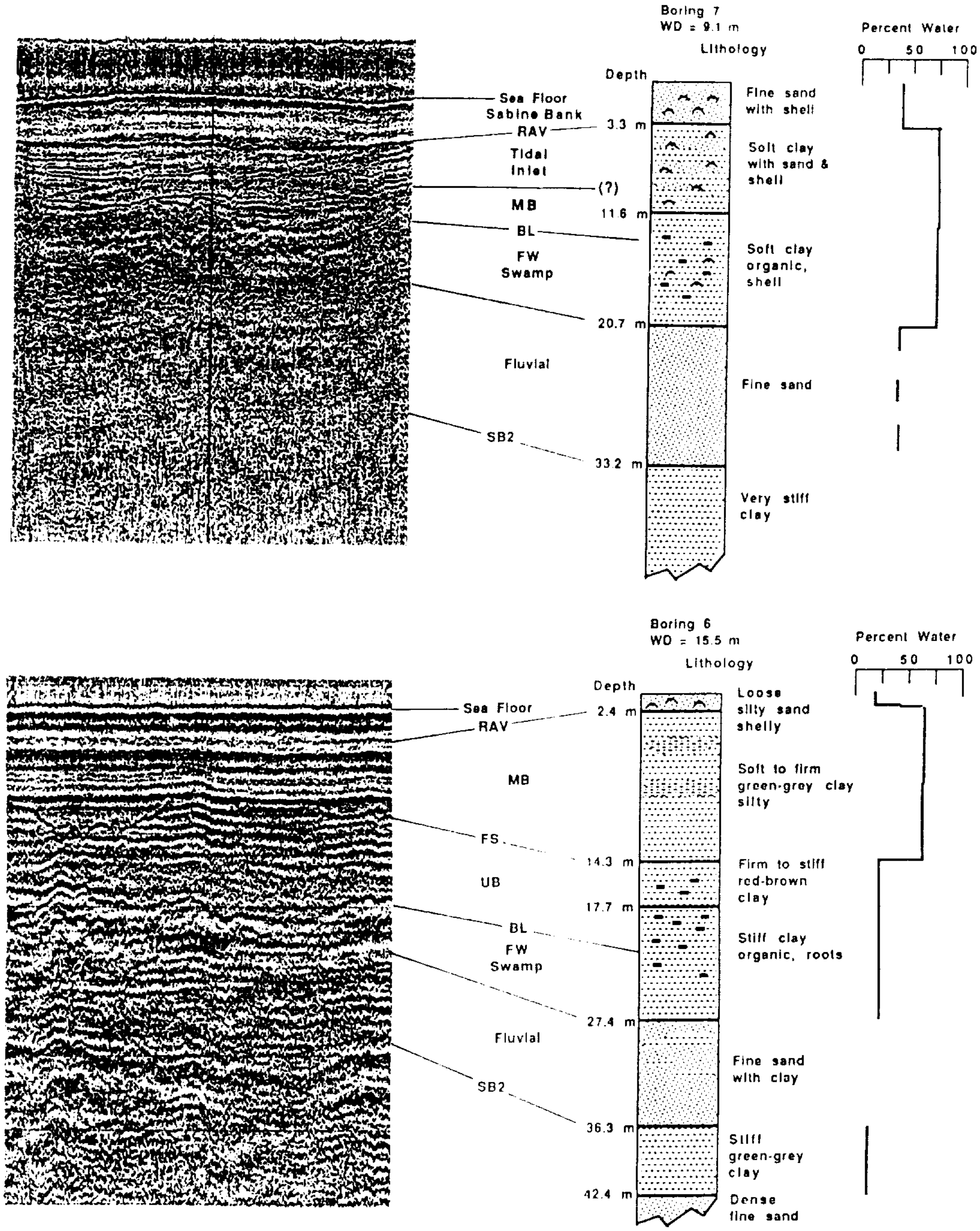

Figure 10. Example of associated seismic facies and lithofacies used to study the sea level record of the Trinity/Sabine incised valley. The interpreted seismic record at the top (a) shows a valley fill sequence formed during the slow rise/still stand of the past 2500 years. Note that fluvial deposits are overlain by estuarine deposits and these ,in turn, are overlain by tidal inlet/flood tidal delta deposits. The interpreted seismic record at the bottom (b) was acquired in the offshore Sabine Valley and within a segment of the valley where rapid flooding took place. This is indicated by the absence of tidal inlet/flood tidal delta facies and by seismic records collected up the valley axis and through the location of this profile that show a back-stepping parasequence boundary between the estuarine and marine deposits. WD = water depth; RAV = ravinement surface; MB = middle bay; FS = flooding surface; UB = upper bay; BL = bay line; FW Swamp = fresh water swamp; SB2 = sequence boundary 2.

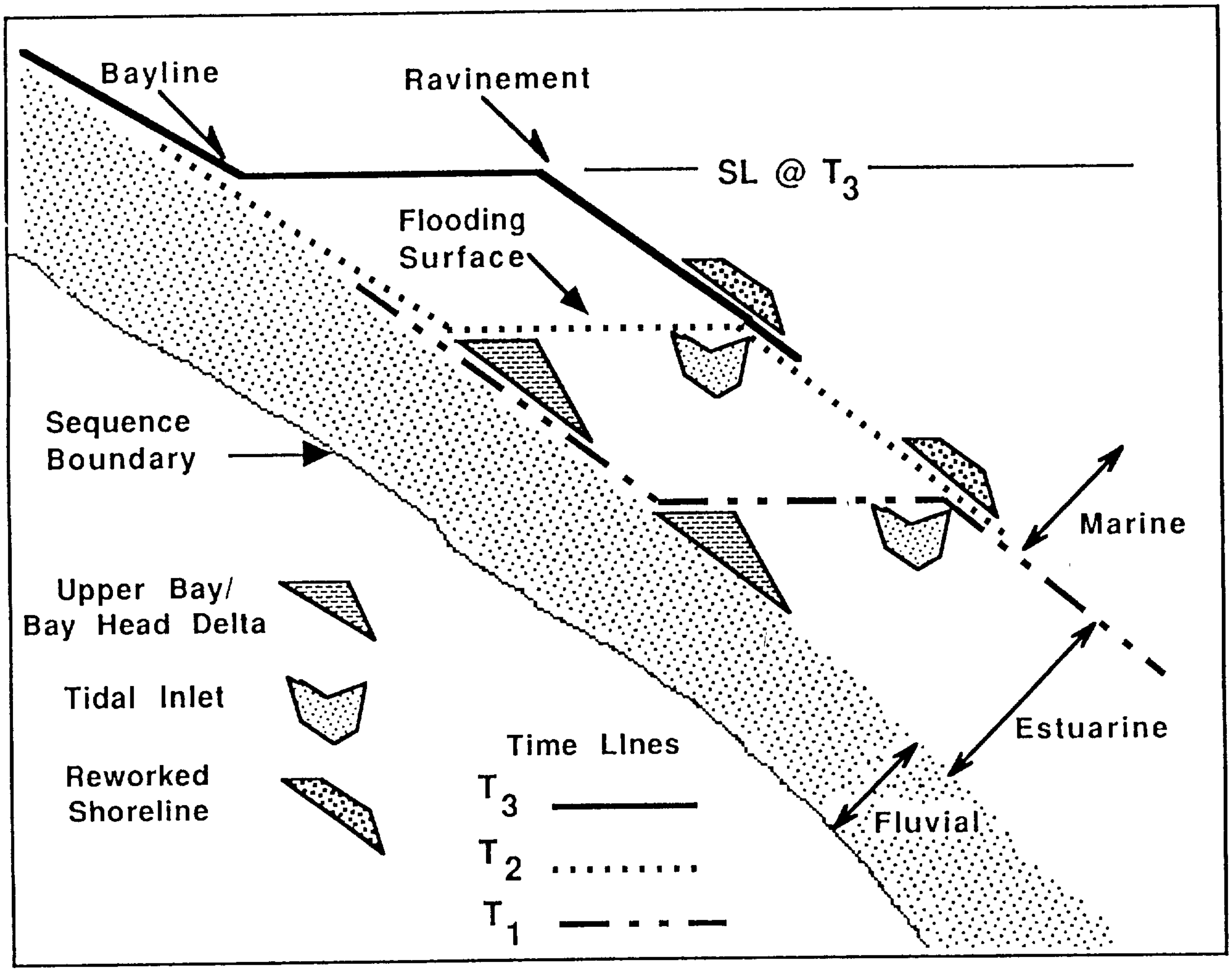

Figure 11. Model depicting the method used to measure sea level changes from high resolution seismic records (from Thomas, 1990). During still stands and slow rises, paired bay-head delta/flood tidal delta-tidal inlet facies develop. During rapid rises, these systems are overstepped and the flooding surface is manifested as a back-stepping parasequence boundary.

REFERENCES CITED

Alley, R.B., Blankenship, D.D., Rooney, S.T., and Bentley, C.R., 1989, Sedimentation beneath ice shelves-The view from ice stream B: Marine Geology, v. 85, p. 101-120.

Anderson, J.B., Domack, E.W., Kennedy, D., and Smith, M., in press, Sedimentary facies associated with Antarctica's floating ice masses: in Anderson, J.B. and Ashley, G.M., eds., Paleoclimatic Interpretation from Glacial Marine Deposits, Geological Society of America Special Publication.

Anderson, J.B, Kurtz, D.D., Domack, E.W., and Balshaw, K.M., 1980, Glacial and glacial marine sediments of the Antarctic continental shelf: Journal of Geology, v. 88, p. 399-414.

Anderson, J.B., Brake C., and Myers N., 1984, Sedimentation on the Ross Sea continental shelf, Antarctica: Marine Geology, v. 57, p. 295-333.

Anderson, J.B. and Thomas, M.A., in press, Marine ice sheet decoupling as a mechanism for rapid, episodic sea level change: the record of such events and their influence on sedimentation: Marine Geology.

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, 140p.

Bartek, L.R., 1989, Sedimentology and stratigraphy of McMurdo Sound and the Ross Sea: implications for Cenozoic glacial history and basin analysis of high latitude marginal basins: Unpublished Ph.D. Dissertation, Rice University, Houston, Texas, 416p.

Bartek, L.R. and Anderson, J.B., 1990, Interpretation of glacial marine deposits and the stratigraphic record of Antarctica's glacial, climatic, and oceanographic history: Problems, progress, and future needs: in Cooper, A.K. and Webb, P.N., eds., International Workshop on Antarctic Offshore Seismic Stratigraphy (ANTOSTRAT): Overview and Extended Abstracts, U.S. Geological Survey Open-File Report 90-309, p. 25-30.

Bartek, L.R. and Anderson, J.B., in press, Facies distribution resulting from sedimentation under polar interglacial climatic conditions within a high latitude marginal basin, McMurdo Sound, Antarctica: in Anderson, J.B. and Ashley, G.M., eds., Paleoclimatic Interpretation from Glacial Marine Deposits, Geological Society of America Special Publication.

Belknap, D.F. and Kraft, J.C., 1977, Holocene relative sea-level changes and coastal stratigraphic units on the northwest flank of the Baltimore Canyon Trough geosyncline: Journal of Sedimentary Petrology, v. 47, p. 610-629.

Belknap, D.F. and Kraft, J.C., 1981, Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic shelf: in Nittrouer, C.A., ed., Sedimentary Dynamics of Continental Shelves, Elsevier, Amsterdam, p. 429-442.

Bloom, A.L., 1970, Paludal stratigraphy of Truk Ponape and Kusaie, eastern Caroline Islands: Geological Society of America Bulletin, v. 81, p. 1895-1904.

Carter, R.M., Carter, L., and Johnson, D.P., 1986, Submerged shorelines in the SW Pacific: evidence for an episodic post-glacial transgression: Sedimentology, v. 33, p. 629-649.

Chappell, J. and Shackleton, N.J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137-140.

Chriss, T. and Frakes, L.A., 1972, Glacial marine sedimentation in the Ross Sea: in Adie, R.J., ed., Antarctic Geology and Geophysics, Commission on Antarctic Research, Oslo, p. 747-762.

Clark, J.A., and Lingle, C.S., 1979, Predicted sea-level changes (18,000 years b.p. to present) cuased by late glacial retreat of the Antarctic ice sheet: Quaternary Research, v. 11, p. 279-298.

Clark, J.A., Farrel, W.E., and Peltier, W.R., 1978, Global changes in postglacial sea level: a numerical calculation: Quaternary Research, v. 9, p. 265-287.

Curray, J.P., 1960, Sediments and history of the Holocene transgression, continental shelf, Northwest Gulf of Mexico: in Shepard, F.P., Phleger, F.B., and Van Andel, T.H., eds., Recent Sediments, Northwest Gulf of Mexico: American Association of Petroleum Geologists, Tulsa, Oklahoma, p. 221-266.

Curray, J. R., 1965, Late Quaternary history, continental shelves of the United States: in Wright, H.E. and Frey, D.E., eds., The Quaternary of the United States, Princeton University Press, Princeton, p. 723-735.

David, T.W.E. and Priestley, G.E., 1914, Glaciology, physiography, stratigraphy, and tectonic geology of South Victoria Land: British Antarctic Expedition, 1907-1909: Reports of the Scientific Investigations, Geology, 1.

Debenham, F., 1921, Recent and local deposits of McMurdo Sound region: Natural History Report, British Museum, British Antarctic Expedition, Geology, v. 1, p. 63-90.

Denton, G.H. and Hughes, T.J., 1981, The Last Great Ice Sheets, John Wiley and Sons, New York, 484p.

Domack, E.W., 1982, Sedimentology of glacial and glacial-marine deposits on the George V-Adelie continental shelf, East Antarctica: Boreas, v. 11, p. 79-97.

Domack, E.W., Anderson, J.B., and Kurtz, D.D., 1980, Clast shape as an indicator of transport and depositional mechanisms in glacial marine sediments: George V Continental Shelf, Antarctica: Journal of Sedimentary Petrology, v. 50, p. 813-820.

Domack, E.W. and Jull, A.J.T., in press, Holocene chronology for the unconsolidated sediments at Site 740A: Prydz Bay, East Antarctica: in Barron, J. and Larsen, B., eds., Proceedings of the Ocean Drilling Program, Scientific Results, College Station, Texas, v. 119B.

Domack, E.W., Jull, A.J.T., Anderson, J.B., Linick, T.W., and Williams, C.R., 1989, Application of tandem accelerator mass-spectrometer dating to late Pleistocene-Holocene sediments of the East Antarctic continental shelf: Quaternary Research, v. 31, p. 277-287.

Drewry, D.J., 1979, Late Wisconsin reconstruction for the Ross Sea region, Antarctica: Journal of Glaciology, v. 24, p. 231-244.

Drewry, D.J., 1983, Antarctica: Glaciological and Geophysical Folio, Scott Polar Research Institute, Cambridge.

Dunbar, R.B., Anderson, J.B., Domack, E.W., and Jacobs, S.S., 1985, Oceanographic influences on sedimentation along the Antarctic continental shelf: in Jacobs, S.S., ed., Oceanology of the Antarctic Continental Shelf, American Geophysical Union, Antarctic Research Series, v. 43, p. 291-312.

Edwards, B.D., Lee, H.J., Karl, H.A., Reimnitz, E., and Timothy, L.A., 1987, Geology and physical properties of Ross Sea, Antarctica, continental shelf sediment: in Cooper, A.K. and Davey, F.J., eds., The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 5B, p. 191-216.

Fairbanks, R.G., 1990, A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation: Nature, v. 342, p. 637-642.

Fairbridge, R.W., 1961, Eustatic changes in sea-level: Physics and Chemistry of the Earth, v. 5, p. 99-185.

Fillon, R. J., 1975, Late Cenozoic paleo-oceanography of the Ross Sea, Antarctica: Bulletin of the Geological Society of America, v. 86, p. 839-845.

Frazier, D.E., 1974, Depositional Episodes: their relationship to the Quaternary stratigraphic framework in the Northwest portion of the Gulf Basin: Texas Bureau of Economic Geology, Geological Circular 74-1, 28p.

King, L.H. and Fader, G.B.J., 1986, Wisconsinan glaciation of the Atlantic continental shelf of southeast Canada, Geological Society of Canada, Geological Survey Bulletin, 363, 72p.

Frazier, D.E., 1974, Depositional Episodes: their relationship to the Quaternary stratigraphic framework in the Northwest portion of the Gulf Basin: Texas Bureau of Economic Geology, Geological Circular 74-1, 28p.

Harwood, D.M., Scherer, R.P., and Webb, P-N., 1989, Multiple Miocene marine productivity events in West Antarctica as recorded in Upper Miocene sediments beneath the Ross Ice Shelf (Site J-9): Marine Micropaleontology, v. 15, p. 91-115.

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

Houtz, R.E. and Davey, F.J., 1973, Seismic profiler and sonobuoy measurements in the Ross Sea, Antarctica: Journal Geophysical Research, v. 78, p. 3448-3468.

Houtz, R.E. and Meijer, R., 1970, Structure of the Ross Sea shelf from profiler data: Journal of Geophysical Research, v. 75, p. 6592-6597.

Hughes, T., 1973, Is the West Antarctic Ice Sheet disintegrating?: Journal of Geophysical Research, v. 78, p. 7884-7910.

Hughes, T., 1977, West Antarctic ice Streams: Review of Geophysics and Space Physics, v. 15, p. 1-46.

Hughes, T.J., 1987, Deluge II and the continent of doom: rising sea level and collapsing Antarctic ice: Boreas, v. 16, p. 89-99.

Imbrie, J., Hays, J.D., Martinson, D., McIntyre, A., Mix, A., Morley, J., Pislas, N., Prell, W., and Shackleton, N.J., 1984, The orbital theory of Pleistocene climate: support from a revised chronology of the marine $d^{18}O$ record: in Berger, A.L. et al., eds., Milankovitch and Climate, Part I, p. 269-305.

Jacobs, S.S., Fairbanks, R.G., and Horibe, Y., 1985, Origin and evolution of water masses near the Antarctic continental margin: evidence from $H_2{}^{18}O/H_2{}^{16}O$ ratios in seawater: in Jacobs, S.S., ed., Oceanology of the Antarctic Continental Shelf, American Geophysical Union, Antarctic Research Series, v. 43, Washington, D.C., p. 59-86.

Jelgersma, S., 1961, Holocene sea-level changes in the Netherlands: Med. Geol. Stich., C-VI, 101 p.

Jelgersma, S., 1966, Sea-level changes during the last 10,000 years: Proceedings of the International Symposium on World Climates from 8000 B.C. to 0 B.C. Imperial College, London, Royal Meterological Society, p. 54-71.

Karl, H.A., Reimnitz, E., and Edwards, B.D., 1987, Extent and nature of Ross Sea Unconformity in the western Ross Sea, Antarctica: in Cooper, A.K. and Davey, F.J., eds., The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, 5B, p. 77-92.

Kellogg, D.E. and Kellogg, T.B., 1986, Diatom biostratigraphy of sediment cores from beneath the Ross Ice Shelf: Micropaleontology, v. 32, p. 74-94.

Kellogg, T.B. and Truesdale, R.S., 1979, Late Quaternary paleoecology and paleoclimatology of the Ross Sea: The diatom record: Marine Micropaleontology, v. 4, p. 137-158

Kellogg, T.B., Truesdale, R.S., and Osterman, L.E., 1979, Late Quaternary extent of the West Antarctic Ice Sheet: New evidence from Ross Sea cores: Geology, v. 7, 249-253.

Kendall, C.G.St. C. and Lerche, I., 1988, The rise and fall of eustasy: in Wilgus, C.K., Hastings, B.S., Kendell, C.G. St. C., Posamentier, H.W., Ross, C.A., and Van Wagoner J.C., eds., Sea-Level Changes: An Integrated Approach, Society of Econonic Paleontologists and Mineralogists Special Publication No. 42, Tulsa, p. 3-18.

Kennedy, D.S and Anderson, J.B., 1989, Quaternary glacial history of Marguerite Bay, Antarctic Peninsula: Quaternary Research, v. 31, p. 1-22.

Kidson, C., 1982, Sea level changes in the Holocene: Quaternary Science Reviews, v. 1, p. 121-151.
Kurtz, D.D. and Anderson, J.B., 1979, Recognition and sedimentologic description of recent debris flow deposits from the Ross and Weddell Seas, Antarctica: Journal of Sedimentary Petrology, v. 94, p. 1157-1170.
Ledford-Hoffman, P.A., DeMaster, D.J., and Nittrouer, C.A., 1986, Biogenic-silica accumulation in the Ross Sea and the importance of Antarctic continental-shelf deposits in the marine silica budget: Geochemica et Cosmochimica Acta, v. 50, p. 2099-2110.
Leventer, A. and Dunbar, R.B., 1988, Recent diatom record of McMurdo Sound, Antarctica: Implications for history of sea ice extent: Paleoceanography, v. 3, p. 259-274.
Mayewski, P.A., 1975, Glacial geology and late Cenozoic history of the Transantarctic Mountains, Antarctica: Institute of Polar Studies Report No. 56, 168p.
Milliman, J. D. and Emery, K. O., 1968, Sea levels during the past 35,000 years: Science, v. 162, p. 1121-1123.
Morner, N. A., 1969, The Late Quaternary history of the Kattegatt Sea and the Swedish west coast: Sveriges Geol. Under., C640, 487p.
Myers, N.C., 1982, Petrology of Ross Sea basal tills: Antarctic Journal of the United States, v. 17, p. 123-124.
Myers, N.A., 1982, Marine geology of the western Ross Sea: implications for Antarctic glacial history, Unpublished MA thesis, Rice University, Houston, Texas, 234 p.
Nelson, H.F. and Bray, E.E., 1970, Stratigraphy and history of the Holocene sediments in the Sabine-High Island area, Gulf of Mexico: in Morgan, J.P., ed., Deltaic Sedimentation Modern and Ancient: Society of Econonic Paleontologists and Mineralogists Special Publication No. 15, Tulsa, p. 48-77.
Peltier, W.R., 1980, Models of glacial isostacy and relative sea-level: in Bally et al., A.W., eds., Dynamics of Plate Interiors, Geodynamics Series, v. 1, American Geophysical Union, Washington, D.C., p. 111-128.
Penland, S., Suter, J.R., and McBride, R.A., 1988, Delta-plain development and sea level history in the Terrebonne coastal region, Louisiana: in S. Penland, S. and Suter, J.S., eds., Coastal and Shallow Marine Sedimentation on the Mississippi River Delta Plain and Chenier Plain: Society of Econonic Paleontologists and Mineralogists Field Trip No. 2 Guidebook, p. 2-23.
Penland, S, Suter, J.R., Boyd, R., and Williams, S.J., 1990, Effects of sea level rise on river delta coasts (abstract): American Association of Petroleum Geologists Bulletin, v. 74, p. 738.
Priestley, R.E., 1923, Physiography (Robertson Bay and Terra Nova Bay regions): British Antarctic (Terra Nova) Expedition, 1910-1913, Harrison and Sons, London.
Rehkemper, L.J., 1969, Sedimentology of Holocene estuarine deposits, Galveston Bay: in Lankford, R.R. and Rodgers, J.J.W., eds., Holocene Geology of the Galveston Bay Area, Houston Geological Society, p. 12 - 52.
Reid, D. E., 1989, Late Cenozoic glacial-marine, carbonate, and turbidite sedimentation in the northwestern Ross sea, Antarctica: Unpublished Master's Thesis, Rice University, Houston, Texas, 178p.
Ruddiman, W.F., 1987, Synthesis; the ocean/ice sheet record: in Ruddiman, W.F. and Wright, H.E., Jr., eds., North America and Adjacent Oceans During the Last Deglaciation, Decade of North American Geology, v. K-3, Geological Society of America, Boulder, p. 463 - 478.
Ruddiman, W.F. and Duplessy, J.-C., 1985, Conference on the last deglaciation; Timing and mechanism: Quaternary Research, v. 23, p. 1-17.

Savage, M.L. and Ciesielski, P.F., 1983, A revised history of glacial sedimentation in the Ross Sea region, in Oliver, R.L., James, P.R., and Jago, J.B., eds., Antarctic Earth Science, Australian Academy of Science, Canberra, p. 555-559.

Scott, R.F.,1905, The Voyage of the Discovery, Charles Scribner's Sons, 2 volumes, 556p and 508p.

Shennan, I., 1987, Global analysis and correlation of sea-level data: in Devoy, R.J.N., ed., Sea Surface Studies, a Global View, Croom Helm, New York, p. 197-232.

Shepard, F.P., 1931, Glacial troughs of the continental shelves: Journal of Geology, v. 39, p. 345-360.

Shepard, F. P., 1963, 35,000 years of sea level: in Clements, T., ed., Essays in Marine Geology, University of Southern California Press, Los Angeles, p. 1-10.

Stuiver, M., Denton, G.H., Hughes, T.J., and Fastook, J.L., 1981, History of the marine ice sheet in West Antarctica during the last glaciation: a working hypothesis: in Denton, G.H. and Hughes, T.J., eds., The Last Great Ice Sheets, Wiley, New York, p. 319-439.

Ters, M., 1973, Les variations du niveau marin depuis 10, 000 ans le long du littoral Atlantique Francais: in Le Quaternaire: geodynamique, stratigraphie et environment, travaux Francais recents, 9th Congres International de l'I.N.Q.U.A., Christchurch, New Zealand, p. 114-135.

Thomas, M.A., 1990, The impact of long-term and short-term sea level changes on the evolution of the Wisconsinan-Holocene Trinity-Sabine incised valley system, Texas continental shelf: Unpublished Ph.D. Dissertation, Rice University, Houston, Texas, 295p.

Thomas, M.A. and Anderson, J.B., 1988, The effect and mechanism of episodic sea level events: the record preserved in late Wisconsinan-Holocene incised valley-fill sequences: Transactions of the Gulf Coast Geological Societies, v. 38, p. 399-406.

Thomas, R. H. and Bentley, C.R., 1978, A model for Holocene retreat of the West Antarctic Ice Sheet: Quaternary Research, v. 10, p. 150-170.

Tooley, M.J., 1978, Sea level changes, North-West England during the Flandrian Stage, Clarendon Press, Oxford, 232p.

Truswell, E.M. and Drewry, D.J., 1984, Distribution and provenance of recycled palynomorphs in surficial sediments of the Ross Sea, Antarctica: Marine Geology, v. 59, p. 187-214.

Vanney, J.R., Falconer, R.K.H., and Johnson, G.L., 1981, Geomorphology of the Ross Sea and adjacent oceanic provinces: Marine Geology, v. 41, p. 73-102.

Whillans, I.M., 1976, Radio-echo layers and the recent stability of the West Antarctic ice sheet: Nature, v. 264, p. 152-155.

Wong, H.K. and Christoffel, D.A., 1981, A reconnaissance seismic survey of McMurdo sound and Terra Nova Bay, Ross Sea: in McGinnis, L.D., ed., Dry Valley Drilling Project, Antarctic Research Series 33, Washington, D.C., p. 37-62.