36. GENERAL SYNTHESIS, DEEP SEA DRILLING PROJECT LEG 28[1]

Dennis E. Hayes, Lamont Doherty Geological Observatory of Columbia University, Palisades, New York; also Department of Geological Sciences, Columbia University, New York, New York
and
Lawrence A. Frakes, Department of Earth Sciences, Monash University, Clayton, Victoria, Australia

ABSTRACT

A general summary and synthesis of the results of the first DSDP Antarctic drilling leg are presented as discussions of several subtopics. These include: (1) the oceanic crustal petrology, its age and magnetic properties; (2) the general lithology and biostratigraphy of two groups of sites, one exhibiting dominantly pelagic sedimentation and the other exhibiting a strong terrigenous influx of sediment; (3) initial ice rafting and the inception of Antarctic glaciation; (4) sediment accumulation rates, and unconformities and their relationship to paleocirculation; (5) paleooceanography and climate, and models for climatic deterioration; (6) the geologic, climatologic, and oceanographic evolution of the Southeast Indian Ocean during the Cenozoic; and (7) speculations regarding a model for climatic evolution of the Antarctic continent as related to processes of global tectonics, ocean and atmospheric circulation. Some important conclusions are that major continental glaciation began in Antarctica in the late Oligocene, about 25 m.y. ago. The climate gradually began deteriorating then and cool ocean waters gradually pushed further north until the end of the Miocene when a major glacial pulse occurred involving a rapid buildup and subsequent retreat of the Antarctic ice sheet. The diachronous distribution of facies boundaries and of the first ice-rafted detritus and the timing of a major erosional event on the Ross continental shelf all provide evidence in support of this generalized history. The inferred ages of the basalt basement and its petrology as sampled at four sites are in reasonably good agreement with the evolution predicted from studies of magnetic lineations and sea-floor spreading. Small quantities of gaseous hydrocarbons were encountered in three of the four holes drilled on the Ross continental shelf area. It is premature to attach any economic significance to the presence of the Ross Sea hydrocarbons. The results from Leg 28 have raised many new, important problems regarding theories of the Cenozoic geologic history of the Antarctic continent and its environs.

INTRODUCTION

Leg 28 was the first of five scheduled DSDP legs designed to investigate the long-term glacial and geologic history of the South Pole continent, and the associated climate, circulation, and ecology of its ocean environs. To date, four of the five legs (28, 29, 35, 36) have been completed and the fifth (Leg 40) cancelled because of logistics difficulties. As Leg 28 was the most successful in terms of numbers of high-latitude sites, it has taken on an element of greater importance, as the results from this leg have by default become a standard by which hypotheses of Antarctic Cenozoic history must be tested.

In a sense Leg 28 was a test of the operational feasibility of drilling in high latitudes under severe weather conditions and in an area where the iceberg threat was a constant concern. Additionally, several holes were planned for water depths of about 500 meters (the Ross continental shelf), much shallower than any previously successful attempts by DSDP. Both of the operational handicaps were overcome through careful planning, continual reconnaissance and surveillance, and a little good luck.

It is ironic that the operational and scientific successes recognized during Leg 28 led to arbitrary and more

[1]Lamont-Doherty Contribution No. 2197.

restrictive logistics requirements by the operators, a relaxation of attitudes regarding the importance of using an optimum season and weather window, and the reduction of time contingencies so necessary to insure success. Consequently the programs designed for Legs 35 and 36 were altered dramatically, and the potential for the important geographic comparison of results largely lost. It is likely that the results represented here will be the primary high latitude deep-sea drill sites (seven sites south of 60°S) available for attempting to unravel the Cenozoic history of the Antarctic continent.

The drilling vessel *Glomar Challenger* departed Fremantle, Australia, on 20 December 1972 and arrived in Christchurch, New Zealand, on 28 February 1973 after steaming 7400 n.m. and drilling 16 holes at 11 sites (see Figure 1).

A total of 5637 meters was penetrated, 3014 meters cored, and 1405 meters recovered (Table 1).

Aside from the broad objectives mentioned earlier, other specific objectives included:

1) Determination of age of the oceanic crust and pelagic sedimentation environment along a profile across the south flank of the Southeast Indian Ridge (Holes 265, 266, 267);

2) Comparison of the processes of continental margin sedimentation at widely separated locales (Holes 268, 269, 274);

3) Sampling of basement rocks in the central Ross Sea (Hole 270);

4) Determination of the age and nature of a widespread erosional surface near the sea floor over much of the Ross Sea shelf (Holes 270, 271, 272, 273);

5) Sampling of oceanic crust beneath the magnetically quiet zone in the Southeast Indian Basin; and

6) Determination of the nature of the crust underlying the Iselin Plateau.

Objectives 5 and 6 were not realized.

OCEANIC CRUSTAL PETROLOGY, MAGNETIC PROPERTIES, AND AGE

Oceanic basalt was recovered from four locations, Sites 265, 266, 267, situated along a north-south profile near 105°E, and at Site 274 near 175°E longitude. All sites are located on the Antarctic plate in areas where the pattern of Cenozoic sea-floor spreading lineations is well mapped and thus afford an opportunity to check the age of the crust as inferred from the paleomagnetic time scale of Heirtzler et al. (1968) with the paleontological age of the basal sediments at each site. In all cases, the basalt samples that were recovered were too badly weathered to be dated by radiometric techniques.

The basalts at Sites 265, 266, and 267, which are located on progressively older portions of the south flank of the Southeast Indian Ridge, have compositions that are generally typical of ocean-floor tholeiites, differing only slightly in their K_2O compositions (Ford, this volume). The basalt recovered at Site 274 differs significantly from the basalts recovered to the west and

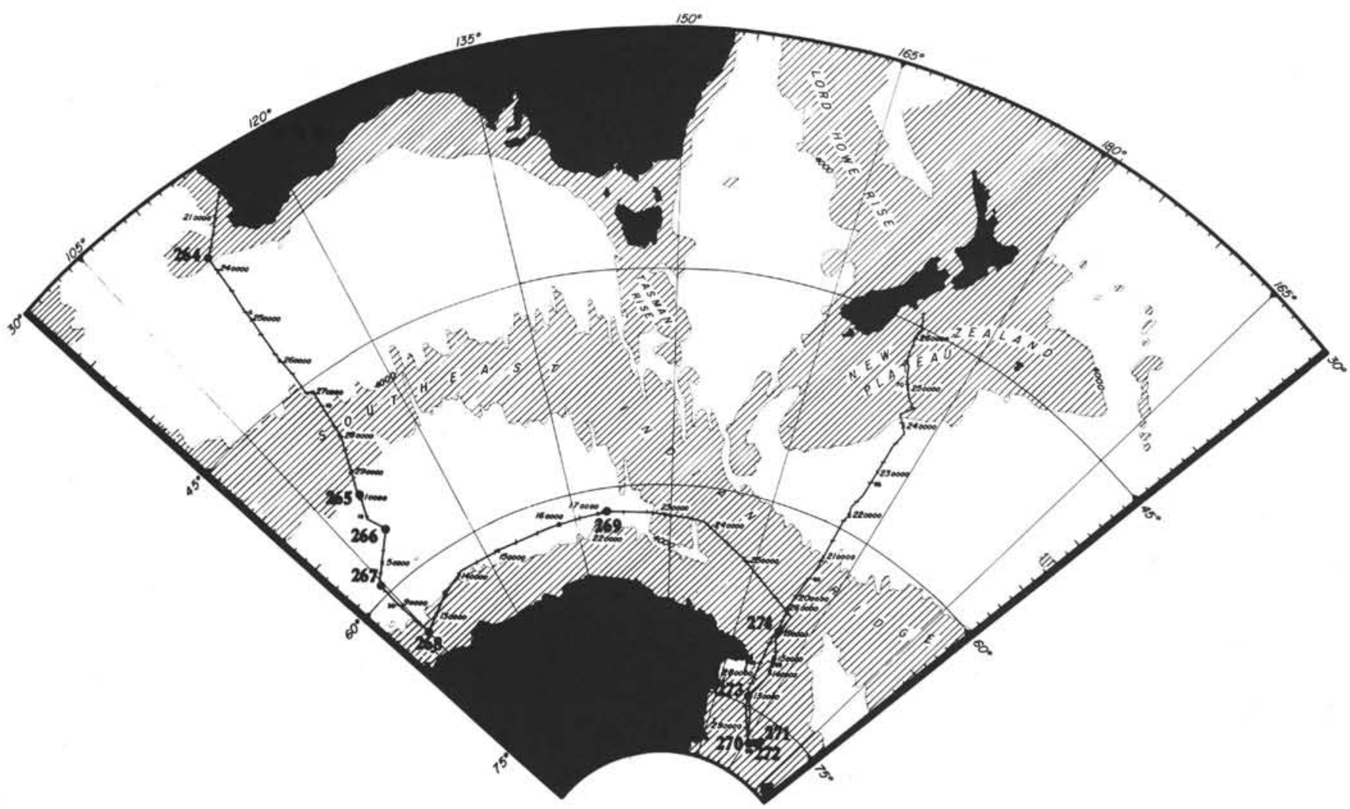

Figure 1. *Site locations and regional bathymetry (polar projection) depths <4000 meters shown shaded.*

TABLE 1
Leg 28 Coring Summary

Hole	Dates (1972 and 1973)	Latitude	Longitude	Water Depth (m)	Penetration (m)	No. of Cores	Cored (m)	Recovered (m)	Recovery (m)
264	22–23 Dec.	34°58.13'S	112°02.68'E	2873	215.5	15	142.5	65.2	46
264A	23 Dec.	34°58.13'S	112°02.68'E	2873	158.5	4	38.0	33.2	87
265	30–31 Dec.	53°32.45'S	109°56.74'E	3582	462.0	18	169.0	108.0	64
266	2– 4 Jan.	56°24.13'S	110°06.70'E	4173	384.0	24	219.5	145.2	66
267	6 Jan.	59°15.74'S	104°29.30'E	4564	219.5	7	58.0	25.9	45
267A	7 Jan.	59°15.74'S	104°29.30'E	4564	70.5	3	28.5	11.6	41
267B	7– 8 Jan.	59°14.55'S	104°29.94'E	4539	323.0	10	95.0	53.5	56
268	10–12 Jan.	63°56.99'S	105°09.34'E	3544	474.5	20	189.5	65.6	35
269	18 Jan.	61°40.57'S	140°04.21'E	4285	397.5	11	103.0	38.8	38
269A	19–21 Jan.	61°40.57'S	140°04.21'E	4285	958.0	13	123.5	55.4	45
270	30 Jan.–2 Feb.	77°26.48'S	178°30.19'W	634	422.5	49	422.5	263.7	62
271	3– 5 Feb.	76°43.27'S	175°02.86'W	554	265.0	24	233.0	15.3	7
272	6– 8 Feb.	77°07.62'S	176°45.61'W	629	443.0	48	439.0	162.0	37
273	10 Feb.	74°32.29'S	174°37.57'E	495	76.0	9	76.0	27.9	37
273A	11–13 Feb.	74°32.29'S	174°37.57'E	495	346.5	29	256.5	55.5	22
274	16–19 Feb.	68°59.81'S	173°25.64'E	3326	421.0	45	421.0	279.1	66
Total						329	3013.5	1404.9	47

from typical ocean-ridge basalts. Although the variations are not definitive, there is a suggestion that the Site 274 basalts may be formed in association with oceanic-island or seamount rocks, and the proximity of the volcanic Balleny Islands suggests a possible, and convenient genetic affinity (Ford, this volume).

It is likely that the close correspondence of stable magnetizations measured in basalt at Sites 265, 266, and 267 and the presence of large unstable remanent components at Site 274 taken with the contrasting petrologic types mentioned above indicate a different genesis for the basalt at Site 274 than elsewhere. The remanent intensities at Sites 265-267 are unusually low in comparison to values inferred from model studies of magnetic lineations (Lowrie and Hayes, this volume). The inclinations inferred from measured remanances were used to compute an "instantaneous VGP" which is consistent with the proposal that the Antarctic continent (plate) has been essentially fixed in its present latitudinal position for at least the last 40 m.y. (Lowrie and Hayes, this volume).

The age of the basalts as deduced from magnetic lineations and the age of the basal sediments are summarized in Table 2. There are no serious discrepancies between the ages of the sea floor inferred by the two methods. Unfortunately, the stratigraphic control is not adequate to provide any very useful calibration points to the Heirtzler et al. (1968) magnetic time scale. The only conclusion is that the age of the basal sediments is in reasonably good agreement with the ages deduced from magnetic lineations, thus indicating the lineations were correctly identified. The basal sediment ages tend to be slightly younger (as has generally been the case for other DSDP sites) and may either indicate small errors in the geomagnetic time scale or the failure of the basal sediments to precisely record the age of the underlying basalt. The latter is probably the case.

TABLE 2
Comparison Between Predicted Magnetic Anomaly Age and Age of Sediments Above Basement

Site	Magnetic Lineation Age (m.y.)	Basal Sediment Age (m.y.)	Remarks
265	12–14	12–14	(Based on 40 m extrapolated assumed accumulation rate of 15–20 m/m.y. below the mid/late Miocene boundary)
266	23.5–24	22+	(Based on 20 m extrapolated observed accumulation rate)
267A	41	38+	(Basal unconformity at nearby Hole 267B)
274	38–39	38–42	(Based on 10 m extrapolated observed accumulation rate)

LITHOLOGY AND BIOSTRATIGRAPHY

The sites drilled during Leg 28 fall conveniently into three sedimentary subgroups which lend themselves readily to a brief summary and synthesis:

1) Those sites situated in an environment dominated by pelagic sedimentary processes. They include Sites 265, 266, and 267. Although Site 268 does not fit into this category, it is the end member of a north-south profile of the above sites from near the crest of the Southeast Indian Ridge to the Wilkes Land continental margin and is briefly discussed in this subgroup.

2) Those sites situated in a deep-water continental margin environment which has been dominated or

profoundly influenced by terrigenous sedimentary processes. They include Sites 268, 269, and 274.

3) Those sites situated on the depressed Ross Sea continental shelf, whose sedimentary record most directly reflects the presence and fluctuations of the Ross Ice Shelf and the geologic (particularly tectonic) evolution on the periphery of the Ross Embayment. They include Sites 270, 271, 272, and 273.

The brief summaries presented here draw heavily on the more detailed analysis of these groups of sites by members of the Leg 28 scientific staff and other contributors, presented in this volume. Site 264, drilled on the Naturaliste Plateau in part as an equipment test, is not discussed specifically in this synthesis chapter.

Pelagic Sites

Sites 265 through 268 lie along a nearly north-south line that runs from the crestal region of the Southeast Indian Ridge to the lower continental rise of the Wilkes Land margin (see Figure 1). These sites provide an excellent opportunity to examine the temporal and spatial evolution of an area dominated by pelagic sedimentation. Furthermore, the sea-floor spreading history and the associated changes in the depth and location of these sites is well known (Weissel and Hayes, 1972) or reasonably inferred (Kemp et al., this volume). The area is unique in the sense that sea-floor spreading has been nearly in a north-south direction, and further that the Antarctic plate has essentially been fixed geographically throughout at least the Cenozoic. Hence, the primary variables involved in altering the sedimentary environment can be examined in terms of their latitudinal dependence which in turn can perhaps be related to other factors such as climate and ocean circulation. Present-day pelagic processes here are controlled by the surface distribution of pelagic organisms which depend on the somewhat complicated interaction of surface temperature, and oceanic and atmospheric circulation. A brief review of these factors, as well as the present distribution of sedimentary facies, is given in Kemp et al. (this volume) and Frakes and Kemp (1972a).

Figure 2, taken from Kemp et al. (this volume), illustrates the changes in the major sediment components as well as the stratigraphy and gross lithology. At each of the sites a down-hole transition from siliceous (diatomaceous) to calcareous (nannofossiliferous) sediments constitutes the most dramatic change observed. This transition is somewhat less obvious at Site 268, where the diluting influence of terrigenous components is much stronger. For each site (excluding Site 265) the first appearance of ice-rafted detritus occurs near, but generally slightly higher than, the change from dominantly calcareous to siliceous sediments.

After removing the known effects of depth changes associated with a spreading, cooling lithosphere, the position of an assumed vertical oceanographic boundary that separates calcareous deposits to the north from siliceous deposits to the south can be traced. The inference is that this carbonate/silica boundary migrated slowly northward from about 22 m.y. to 5.5 m.y. at a rate of 2-3 cm/yr and remained essentially fixed with respect to the position of the northward-migrating ridge crest. A rapid northward shift of this boundary occurred in the early Pliocene and may correspond to the birth of our modern Antarctic Convergence zone (Kemp et al., this volume).

The paleoclimatic interpretation of the diachronous biogenic facie boundary and the diachronous appearance of ice-rafted detritus indicate a gradual cooling of surface waters from the early Miocene. This gradual cooling, which no doubt was related to regional climatic deterioration and Antarctic continental glaciation, was eventually felt farther and farther north as the cooling persisted and progressed. The general lag in the appearance of ice-rafted detritus with respect to the biogenic facies change, and its confinement to the more southerly regions, suggests that there were no dramatic events in the cooling history until the early Pliocene, when both the zone of iceberg melting and the carbonate/silica facies boundary jumped abruptly northward.

Continental Margin Sites

Sites 268, 269, and 274 all lie in deep water on the continental rise of Antarctica with a separation of 70° of longitude from the Wilkes Land margin to the Victoria Land margin. Figure 3 shows the distribution of the main sedimentary components and the stratigraphy. Although detrital sediments are the dominant component at all sites, there are contrasts in the relative importance of turbidity current, contour current, pelagic, and ice-rafting processes between the three sites. These contrasts result from a variety of factors such as subtle differences in the tectonic and/or physiographic settings of the sites, the intensity and effectiveness of near bottom currents in transporting fine detritus, and the proximity of icebergs and ice-rafted detritus. The detailed analysis of these factors is given by Piper and Brisco (this volume), and only the briefest summary is repeated here in Table 3. Porcelaneous cherts are found in the Miocene and Oligocene sections of all the continental margin sites, as well as in the Miocene at Site 272 on the Ross continental shelf.

The importance of considering the distribution of ice-rafted debris in reconstructing the paleoclimatic history of the Antarctic region is clear, although the interpretation may not be. However, the dominant components of the enclosing clastic sediments, silt and clay, offer few obvious clues to climatic variation. These sediment types underlie the continental rise and fill the South Indian abyssal plain to the north in a great wedge probably exceeding 2 km in thickness in places (Houtz and Markl, 1972), and to a level about 1 km shallower than its counterpart north of the ridge axis. Their special significance lies in the fact that filling of this large basin has exceeded that of the other basins around Antarctica and is apparent from bathymetric maps of the Southern Ocean (see, for example, Heezen et al., 1972). Deposition has apparently been concentrated here, probably because continental erosion has been more extensive hand has acted over the large proximal sectors of the Antarctic continent.

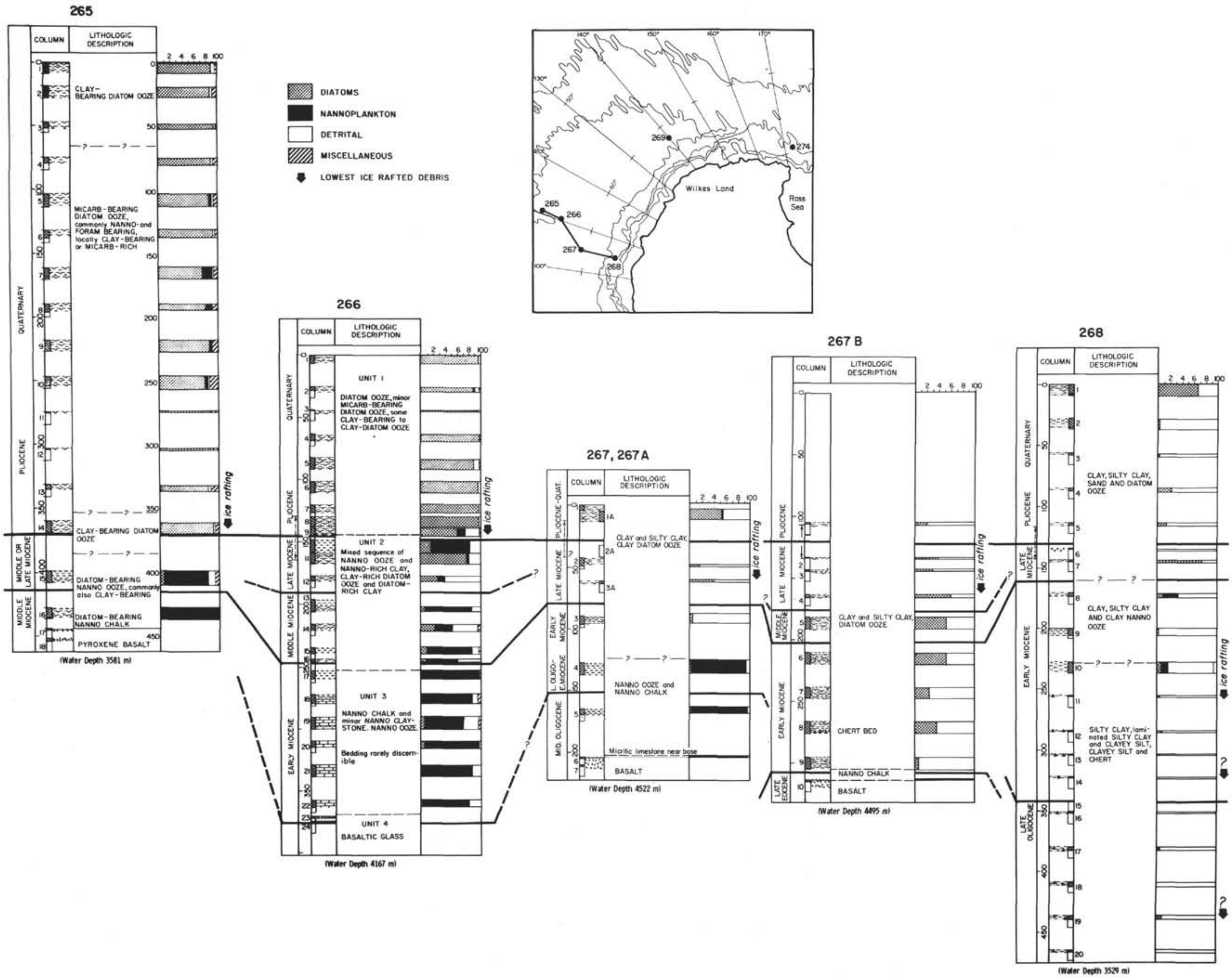

Figure 2. *Stratigraphic and sedimentologic record of Sites 265-268 (from Kemp et al., Chapter 34).*

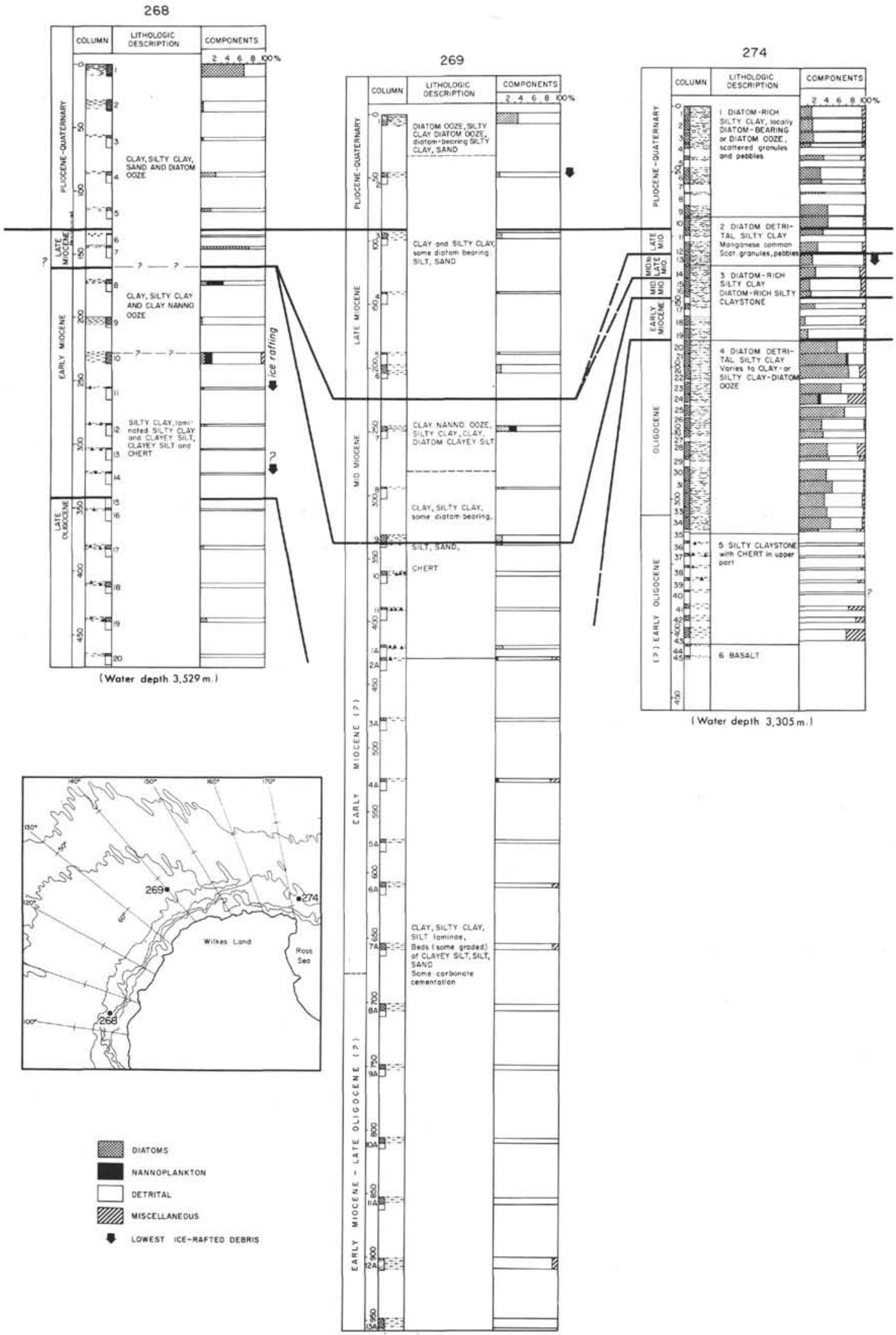

Figure 3. *Stratigraphic and sedimentologic record of Sites 268, 269, and 274 located along the Wilkes Land Continental Margin.*

TABLE 3
Summary of Continental Margin Sites

Site	Turbidites	Current Controlled Deposition (Contourites)	Pelagic Sediments	Ice-Rafted Detritus
268	Dominant in upper 160 meters (including slumped ice-rafted sediments)	Important in lower 250 meters	Calcareous nannofossils only in early Miocene	Generally common in early Miocene and younger, increasing in abundance uphole Provenance: Wilkes Land, East Antarctic
269	Dominant in entire section	Less important than at Site 268	Significant only in mid-Miocene and younger calcareous grading near shore to siliceous	Much less abundant than at Site 268
274	Largely protected upslope by structural barrier	During late Oligocene and middle Miocene to Pliocene evidence for vigorous bottom current activity	Higher proportional biogenic components than at 268 or 269	Common in late Miocene and younger, rare to lower Miocene Provenance: Marie Byrd Land, West Antarctica

There is a gradual decrease in abundance of silt and sand in laminae and beds from the continental rise through the proximal abyssal plain and into the distal abyssal plain (Payne and Conolly, 1972). In Leg 28 drill sites the amounts of silt and sand are small, and they occur primarily as laminae within an envelope of silty clay or claystone. Because of the general scarcity of coarse detritus in discrete beds, however, it is difficult to determine the dominant mode of deposition. Some of the coarse laminae no doubt originated through the action of turbidity currents; others seem to reflect deposition from contour currents. Further, the mechanism of transport for the predominantly silty clays cannot be positively ascertained. These may have been carried in the dilute tails of classical turbidity currents, particularly those laid down in the distal portion of the abyssal plain, or, more likely, they may have settled out from the well-developed nepheloid layers which are known to cross the area at present (Eittreim et al., 1972). All three transport mechanisms—turbidity currents, contour currents, and nepheloid layers—would seem to have contributed to the general decrease in grain size away from the continent, as well as the progradation of the continental margin.

Evidence of Cenozoic coastal tectonism is rare in materials of Leg 28 drill sites. Accumulation rates are high in the post-Miocene at all continental margin and near-coastal sites, and detritus becomes coarser upward at Sites 268 and 269, roughly during the Miocene-Pliocene interval (Piper and Brisco, this volume). An increased detrital flux in eastern holes may coincide with the interval of post-middle Miocene volcanism in the Ross Sea sector (Hamilton, 1972). However, all near-coastal drill sites are almost completely devoid of glass shards and other definite indicators of volcanic activity. At Site 274, beds and laminae of silt and coarser material are not apparent in strata younger than middle Miocene. This suggests that the large graben lying higher on the continental rise has served as a trap for any current-transported and land-derived coarse sediment since the middle Miocene. Normal faults of roughly north-northwest orientation on the continental rise and in the Ross Sea, if related to the graben, may have originated at this time as well, and middle Miocene may prove eventually to have been an important tectonic stage.

Ross Sea Continental Shelf Sites

Sites 270 through 272 lie in the southeastern quadrant of the Ross continental shelf and Site 273 lies in the west-central portion of the shelf. The continental shelf here is abnormally deep (~500 to 900 m) by a factor of 3 or 4 when compared with the global average. The relief of the shelf is characterized by linear swale and valley features trending roughly north-south (Hayes and Davey, this volume), which are closely related to both deposition and major erosion by an extensive (and sometimes grounded) Ross Ice Shelf. The inferred structural setting of these sites and summary lithostratigraphy is shown in Figure 4.

The Ross Sea glacial sediments consist of three main types: (1) silty clay (or lithified equivalent), (2) diatomaceous silty clay or silty and clayey diatom ooze (or lithified equivalent), and (3) mixtures of sand, silt, and clay. Subunits are defined almost solely on the degree of lithification.

Granules, pebbles, and cobbles are ubiquitous, but rarely form more than 2% of the sediment. The pebbles are mainly subangular and about 10% are striated; this represents a high proportion, even for continental till (Barrett, this volume). In overall texture the sediments are very poorly sorted, indicating relatively little bottom current activity. Stratification is poorly developed, and in some intervals, tens of meters of section seem to be unstratified. Where stratification can be seen, it is usually evident as faint color differences. In a few instances

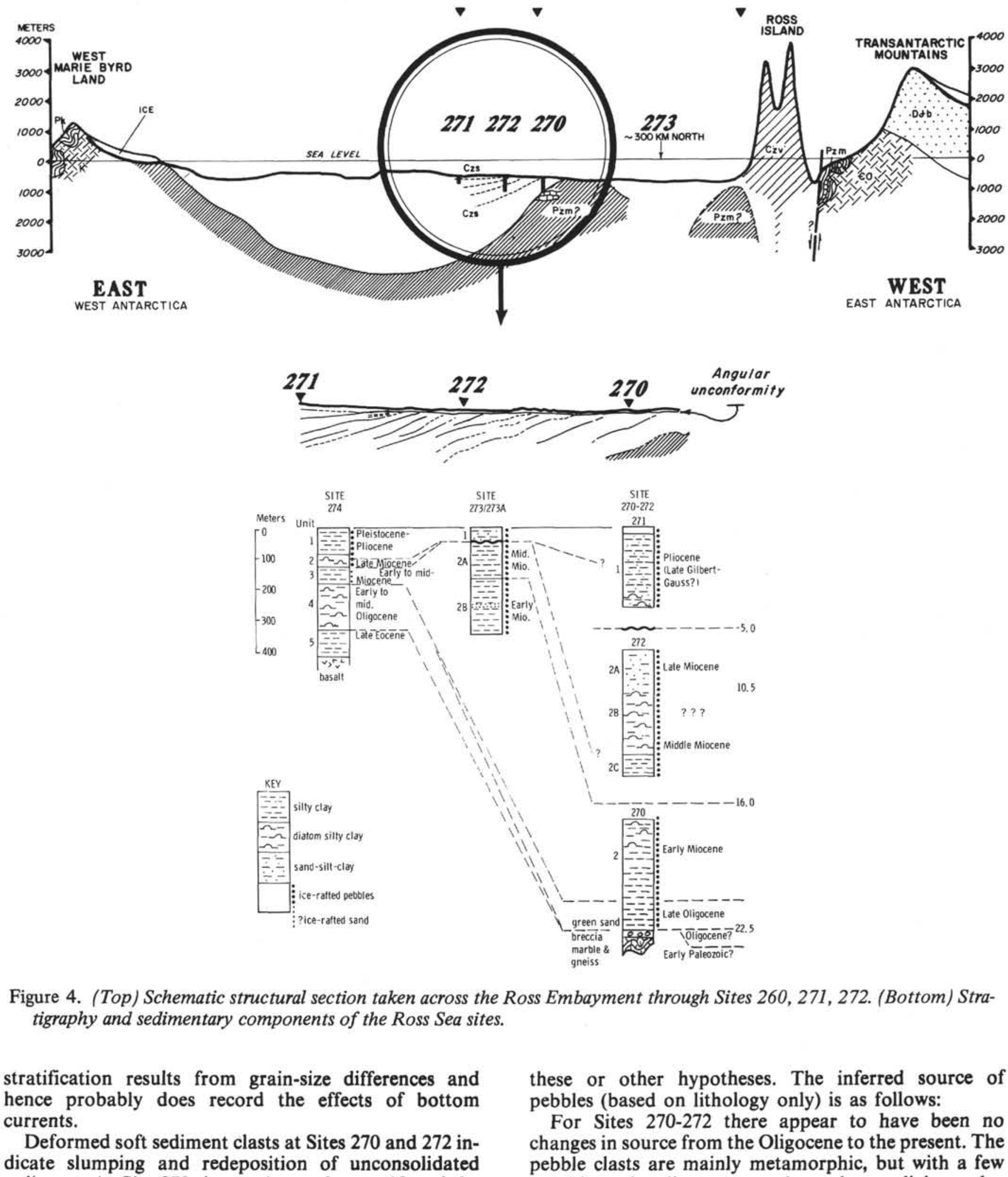

Figure 4. *(Top) Schematic structural section taken across the Ross Embayment through Sites 260, 271, 272. (Bottom) Stratigraphy and sedimentary components of the Ross Sea sites.*

stratification results from grain-size differences and hence probably does record the effects of bottom currents.

Deformed soft sediment clasts at Sites 270 and 272 indicate slumping and redeposition of unconsolidated sediment. At Site 270, in two intervals, one 10 and the other 23 meters thick, the sediments remained coherent as "packets" of strata and apparent dips range from 30° to 70°. The reason for this is unknown, but a possible cause is local oversteepening of the bottom. Another possibility is disturbance by grounded ice, but there is no direct or indirect evidence to discriminate between these or other hypotheses. The inferred source of pebbles (based on lithology only) is as follows:

For Sites 270-272 there appear to have been no changes in source from the Oligocene to the present. The pebble clasts are mainly metamorphic, but with a few granitic and sedimentary rocks and rare diabase also present late Cenozoic tills in the Transantarctic Mountains contain numerous diabase clasts; therefore, by default, the most likely pebble source for Sites 270-272 is southern Marie Byrd Land.

Site 273 contains a high proportion (28%) of diabase pebbles in the Miocene section in contrast to the Plio-

Pleistocene section (6%), indicating that there was much more ice from the Transantarctic Mountains passing over Site 273 in the Miocene. The source was probably from south of 77° where most of the diabase is found today. Presently most of the sediment from this region is dumped before it reaches the ice shelf edge. The change in source may simply represent a subtle change in the ice dynamics and surface circulation in the Ross Sea, or alternatively may reflect an increase elevation of the Transantarctic Mountains thus cutting off the supply of East Antarctic ice. Most of the ice in the Ross Ice Shelf today comes from the east and south in Marie Byrd Land. Perhaps the East Antarctic region supplied such an significant influx of ice that it contributed to the large buildup of ice in the Ross Embayment near the end of the Miocene.

Most terrigenous sediment in the Ross Sea shelf area was probably contributed by ice rafting. Sorting characteristics of these sediments are closely comparable with those of modern Ross Sea glacial marine sediments (Chriss and Frakes, 1972). Bottom currents in general seem not to have been very strong.

The presence of scattered benthonic foraminifers and molluscs indicates deposition under open glacial marine conditions as opposed to deposition beneath an ice shelf. A few of the molluscs have definitely been reworked, despite their frail appearance. The diatomaceous intervals most probably represent times of marine sedimentation with at least seasonally open seas.

ICE RAFTING AND THE BEGINNING OF ANTARCTIC GLACIATION

The question of the inception of sea-level glaciation can be addressed by considering the earliest occurrence of ice-rafted debris in marine sediments. The interpretation of such data, however, is complicated by the need to assess the importance of several factors which control the rates and geographic extent of ice rafting. These include: (1) the extent of both preglacial and glacial erosion on the continents; (2) the thermal structure of the glaciers; (3) the size of the glaciers and ice shelves and their total seaward flux; and (4) the near-surface (upper few hundred meters) seawater temperatures. The relative importance of theses and other factors in interpreting temporal and spatial variations in rates of ice-rafted sedimentation is controversial. For the Ross Sea shelf the first occurrence of ice-rafted debris is clearly in the latest Oligocene. The record of the *first* occurrence of ice-rafted debris at other Leg 28 sites is not so straightforward and although it is possible to make an unambiguous statement regarding the presence of this material, its absence is not so easily confirmed. Hence in this discussion the first occurrence of ice-rafted detritus should be taken as the *minimum* age of ice rafting at each site locale.

Figure 5 shows a plot of the age of the first occurrence of ice-rafted material as a function of inferred site latitude at the time the material was deposited. The identification of ice-rafted detritus was done in a variety of ways: e.g., the study of the sand size fraction of the sediments (Piper and Brisco, this volume); megascopic identification of pebbles (Barrett, this volume). All sites located on the Antarctic plate are assumed to have remained geographically fixed.

Even though the sites are from widely separated localities, and thus subject to differing local effects, an "envelope" crudely defines the latitudinal regions susceptible to ice rafting at various times in the late Cenozoic. The trend also suggests a situation where the ability of debris-laden icebergs to reach northward from the continent increased more or less gradually with time, implying a slow systematic decrease in the temperature of "surface waters" accompanied by an increasing quantity and dispersal of icebergs in a radial pattern away from the continent.

The northward migration of the biogenic facies boundary separating siliceous from calcareous microfossils is further, independent evidence of the systematic cooling of surface waters in a radial pattern with no dramatically abrupt changes occurring until near the Miocene/Pliocene boundary.

The only clear evidence of grounded ice in the Ross Sea and thus major continental glaciation is the deep water (500 m) erosional surface recorded over much of the continental shelf. About 800 meters of material may have been removed at Site 270 judging from the stratigraphy and degree of lithification. This, together with the extensive, glacially carved bottom topography of the Ross Sea (see Hayes and Davey, this volume) makes the argument for a much larger Ross Ice Shelf quite convincing. The glacial scouring appears not to have significantly affected Site 271. Sediment there continued to accumulate at more or less the same rate (~70 m/m.y.) from Pliocene to Recent. One of the deepest grounding lines of the extended early Pliocene Ross Ice Shelf apparently lay between Sites 270 and 272 and other grounding lines probably coincided with the major erosional valleys to the west including that near Site 273.

ACCUMULATION RATES

Accumulation rates for Leg 28 drill sites are shown schematically in Figure 6. The rate curves are useful for illustrating the most probable positions of unconformities, and for deciphering regional trends in sedimentation history. The curves are accordingly grouped into pelagic and continental margin categories; because of poor stratigraphic control the curves for the Ross Sea drill sites represent only very crude "best guesses."

Pelagic sedimentation on the south flank of the Southeast Indian Ridge has been quite variable during the post-late Eocene interval. This is most apparent from the extraordinarily high (>100 m/m.y.) post-mid-Pliocene accumulation rate at Site 265, and from the contrasts at nearby Holes 267, 267A, and 267B and the local unconformity of Oligocene age there. The unconformity at Hole 267 is best explained by localized erosion due to strong bottom currents. The thick sediment pile at Site 265 could perhaps results from loss of competence by surface currents of the West Wind Drift, which are seasonably diverted northward by the south-

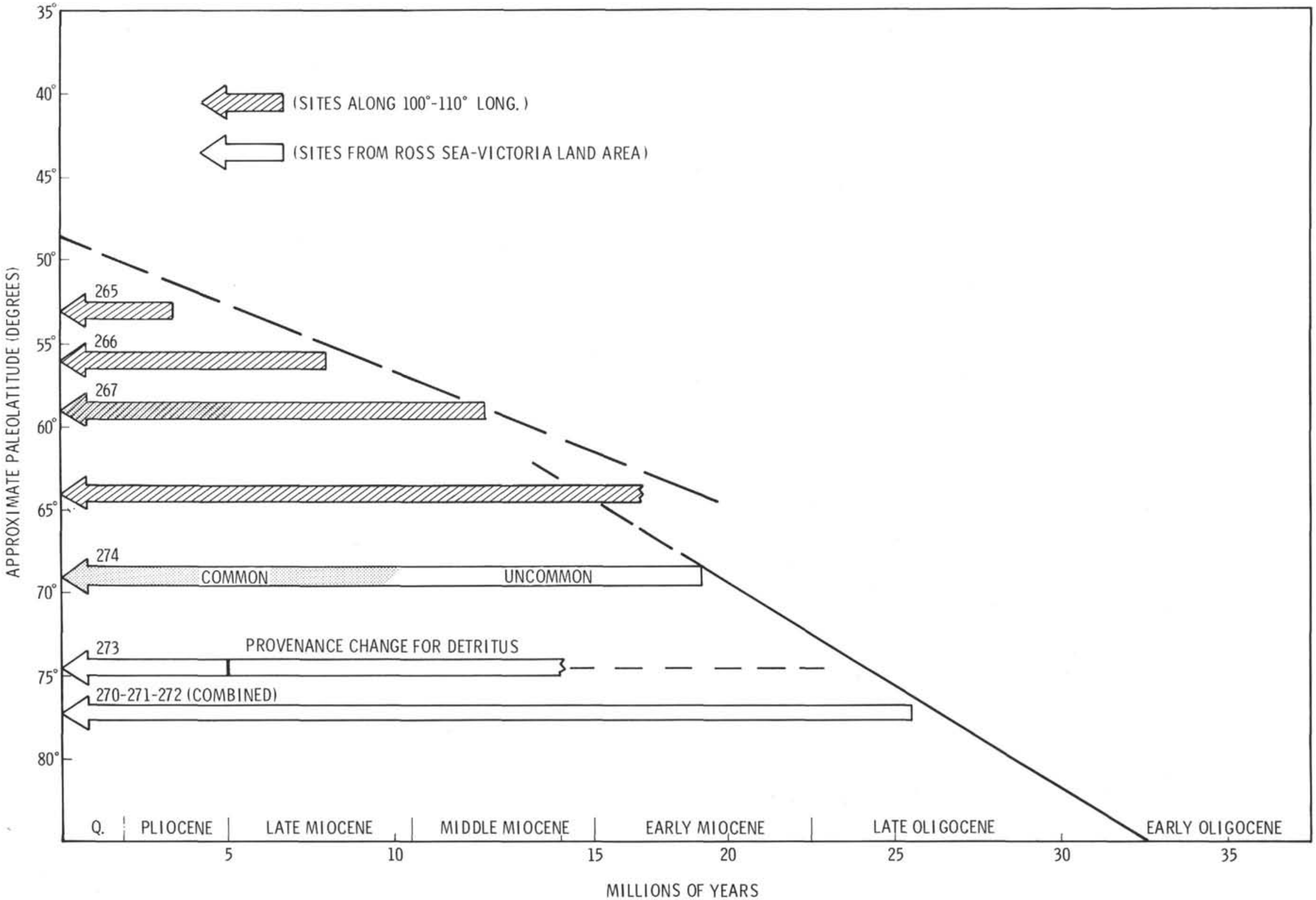

Figure 5. *Age of initial (first evidence) ice rafting as a function of site paleolatitude.*

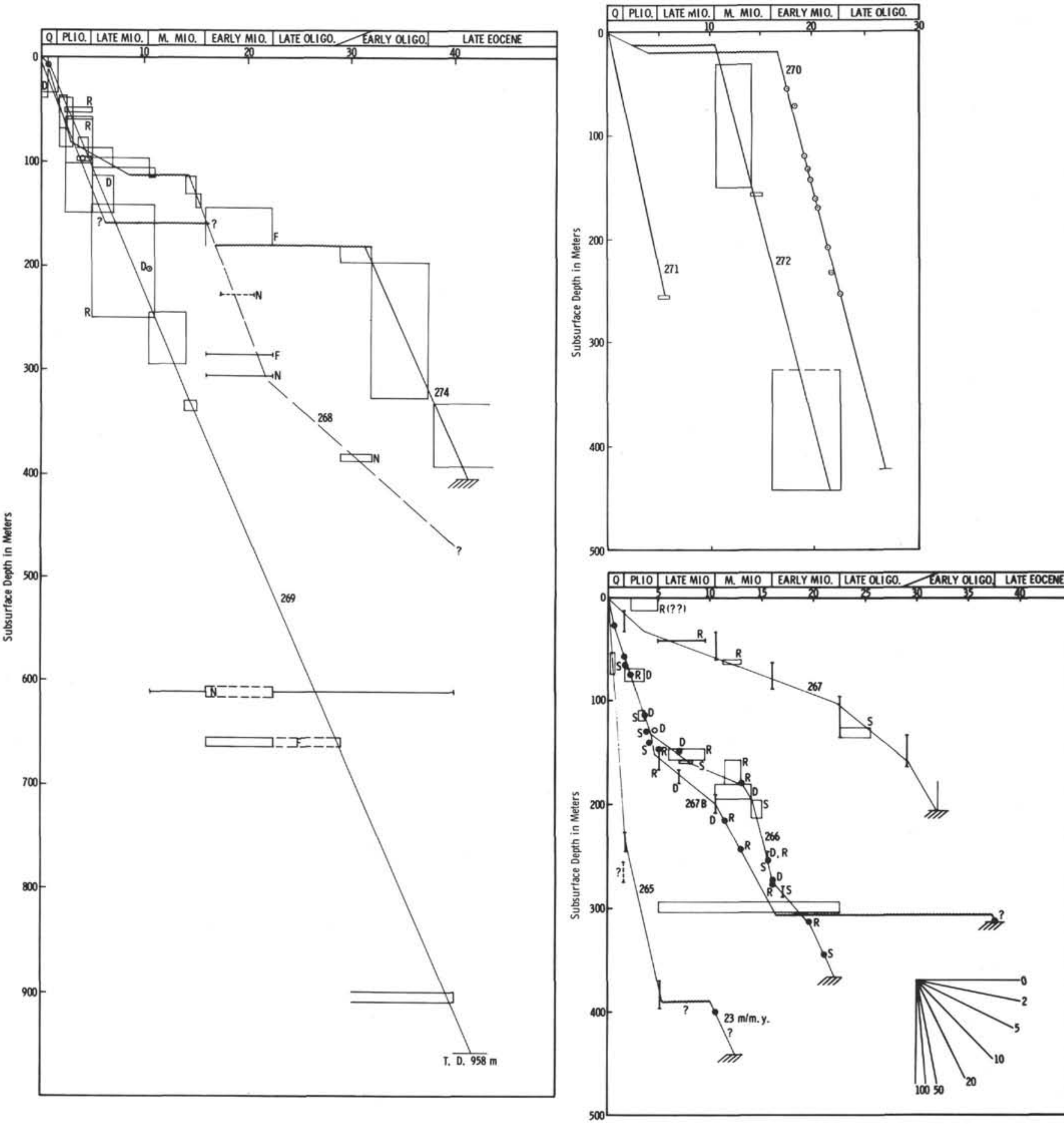

Figure 6. *Accumulation rates at Leg 28 sites. Time scale and zonal boundaries are from Figure 3 in Chapter 1 (Introduction) Letters refer to particular fossil group used in defining time horizon (radiolarian, diatom, silicoflagellate, foraminifer, nannofossil), except for Site 270, where paleomagnetic age datums were used (see Allis et al., this volume).*

western coast of Australia. Relatively low post-Miocene accumulation characterized the region lying only 500 km to the west, suggesting that these pelagic components have not been reaching the sea floor in abundance. The position of Site 265 high on the ridge flank makes it unlikely that transfer of sediment from the western region is affected by gravity-driven bottom currents. Although no oceanographic singularity (upwelling) is known which could explain by variations in microplankton productivity the marked increase in sedimentation rate at Site 265, this still seems to be the most plausible explanation.

The uninterrupted pelagic sequence at Site 266 can be thought of as displaying normal accumulation rates for the ridge flank. Here rates range from 14 to 53 m/m.y. for diatomaceous deposits and from 10 to 35 m/m.y. for calcareous types and compare well with rates estimated for both lithologies from post-Miocene piston cores taken in the region (10 to 40 m/m.y. and 20 to 30 m/m.y., respectively; Frakes, unpublished data). The close correspondence of post-early-Miocene rates in Hole 267B with those for Site 266 indicates that infilling of the basement valley at Hole 267B proceeded at normal rates without introduction of large amounts of material by mass-movement processes; that is, at an average rate of about 20 m/m.y. The very low rates (~10 m/m.y.) at nearby Holes 267, 267A, however, suggest that pelagic materials were removed from the topographically high areas and dispersed over a broad area into the lows, possibly through the action of local bottom currents, channeled by the topographic deeps.

The proportion of mud in the mixed lithologies at Site 266 is inversely related to sedimentation rate, indicating that the detrital material is derived primarily from settling through the water column rather than from classical turbidity currents. Site 266 has maintained a topographic position throughout its depositional history well above the abyssal plain to the south. This is not the situation for the continental rise holes, which show variable relationships between mud abundance and sedimentation rates, and which display evidence of deposition from turbidity currents and, possibly, nepheloid layers. Near-coastal drill sites are subject to variable influxes of terrigenous sediment from Antarctica and reflect this in high accumulation rates, generally exceeding 25 m/m.y. Unconformities, on the other hand, seem to be developed on the continental rise as well as on the ridge flank, and this possibly results from the more active tectonic setting of the continental margin and/or stronger bottom current activity in association with ice-generated, cold, bottom waters. Evidence of turbidity current activity is present, though not abundant, in the detrital portions of all continental rise holes, much of the fine sediment apparently having been transported either by nepheloid layers or by contour currents. Although the stratigraphic control at Site 269 is not precise, it is possible to satisfy the data by assuming a nearly constant accumulation rate of about 25 m/m.y. for the late Eocene to the present. If this is correct, it is a remarkable situation in view of the extremely variable accumulation rates at other rise sites, and by virtue of the fact that during this period the adjacent continental source area has experienced the entire spectrum of geologic conditions from cool-temperate, ice-free conditions, to fully glaciated conditions, including one major glacial pulse in the early Pliocene. One must assume that the processes of turbidite sedimentation are effective filters in masking the variations in sediment supply from the continent.

The importance of ice rafting in contributing to the total sediment column is thought to be relatively small, generally less than 10% of the total sediment being sand sized or larger (Piper and Brisco, this volume).

An interesting aspect of the continental rise holes is that accumulation rates for Sites 268, 269, and 274 are about the same for the post-Miocene interval (25-30 m/m.y.), although quite variable and generally lower in older strata. The low average Miocene rates at Sites 268 and 274 very likely reflect the presence of one or more unconformities. If widespread erosion took place along the Antarctic continental margin (probably during the late Miocene), it was probably confined to the continental rise, and thus did not affect accumulation at Site 269. This was followed by a period of relatively uniform accumulation along the continental margin between 105° and 170°E long. The establishment of these uniform rates may thus date the advent of a rather stable environment of sea level, shelf glaciation throughout this sector of Antarctica. The biostratigraphic control is inadequate to determine whether the observed stable sedimentation rates were established simultaneously at all sites, but major increases did occur at most sites 3 to 5 m.y. ago.

Accumulation rates for the Ross Sea drill sites are poorly determined. Although well over 75% of the gently dipping, truncated sequence was penetrated at Sites 270, 271, and 272, the undrilled gaps between sites and poor biostratigraphic control prevent a systematic analysis of sedimentation rates for the entire sequence. The 26.5-m.y. age of glauconitic sands beneath the ~1400 meters of glacial marine sequences inferred from the seismic records yield an average accumulation rate of 53 m/m.y. The actual mean sedimentation rate must be greater in view of the presence of at least one unconformity high in the section and the additional undrilled portions. Rates of ~40 m/m.y. and 75 m/m.y. can be calculated for the Miocene glacial marine sequence at Site 270 and for the complete sequence drilled at Site 271, respectively. At all sites with pertinent data, except Site 269, a major change in sedimentation rates is indicated in the early Pliocene. At the pelagic sites and continental margin sites the change is manifested as a relatively abrupt increase in rate (see Figure 7). At Sites 270, 272, and 273 on the continental shelf, the change is manifested as a dramatic decrease in rates to values of 6-8 m/m.y. concurrent values at Site 271, however, are extremely high, 71-88 m/m.y., and are probably related to sediment redistribution on the Ross Sea shelf by active bottom currents.

UNCONFORMITIES

At Leg 28 drill sites, several unconformities are evidenced by biostratigraphic discontinuities. A few of these unconformities are characterized by recognizable physical or lithologic contrasts as well, such as at Site 264. In most cases, however, the presence of a stratigraphic hiatus is inferred only by a very marked decrease in sedimentation rate, to such an extent that the rate is much less than expected for sediments of the lithologic type involved. The procedure adopted for defining unconformities was similar to that of Pimm and Hayes (1972). In general, sedimentation rates below about 2-3 m/m.y. are considered to represent effective unconformities, although the actual interval in question may be typified by uniformly slow deposition rather than nondeposition or erosion. Submarine erosion probably occurred in relation to all major unconformities but the biostratigraphic resolution is usually not

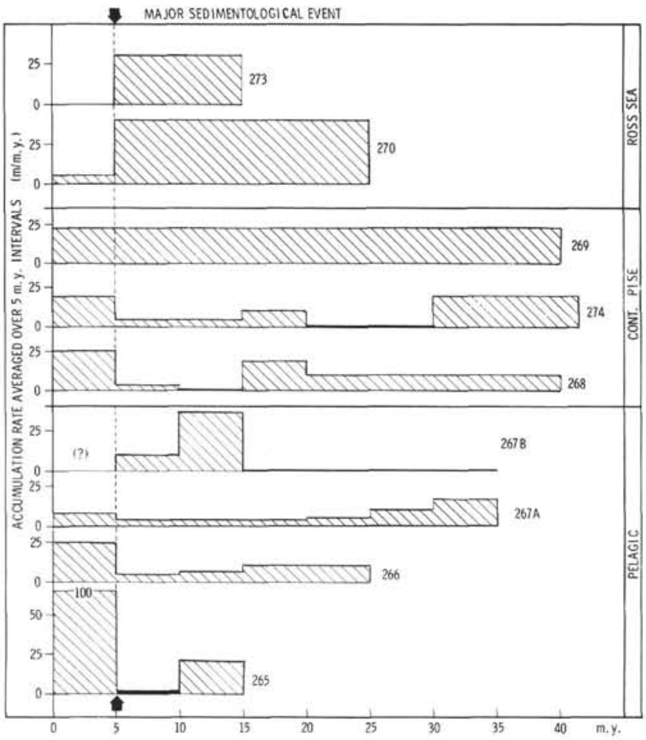

Figure 7. *Plot of average sedimentation rates over 5 m.y. intervals vs. time.*

sufficient to allow for the precise definition of any erosional surfaces. Some unconformities described here may thus be artifacts of insufficient paleontological information.

At Sites 265, 266, 267, which have dominantly pelagic sections, there is no evidence of regionally extensive unconformities analogous to the Oligocene hiatus of the Tasman Sea (Kennett et al., 1972; Hayes, Frakes, et al., 1973), at least throughout the post-middle Miocene interval (see Figure 8). A local unconformity, probably of early Miocene age, occurs between the two localities drilled at Site 267 but is not detected elsewhere. Although the missing Oligocene strata in Hole 267B may correspond to the hiatus of the Tasman Sea, the suggestion is that here, erosional processes were localized rather than regional in scope.

Hiatuses spanning parts of the Oligocene occur at Site 264 off southwestern Australia, and at Site 274 near the Ross Sea. At Site 264 upper Miocene or lower Pliocene directly overlies the upper Eocene, and at Site 274 all of the upper Oligocene is missing. Yet, there is no evidence of missing Oligocene in other Leg 28 continental margin holes; Site 268 contains an apparently uninterrupted lower Oligocene to lower Miocene sequence, and at Site 269 the simplest interpretation calls for an uninterrupted section from upper Eocene to Recent. In Leg 29 drill sites the observed Oligocene hiatus seems shortest at Site 282, west of Tasmania and there is no indication of an Oligocene gap at Site 278 in the Emerald Basin (Kennett, Houtz, et al., 1975).

These data suggest that although the Oligocene unconformity, or unconformities, of the Tasman region may extend to the Antarctic margin near Site 274, it is less well developed, and perhaps essentially absent slightly farther west. The main conclusion drawn is that even though middle Cenozoic circulation changes were regional, their manifestation as submarine erosion was not operative throughout the entire Southeast Indian Ocean but, rather, was restricted to the extreme western portion and probably included the Kerguelen Plateau (Kaharoeddin et al, 1973), the Naturaliste Plateau, the Wharton Basin, and the area east of Tasmania. The erosion recorded in these regions is best explained by localized intensification of bottom water circulation, no doubt related to increased production of bottom water in nearby polar regions and modulated by topographic sea-floor barriers that evolved in response to continuing sea-floor spreading (see e.g., Kennett et al., 1972; Kennett Houtz et al., 1975). It seems likely that the local effects of topographic barriers and regional contrasts in what may have been a general environment of increased bottom-water circulation have complicated the record of an extensive, regional intra-Oligocene unconformity presented by Kennett et al., 1972. The initiation in the late Oligocene of sea-level glaciation in the Ross Sea corresponds well in time with the early Miocene-middle Oligocene hiatus at Site 274 and may well have been the "driving force" for erosional bottom currents in the eastern sector of the rifted Ross Sea margin.

An angular unconformity of considerably paleoclimatological significance is seen in seismic profiles from the Ross Sea and was first recognized by Houtz and Davey (1973). The gently dipping sequence penetrated at Sites 270, 271, and 272 is seen to pass northward into a broad synclinal structure beyond Site 271. Within the syncline the apparently flat-lying strata which overlie the dipping sequence in the south become indistinguishable from older beds within the syncline; that is, angularity appears to be lacking on the unconformity. The syncline thus was the site of relatively rapid and nearly continuous sedimentation as reflected in the high sedimentation rates(~75 m.y.) observed at Site 271.

PALEOCLIMATES AND PALEOOCEANOGRAPHY

The study of Leg 28 litho- and biostratigraphy provides a broad basis for understanding Cenozoic climates in this polar regime, where changes have been extreme and of global significance. The Leg 28 drill sites cover a vast geographic region and, although widely scattered, allow refinements in reconstruction of climatically controlled oceanographic circulation patterns, as attempted earlier by Frakes and Kemp (1972b) and Kennett et al. (1972). Distribution and timing of climatic events, as revealed by study of sedimentary components, both terrigenous and biogenic, and in the near-shore and offshore environments, give a reasonably coherent picture of the evolution of circulation and climate south of Australia during the Neogene especially, and document further the known framework for the Paleogene.

The broad climatic history of Antarctica, as known from study of Neogene strata on and around the continent, has recently been reviewed by Hughes (1973). The review necessarily relies heavily on the chronology of events in the Ross Sea region (Denton et al., 1971) and

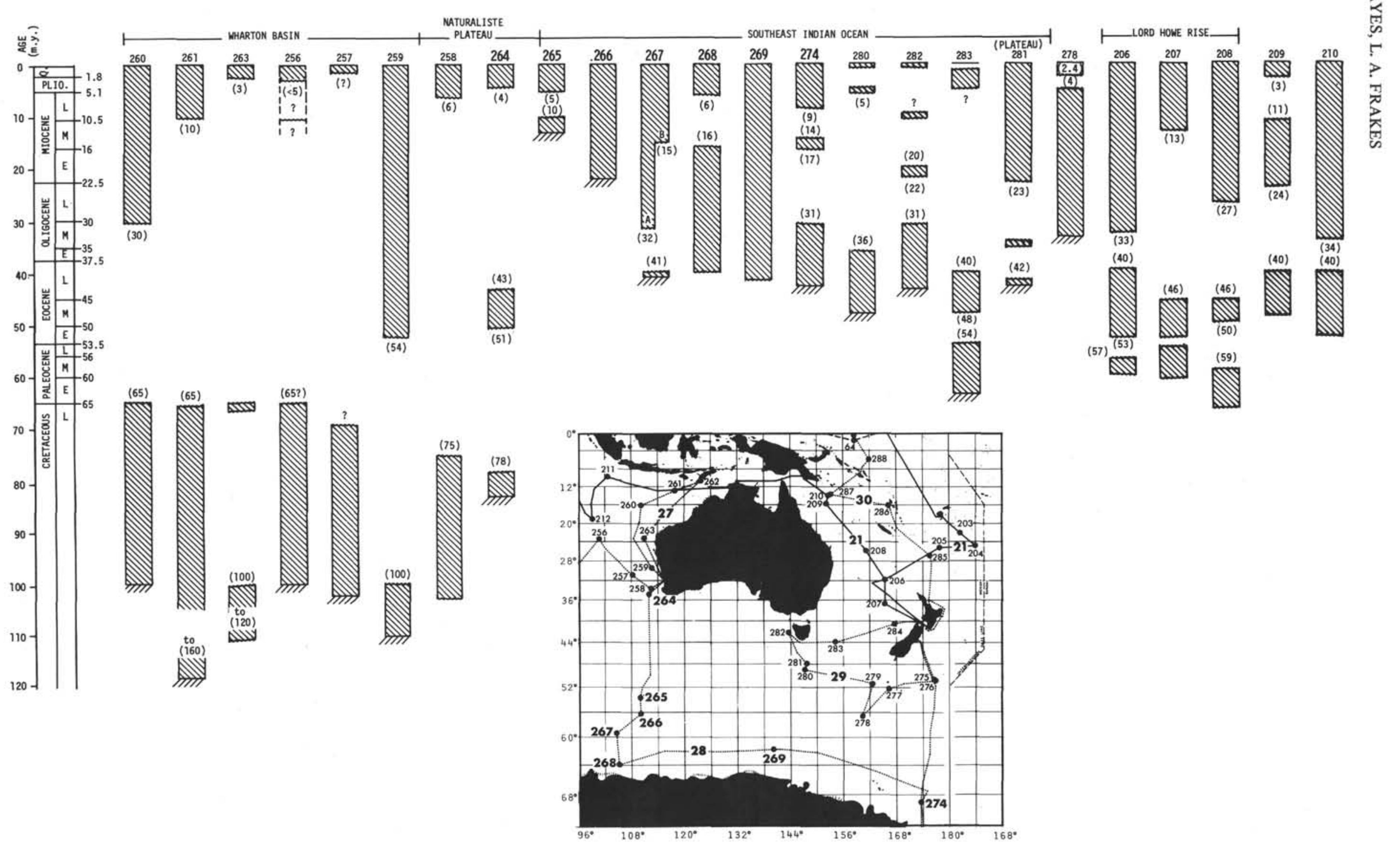

Figure 8. *Time span inferred sedimentary hiatuses recorded in the Southeast Indian Ocean and environs.*

in the Weddell Sea, which may have had considerably different histories (Anderson, 1972). The Paleogene record is understandably less clear, although significant changes have been recognized (Kemp, 1972). Major late Cenozoic ice advances in the Ross Sea sector occurred prior to 3.7 m.y. as well as more recently (Denton et al., 1971). The ice conditions prior to the earliest of these advances is largely unknown, except that a still earlier but undated advance must have sculptured the glacial form of the Dry Valleys of Victoria Land. Data from the Leg 28 drill sites indicate a lengthy history of glaciation in the Ross Sea region extending uninterruptedly back to the late Oligocene.

Marine sediment data, primarily from piston cores taken in the region of the Southeast Indian Ocean, are contradictory concerning pre-Oligocene climatic conditions, relative warmth being suggested by silicoflagellates (Mandra and Mandra, 1971) and by plant fossils derived from the continent (Kemp, 1972), and relative cold by ice-rafted quartz and diversity in foraminifera (Margolis and Kennett, 1971). Similarly, the middle Cenozoic gives evidence of cold conditions in some places but not in others (Weaver, 1973; Kennett and Brunner, 1973); the best evidence from piston cores seems to suggest a marked cooling beginning about 4 m.y. ago, but no doubt reflects the late Miocene/early Pliocene "glacial pulse."

Near-Shore Environments

The change from glauconitic sand to glacial marine deposits recorded at Site 270 marks a change from relatively shallow water deposition with no indication of cold conditions, to an environment characterized by melting of icebergs, or possibly a thin ice shelf. The water depth increased as well, as a result of the regional loading of the continent or local tectonic depression of the Ross Sea shelf. Judging from the K-Ar date for the glauconite (McDougall, personal communication), and the apparent lack of an unconformity below the glacial marine sediments, it is likely that sea-level glaciation in the Ross Sea region began in the late Oligocene. It is not possible to determine whether glaciation was in the form of a regionally connected body of ice, an ice shelf, or alternatively, several outlet glaciers separated by snowfields or bare rock and soil. Lithologic similarity of the Neogene glacial marine sequence at Sites 270-273 to the modern glacials deposits of the Ross and Weddell seas (Chriss and Frakes, 1972; Anderson, 1972) suggests that processes similar to those around modern ice shelves have been operative in the Ross Sea since the late Oligocene. However, palynomorphs of middle to late Oligocene age from near the base of the glacial sequence at Site 270 indicate that a flora existed in the region, so that ice probably did not completely cover the adjacent continental area. The occasional presence of fine and coarse stratification in the deposits is taken to indicate sorting action by bottom currents. It is expected that thermohaline interaction of seawater with the underside of ice shelves increases the vigor of the shelf circulation and probably increases the production of Antarctic bottom water, (Jacobs et al., 1970; Gordon, 1971).

Although the complete extent or nature of the ice in the Ross Sea during the post-Oligocene cannot be determined from Leg 28 materials, they do indicate clearly that ice rafting has been operative and important throughout the interval. Extensive oxidation, which probably accompanied reworking by bottom currents, is evident in high Fe and Mn concentrations in the post-Miocene of Sites 271 and 273, and possibly in the middle Miocene at Site 273 (Frakes, this volume). The top of the dipping sequence seen on seismic profiles was truncated by an extreme advance of the grounded ice shelf, which extended well north of Sites 270-272, perhaps as far as the present shelf break. When the ice retreated, probably beginning in the early Pliocene, reworking of the post-Miocene sediments took place. Oxidation of the middle Miocene strata may mark the beginning of especially active bottom currents as described above. This is also suggested by other changes in sedimentation at Site 274 (Frakes, this volume).

In the Ross Sea, most ice-rafted pebbles were derived from a metasedimentary and granitic terrane and positioned in Marie Byrd Land, West Antarctica. The ice shelf in its early history thus seems to have been built primarily from West Antarctic ice. Some contribution from East Antarctica is evident in abundant diabase pebbles, probably from the Transantarctic Mountains, concentrated in the Miocene sediments at Site 273, although the post-Miocene sequence again suggests a dominantly West Antarctic influence. The significance of this apparent change in pebble provenance is uncertain, but the implication is that ice from the East Antarctic plateau was able to reach the western Ross Sea in greater proportion during the Miocene than the Pliocene. Perhaps the Miocene buildup of shelf ice from contributions from the East Antarctic plateau was causally related to the rapid expansion of the entire ice shelf near the end of the Miocene or beginning of the Pliocene.

Among the near coastal holes, Site 274 offers the best information bearing on paleoclimates of the continent, and paleooceanography, and its proximity to the Ross Sea allows comparison of shallow versus deep-water sedimentation (Frakes, this volume). Three events appear most significant: (1) late Oligocene/early Miocene deep erosion by bottom currents to form an early Miocene to early Oligocene unconformity; (2) middle to late Miocene decrease in accumulation rate, probably reflecting active bottom currents; (3) Pliocene-Pleistocene increase in accumulation rate and strong decrease in activity of bottom currents.

Although ice rafting at Site 274 began as early as early Miocene, the most intense rafting took place in the interval between the middle Miocene and the early Pleistocene. It is hazardous to simply relate abundance of ice-rafted grains to paleotemperature (Warnke, 1970) and little can conclusively be said about specific climatic conditions. However, some deductions can be made about paleooceanographic conditions, based on evidence of bottom current activity, and these can be used to infer additional elements of the climate. Assuming that active bottom currents are one result of ocean interaction with extensive ice shelves or large outlet glaciers, the events described at Site 274 lead to the following tentative conclusions about the climatic/oceanographic conditions in the Ross Sea. First, sea-level ice must have been well developed throughout much of the Ross Sea by the early Miocene to allow rafting of debris to this distal site at that time. This conclusion is supported by evidence of erosion by bottom currents. These currents were probably operative at Site 274 some time after the middle Oligocene. Furthermore, the conspicuous bottom current activity at Site 274 recorded in the middle Miocene section suggests the growth of an extensive ice shelf in the Ross Sea by this time. Second, increased sedimentation at Site 274 beginning in the early Pliocene may reflect abundant icebergs derived from an overextended ice shelf. Third, the advent of conditions approximating present ones about 3.5 m.y. ago, suggests retreat of the ice shelf to its modern position by that time.

The other near-shore holes (Sites 268 and 269) reveal less about climatic and oceanographic conditions because of the overwhelming influence of detrital sedimentation there. Also, whereas Site 274 and the Ross Sea holes are related to ice conditions in the Western Ross Ice Shelf drainage system as defined by Giovinetto (1964), Site 269 lies offshore from the drainage system of the Adelie Coast ice and Site 268 offshore from that of the Wilkes Land ice. Thus, the sites might all be expected to record somewhat differing histories.

Ice rafting at Site 268 apparently began in the early Miocene, not long after deposition of the youngest silty clays which later became porcelaneous cherts. Both factors suggest an interval of ice expansion to the sea. Although other ice provenances are possible (some present day icebergs drift to the west [Tcherina, 1974]), the Shackleton Ice Shelf, lying nearby to the west seems to represent a likely source area. Erosion which carved the unconformity between middle and late Miocene strata may have followed soon after. Wilkes Land ice probably reaches the sea at a slightly later time than the ice in the Ross Sea region, with iceberg calving beginning in the early Miocene, and bottom currents generated in connection with bottom freezing of a limited ice shelf or tongue at about that time.

At Site 269, ice rafting is only recognized with difficulty in pre-Pliocene cores and further work utilizing the SEM is necessary before a complete rafting history is known. For the moment, it appears that rafting, as well as erosion by bottom currents, was not as extensive here as to the east or west. Development of sea-level glaciers in the Adelie Coast ice drainage system may therefore have occurred only in recent times, and indeed, at present this coast is characterized by only small ice shelves and glaciers at sea level. The effect of long-range circumpolar ice transport from other continental sectors is thought to be relatively unimportant.

Offshore Environments

The transect across the south flank of the Southeast Indian Ridge (Sites 265, 266, 267, and 268) demonstrates that pelagic sedimentation here has consisted of the accumulation of the remains of dominantly siliceous organisms at some times and places, and of dominantly calcareous ones at others. Detrital materials typified by mud are most common in the abyssal plain and the lower reaches of the ridge flank. In terms of paleoclimates the dichotomy between deep-water calcareous and siliceous forms is most important, since the accumulation of the former as oozes presently is restricted to latitudes north of the Antarctic Convergence and the latter occur in significant quantities only to the south. This results largely from the distribution of near-surface water temperatures which act as a control on microorganisms. This is documented as an environmental (ecologic) rather than dissolution factor by a sharp increase in the abundance of amorphous silica in surface waters south of Australia (Lisitzin, 1971a). The increase takes place over a broad band of about 10° latitude and straddles the Antarctic Convergence. A compensatory poleward decrease in calcium carbonate in surface-suspended matter appears to take place over the same latitudinal belt (Lisitzin, 1971b). Surface sediment distributions reflect these productivity trends but with modifications due to carbonate dissolution factors and current patterns (Lisitzin, 1971a, 1971b; Conolly and Payne, 1972; Frakes, in press).

Among the calcareous oozes presently being deposited south of Australia, the most common type is mixed, containing both nannofossils and foraminifera (e.g., see Frakes, 1973). However, in older portions of Leg 28 sites (265-268 inclusive) and in Site 278, Leg 29, the calcareous oozes are composed primarily of nannofossils. There are two obvious ways to explain this distribution: (1) foraminifera were not common in the region until perhaps 5 m.y. B.P., either because of the existence of an inhospitable environment or the presence of a hydrographic barrier to migration, or (2) the more readily dissolved foraminifera have been removed during settling or while accumulating on the sea floor. Current studies of foraminifera surface textures may resolve this important problem.

Microfossil assemblages from the ridge transect can be used in a general way to specify paleoenvironments. Thus, the occurrence of calcareous oozes is taken to indicate relatively warm surface waters while the occurrence of siliceous oozes reflect relatively cool conditions. At present, individual species or genera cannot be used confidently in defining temperature conditions except in the case of the discoasters. These warm-water nannofossils occur throughout the calcareous portions of Sites 265 and 266 but disappear in the Pliocene. For Site 266, this seems to happen in the earliest Pliocene and at 265, in about the middle of the epoch. Calcareous units at Sites 267 and 268 are entirely of Oligocene and Eocene age and were therefore deposited before the discoasters evolved, in the Neogene. Qualitatively, surface waters in which these forms lived were warm and possibly analogous to modern water masses north of the Subtropical Convergence. The surface water temperatures were certainly significantly warmer than at present in these latitudes.

The regional situation of calcareous oozes lying on oceanic basement and passing upward into siliceous oozes is seen in all holes of the transect, although it is somewhat masked by terrigenous input at Sites 267 and 268. In discussing paleoclimates, the significant aspect of this lithologic change is that it is diachronous—at Site 265 the transition takes place in the early Pliocene/late Miocene, at 266 in the late to middle Miocene, and at 267 in the early Miocene to late Oligocene interval (Kemp et al., this volume). At Site 268 the change probably takes place in the early Miocene to late Oligocene span as well. Thus, there is a general increase in the age at which the boundary effectively separates dominantly calcareous sediments from siliceous ones toward the south and down the ridge flank. Kemp et al. (this volume) have analyzed the paleoclimatic significance of this facies change in relation to the sea-floor spreading processes. Normally, as sea floor is generated at the ridge crest and carried away laterally by spreading, sediments deposited near the ridge crest are carried along with the crust into sedimentary regimes in which they did not originate. However, in the Southeast Indian Ocean, the south flank of the spreading ridge is an integral part of the Antarctic plate which has apparently maintained a nearly fixed latitudinal position during the Cenozoic (see Lowrie and Hayes, this volume; Weissel and Hayes, 1972). Hence, although Sites 265 thru 268 have not moved latitudinally, their positions have changed significantly relative to the ridge crest and their initial depths. In order to determine the original environment of the sites of deposition, it is therefore necessary to remove the effects of spreading and associated subsidence (Frakes and Kemp, 1972b). Utilizing an empirical age-depth curve for oceanic basement and known rates of spreading for this sector of the ridge (Weissel and Hayes, 1972), it is apparent that until the early Pliocene calcareous sedimentation took place on the upper portions of the south ridge flank. At that time (~4-5 m.y. B.P.) accumulation of calcareous deposits became restricted to the crestal zone and north flank as at present. This required a northward shift of about 300 km of the ecologic (hydrographic) singularity controlling the surface temperature and thus the accumulation area of siliceous microorganisms.

The paleoclimatic implications of such a dramatic temperature shift are enormous. Within a relatively short time, surface waters apparently cooled significantly in a belt at least 300 km wide and possibly circling much of the Antarctic continent. Heat transfer from the equatorial zone abruptly became less efficient than previously and atmospheric circulation patterns no doubt changed. It is likely that there are additional effects of global cooling which strongly influenced late Cenozoic glaciation in lower latitudes. From our data alone it is not possible to speculate on the causes of this sudden refrigeration superimposed on an already steadily deteriorating climate. We note that warm surface waters in the seas near Antarctica during the Paleogene could have provided abundant sources of moisture to build glaciers on the continent. A long-term buildup of ice (Frakes and Kemp 1972b) during the Miocene, perhaps eventually caused a significant perturbation in the global albedo and heat transfer by the early Pliocene.

Calcareous sediments accumulated to approximately the same distance south of the ridge crest during the Eocene through Miocene and indicate significant climatic changes, in that the ridge system itself was in motion away from a probably more or less stationary Antarctica (Weissel and Hayes, 1972). A continual expansion of cool, near-continent surface waters is implied, and at a rate roughly equal to one half the spreading rate (2-3 cm/yr; Weissel and Hayes, 1972). From our data, this expansion would have taken place during the interval from about 22 to 5.5 m.y. B.P., and possibly longer.

Diachronism is also shown by the sediments which display evidence of ice rafting (Kemp et al., this volume; also Figure 5). The oldest ice-rafted material at Site 266 is late Miocene, at 267 middle Miocene, and at 268 early Miocene. That is, there is progressive age increase away from the ridge crest. Most significant here is the fact that at all three sites, ice rafting began during the early stages of carbonate deposition and before dramatic surface-water cooling. The continent was sufficiently glaciated during the Miocene to produce icebergs, but these were not completely melted in the cool surface waters of the siliceous biofacies. As might perhaps be expected, their ultimate destruction took place in the warm waters beyond perhaps as suggested by the recent model of Watkins et al. (1974).

A MODEL FOR CLIMATIC DETERIORATION

Climate deteriorated markedly during the Cenozoic in the region of the Southeast Indian Ocean, as demonstrated by changes in sedimentation patterns in near-shore and offshore areas. Culmination of this episode of cooling was in the early Pliocene, when the Ross Ice Shelf expanded dramatically and the cold water belt around Antarctica expanded abruptly by about 300 km. The complete history of this climate change as recorded at Leg 28 drill sites and from other data is a complex one involving many fluctuations, some no doubt undetected, but can be outlined as follows.

After initial rifting possibly beginning as early as the Late Cretaceous (Falvey, 1974), Antarctica and Australia separated in the Paleocene (55 m.y. B.P., Weissel and Hayes, 1972). Sediments known from the initial rifting phase are detrital in nature at Site 274 (upper Eocene) and pelagic at 267 (also upper Eocene), so that the central portion of the narrow Eocene seaway was sufficiently elevated and/or far enough removed from both continents to allow pelagic sediments free of terrigenous components to accumulate. Warm surface waters are indicated by the abundant nannofossil oozes and chalks which characterize this interval. Through time the relatively warm, narrow seaway expanded and concurrently a belt of cool surface waters near Antarctica, characterized by deposition of siliceous microfossils, pushed outward from the continent. The time of inception of this cool water belt is unknown. The presence of a well-diversified diatom flora in the Ross Sea region in the Oligocene suggests that it may have existed prior to the time of deposition of the oldest known diatomaceous sediments (lower Miocene) at Site 268.

It is unknown whether or not the oceanographic boundary between the warm and cool water masses was analogous to the modern Antarctic Convergence, which separates Subantarctic from Antarctic waters. At this time, the atmospheric polar high was probably weak and restricted to the Antarctic continent. The coastal wind systems were therefore dominated by the West Wind Drift and consequently the Antarctic Divergence, in its present configuration, did not exist (see Gordon, 1971).

On some sectors of Antarctica, ice possibly began to accumulate in the early Eocene (Margolis and Kennett, 1971; Le Masurier, 1972), as the result of abundant evaporation of the warm surface water and subsequent precipitation over the continent (Frakes and Kemp, 1972b). The poleward transport of moisture in the atmosphere would have been facilitated by the constricted nature of the polar high pressure area. The earliest concentrations of ice were probably alpine glaciers in West Antarctica, judging from the accumulation of evidence for older glaciations in that sector (Geitzenauer et al., 1968; Rutford et al., 1972; Le Masurier, 1972). Ice conditions in East Antarctica at that time are unknown, but if glaciers were present they had not reached the sea in the Paleogene.

In the Oligocene the now somewhat wider seaway was still receiving detrital sediments along its margin, siliceous oozes were accumulating in a widening belt of cool water near the south coast, and warm waters were retreating northward at a rate of about 2-3 cm/yr. Possibly, also, the circumpolar current and West Wind Drift were migrating northward as a coherent belt, in response to growth of the polar high pressure zone. The overall picture is one of steady, progressive cooling although minor irregularities in this pattern cannot be discounted. In the late Oligocene glacial ice reached sea level in the Ross Sea sector, either in the form of abundant outlet glaciers or as an ice shelf. The climate was not so cold, nor the ice so extensive, as to completely obliterate the existing vegetation. Evidence of erosion by bottom currents at Site 274 suggests an ice shelf was in existence by the early Miocene, and this is the earliest suggestion of a marked intensification in oceanic circulation.

Climatic conditions apparently were more variable during the Miocene. The cold water belt continued to move outward, from the continent; the ice shelf in the Ross Sea may have undergone a minor retreat phase after a middle Miocene culmination; and active bottom currents scoured the continental rise at widely separated sites (268 and 274) in the middle or late Miocene. The Miocene, particularly the late Miocene, must have been a time of substantial buildup of ice in East Antarctica in view of the fact that at some time prior to 4.2 m.y. B.P. ice from the polar plateau penetrated the Transantarctic Mountains and carved the glacial topography of the Victoria Land Dry Valleys (Denton et al., 1971). Early Miocene ice rafting at Site 268 provides the evidence for initial ice buildup in East Antarctica and ice in the Wilkes Land catchment probably first reached the sea at this time. There is little information to characterize the late Miocene climates. Generally, conditions suggest a very cold early and early middle Miocene possibly followed by a slight warming in the later part of the middle Miocene. The dynamic events of the late Miocene and early Pliocene demand a tremendous and rapid buildup of ice, and hence, the existence of both cold and wet conditions.

The early Pliocene expansion of the Ross Ice Shelf is postulated from several lines of evidence. The unconformity incorporating this time interval truncates the glacial marine sequence seen on seismic profiles in the Ross Sea and is thought to have been formed by an advance of a grounded ice sheet. The rate of sedimentation increased markedly at Site 274 at this time, suggesting that cold bottom-water formation and consequent bottom currents were no longer important processes. Further, the Taylor 5 glaciation in the Dry Valleys has been suggested by Hughes (1973) to have occupied the interval from about 7 m.y. (Le Masurier, 1972) to sometime before 3.7 m.y. B.P. (Denton et al., 1971). Dating of the proposed ice shelf expansion at about 4.5 m.y. B.P. is based on assuming it immediately proceeded the 4.30-3.95 m.y. B.P. "interglacial" proposed by Ciesielski and Weaver (in preparation), and was concurrent with the 4.7-4.3 glacial maximum deduced by Shakleton and Kennett, (1975) and was responsible for the inferred hiatus associated with the erosional unconformities at Sites 270-273. That the ice shelf was grounded and possibly overextended as the result of a glacial surge (Wilson, 1964) is suggested by the increased rate of accumulation at Site 274; by the concentration of large stones in Pliocene sediments at Site 271, well out on the Ross Sea shelf; and by the distribution of glacially carved valleys extending essentially to the shelf break. At about 4 m.y. B.P. withdrawal of the ice may have been to the present position of the ice front or even farther inland.

At about the same time (3.7-5.5 m.y.) as the shelf ice expansion, there was a large northward shift of the oceanographic boundary separating siliceous and calcareous microplankton. There is likely a casual relationship between the two events, but our age control is not sufficiently precise to determine if this shift was in response to a glacial pulse, interglacial retreat, or both. It seems feasible that such shifts of water mass boundaries would be closely related to, and controlled by, changes in atmospheric circulation patterns, and this indicates the probable widening of the West Wind Drift in the early Pliocene. It has been suggested by Weaver (1973) that the Antarctic Divergence was in existence in this region and was fluctuating in position by the early Pliocene. No shift of comparable magnitude to that inferred for the northern boundary of siliceous sedimentation was detected. This implies a northward expansion of the belt of cool surface waters and attendant surface winds, but with little change in conditions near Antarctica. The subpolar atmospheric low pressure belt migrated northward to a position approximating its present one. Since the early Pliocene, climatic conditions have been variable around Antarctica and have been documented in several publications (e.g., Goodell et al., 1968; Bandy et al., 1971; Watkins and Kennett, 1972; Fillon, 1972a, 1972b).

GEOLOGIC, CLIMATOLOGIC, AND OCEANOGRAPHIC EVOLUTION OF THE SOUTHEAST INDIAN OCEAN DURING THE CENOZOIC

Paleocene (~65 m.y.)

The central Tasman Sea had just completed a 15-m.y. opening phase, rifting New Zealand/Lord Howe Rise northeast away from a still united, high-latitude Australian/Antarctic continent. The Campbell Plateau continues to drift north from Antarctica but plate motions undergo a major readjustment about this time (Hayes and Ringis, 1973). Australia remains a major barrier to circumpolar circulation. Although initial rifting of Australia and Antarctica had possibly begun, no significant separation has occurred and Antarctic climates are temperate. The present Ross continental shelf stood above sea level at this time.

Early Eocene (~53 m.y.)

Australia has begun to drift northward at about 5 cm/yr, but the extension of the "Continental" South Tasman Rise (Kennett, Houtz, et al., 1975) into the bight of Victoria Land continues to provide a major shallow-water barrier to circumpolar circulation. Although a temperate climate persists throughout much of the Antarctic continent (Kemp, this volume), some ice rafting in the southeast Pacific has begun (Margolis and Kennett, 1971; Geitzenauer et al., 1968). The present Ross shelf continues to remain near sea level.

Early Oligocene (~35 m.y.)

Australia has migrated nearly 1000 km northward from Antarctica (Weissel and Hayes, 1972). A continuous deep-water passage is now opening between Australia and Antarctica. Ice rafting begins in the southernmost Ross Sea area. Small icecaps from Marie Byrd Land archipelago begin to coalesce to form an extensive ice sheet. This would alter the possible paths of water circulation by closing off the intra-continental passes between the Ross Sea, the Bellingshausen Sea, and the Weddell Sea. The cool temperate vegetation, common earlier, is beginning to disappear. Vigorous current activity is present near Site 274 and there is evidence of widespread current-controlled erosion over much of the Tasman Sea. Portions of the Ross Embayment begin to subside, perhaps in a response to regional ice loading on the continent. Remains of warm temperate calcareous microfossils are deposited on the sea floor within about 200 km of the Wilkes Land coast. Siliceous organisms (diatoms) are common further south in the Ross Embayment.

Late Oligocene (28-25 m.y.)

Relief is low in the central Ross Sea. The area is near sea level, with regoliths developing on the metasedimentary talus slopes. Sea level rises slowly and greensands are formed on a low-relief regional surface. Glacial marine pebbly mudstones begin to be deposited on the shelf floor.

Early to Middle Miocene (22-10 m.y.)

Rapid sedimentation with abundant ice rafting is occurring in the Ross Sea shelf area. Glaciation reaches sea level along the Wilkes coast and ice rafting begins, but is confined to near the continent. A relatively unrestricted deep-water passage has been well established; however, a major readjustment in Pacific and Australia plate motions changes the tectonic response along their common boundary and the Macquarie Ridge Complex is generated, creating new topographic barriers to circumpolar circulation. Evidence of a gradual eustatic drop in sea level is felt globally as ice continues to begin to build up on the continent. During this period the ocean basins of the world receive an increased influx of terrigenous materials, especially near major drainage basins. The East Antarctic ice sheet has grown large enough to breach the Transantarctic Mountains, depositing rafted detritus on the western Ross Sea shelf. Cold water masses continue to migrate northward from the continent depositing siliceous oozes in their wake. Ice rafting now reaches some 800 km north of the continent.

Late Miocene-Early Pliocene (~7-3.5 m.y.)

This constitutes most abrupt period of change regarding Antarctic glaciation and circumpolar circulation. The Ross Ice Shelf builds to enormous proportions, reaching a northward limit near the present shelf edge or beyond about 4.5 m.y. ago. Large valleys are carved on the Ross continental shelf along grounding lines of the ice sheet, leaving a great erosional unconformity over much of the shelf area. Vast quantities of detritus are bulldozed off the shelf to be redeposited elsewhere. Ice rafting reaches almost 1500 km north of the continent. At about 5 m.y. an abrupt 300 km northward shift of a cold water mass occurs and the modern Antarctic Convergence or a close analog is born. At this point the total eustatic lowering of sea level has probably reached its maximum value, perhaps approaching 100 meters as compared to the levels for a preglacial Antarctica in the Eocene. The exact value is highly speculative, but must be substantially greater than the 55 meters represented by the present Antarctic icecap. Then, circumpolar surface water temperatures increase significantly from about 4.2 to 3.95 m.y. ago (Ciesielski and Weaver, in preparation) and the overextended Ross Ice Shelf and perhaps others (e.g., Shackelton Ice Shelf) retreat rapidly to positions similar to those of today. This ice retreat was accompanied by a significant eustatic sea-level rise about 4 m.y. ago that may have been as large as 50 meters. The Mediterranean is flooded (Hsü et al., 1973). The East Antarctic ice recedes, and ice can no longer reach the Ross Sea across the Transantarctic Mountains. Subsidence of the Ross shelf stops. Cooling again takes place about 3.8 m.y. ago and fluctuations in the extent of the ice become relatively minor.

Late Pliocene to Pleistocene (3 to <1 m.y.)

Many minor glacial advances occur in the Ross area, but apparently are not synchronous with the Northern

Hemisphere glacial fluctuations which commenced about 3 m.y. ago. Patterns of circumpolar circulation stabilize with minor singularities producing anomalous areas of upwelling, productivity, and contrasts in rates of pelagic sedimentation.

CONCLUSIONS AND SPECULATIONS

Many interesting discoveries were made during Leg 28 of the Deep Sea Drilling Project. These discovereis were pertinent to such diverse topics as high-latitude Cenozoic biostratigraphy, near-shore and abyssal sedimentation patterns, crustal petrology, rates of sea-floor spreading, and hydrocarbons beneath the continental shelves of Antarctica. However, unquestionably the most significant finding and the one with the greatest "global impact" was that of the initiation of major continental glaciation at about 25 m.y. B.P.

The initiation of glaciation on Antarctica at this time, some 15-20 m.y. earlier than previously acepted, now casts a new and important light on our assessment of what factors are important regarding the formation of the south polar icecap. This icecap is a key factor in modulating both oceanic and atmospheric circulation patterns today. It constitutes about 90% of the earth's glacial ice and represents enough water to raise sea level over the entire globe by approximately 55 meters (Denton et al., 1971). The presence, absence, and fluctuations of continental glaciation on Antarctica are manifested through the complicated interaction of circumpolar oceanic circulation, the generation of Antarctic bottom waters and their influence on the overall circulation of the world oceans, major eustatic changes in sea level, variations in the global temperature through changes in meridional heat exchange, and variations in abyssal sedimentation and erosion through generation of vigorous bottom currents.

We have established with reasonable confidence approximately when Antarctic glaciation began but the agonizing factor that remains is why did glaciation begin only 25 m.y. ago and not before! All available data strongly indicate that the Antarctic continent has been nearly fixed in a high latitudinal position for about the last 100 m.y. It is therefore obvious that although a near-polar geography is a necessary condition, it is not a sufficient condition for establishing Antarctic glaciation. Many hypotheses have been put forward to explain the initiation of glaciation previously thought to have been about 5-7 m.y. B.P. These include the suggestions that: (1) the insolation (solar radiation) was dramatically reduced just prior to the onset of glaciation, (2) the albedo (the ratio of solar radiation retained by the earth to that reflected back out to the atmosphere) changed, (3) dramatic changes in sea level and continental configurations have played a significant role in controlling the geography of the water covered areas (effective heat sinks) thereby influencing global climates. While none of these factors can be discounted and it is likely that all of these factors have experienced variations, the question remains—are plausible variations of these parameters large enough to be responsible for initiating glaciation? Even more importantly, are these the only factors to be considered? We must keep in mind that we are dealing with a very long-term phenomenon that has a time constant on the order of millions of years, and the response of the earth to relatively short-period changes ($<10^6$ yr) in these factors serves as an additional "low-pass filter," and finally minimizes their effects.

Gordon (1971) discussed in a general way the interaction between variations in continental glaciation and circumpolar circulation. He primarily addressed the question of seasonal variations for a hypothetically glaciated and nonglaciated Antarctic continent. The emphasis in Gordon's discussion and elsewhere has been to consider what the response of the polar circulation patterns (ocean and atmosphere) might be to changes in the extent of ice cover on the continent. This interaction is obviously one part of a closed-loop system and perhaps can and should be considered from another perspective. Specifically, we know that the earth's crust has been in a state of dynamic motion for at least the last 200 m.y., and the nature of that motion is reasonably well established (especially for the last 65 m.y.) for most of the Gondwanaland continent, which included Antarctica. The motion of continents and the generation of new sea floor through sea-floor spreading processes in part manifests itself in the creation of destruction of land bridges and other topographic barriers to oceanic circulation. We can look particularly for a major event in the pattern of global tectonics that might dramatically alter the nature of circumpolar circulation and in turn perturb the climate in such a way to initiate and gradually increase Antarctic glaciation, then decrease it, and finally maintain it in a stable, steady state.

It should be empahsized here that the following remarks are entirely speculative and are made, not so much with the objective of solving "the problem," but with generating further thought and discussion. The Antarctic Divergence is essentially a wind-driven feature (Gordon, 1971). The wind system giving rise to the divergence is obviously influenced by the presence or absence of an icecap on the Antarctic continent. However, even in the absence of Antarctic glaciation, meridional wind systems would tend to generate an Antarctic Divergence, but one which is less intense than observed today. In a simple-minded way, the very presence of the divergence gives rise to the Antarctic circumpolar current by increasing the baroclinicity of the water column through tilting of the isopycnal (Gordon, 1972) surfaces. The present circumpolar current appears to be fairly uniform in direction and magnitude from its surface all the way to the sea floor (Gordon, 1971). The presence of major topographic barriers, such as a closed Drake Passage, the Kerguelen Plateau, and specifically, a connection between the Tasman Rise system and the Ross continental shelf, would prevent the establishment of an Antarctic circumpolar current. Gordon (personal communication) suggests that any topographic high whose average depth was about 1500 meters or less would serve as an effective barrier against significant circumpolar transport. If such barriers existed, the circulation in the resulting small, semi-enclosed basins would be composed of small, cyclonic gyres. The gradual migration of the Australian plate away from Antarctica, and perhaps the opening of the Drake Passage led to the removal of two major topographic barriers at about 30 m.y. B.P. (middle Oligocene); the circumpolar current could then be established. In its initial phases the current might be relatively strong, due to the channeling effects of the narrow transport lane. One result of the newly established circumpolar flow would be an increase in meridional heat transport. This heat transport would be dissipated by many factors, but by far the largest would be the heat loss due to evaporation at the sea-air interface (see, for example, Gordon, 1971). Thus, there would be a relatively large increase in the amount of moisture in the atmosphere of the Subantarctic regions. With the Antarctic continent still in an unglaciated state, a significant portion of this moist air would move toward the continent and would result in a major increase in precipitation as snowfall. With this condition, a permanent snow field would develop and lead to the formation of continental glaciers. The presence of such glaciers in turn would provide positive feedback conducive to the intensification of the Antarctic Divergence and also in the generation of thermohaline circulation, both factors enhancing circumpolar circulation. The increased circumpolar circulation would give rise to even more evaporation and precipitation and the gradual buildup of ice and associated polar, climatic deterioration.

During the buildup of the continental snow and ice cover, a polar high pressure zone similar to the present one would develop and would tend to restrict the polar flow of Subantarctic air and thus reduce the amount of moisture reaching the continent. This relationship would provide a negative feedback to the system by inhibiting precipitation and the continued buildup of ice on the continent. Another negative feedback factor would involve the continuing northward migration of the Australian plate, thus widening the deep corridors for circumpolar circulation and thereby reducing their vigor. If less vigorous circumpolar current were also accompanied by a reduced total transport, this would reduce the meridional heat transport, the heat loss through evaporation, the total moisture in the air, and the total amount of precipitation, thereby limiting the glacial buildup on the continent.

This generalized process probably existed from 30 to 5 m.y. B.P., when the situation changed dramatically, perhaps becoming unstable with overextended glaciers. The glaciers then retreated rapidly to a position similar to that observed today and have thereby maintained a relatively steady state for about the last 4.5 m.y. Subsequent advances and retreats of the Antarctic icecap could represent relatively small perturbations in the steady-state, wind, current, temperature, and heat exchange balance.

It is therefore entirely plausible that the destruction of topographic barriers, the establishment of a circumpolar current, and the response of the ocean-atmospheric circulation patterns provide a mechanism that is correct in time and space for initiating glaciation, for building it up to an unstable condition, and finally establishing it in the stable, steady-state condition we observe today.

At present, the preceding discussion is pure speculation. We can, however, ask what factors might be examined to further test its plausibility. Prior to the initiation of the circumpolar current (when there was no major production of Antarctic bottom water and relatively little communication of cool polar waters to the basins to the north) the abyssal waters of the world's oceans should have been considerably warmer than at present. Evidence for a decrease in the temperature of bottom water has been found through oxygen isotope analysis of the tests of planktonic foraminifera from abyssal sediments (Emiliani, 1956). A gradual increase in the vigor of abyssal currents should be evidenced on a global scale from the late Oligocene until the latest Miocene. This current activity would be a direct response to the rate of production of Antarctic bottom water. A eustatic lowering of sea level (relative to a non-glaciated Antarctica in the early Oligocene) could perhaps be as much as 100 meters, and would have reached a peak 4-5 m.y.B.P. Levels would then have risen about 50 meters. With sea level at its lowest point (latest Miocene/earliest Pliocene) there should have been increased transport of terrigenous sediments across the then relatively shallow continental shelves to the deep basins. This effect should be most obvious for the basins adjacent to rivers such as the Amazon, the Niger, the Congo, etc (see, for example, Pimm and Hayes, 1972; Damuth and Fairbridge, 1970). The sea-level rise in response to the main Antarctic glacial retreat, about 4 m.y. ago would have been accompanied by a relative decrease in the amount of terrigenous material reaching abyssal depths. Unfortunately, any evidence of wave base erosion of the continental shelves to depths representing sea level at the time of maximum Antarctic glaciation has probably since been destroyed by subsequent erosion associated with lower sea levels of Northern Hemisphere Pleistocene glaciation. The late Miocene isolation of the Mediterranean Sea and subsequent catastrophic flooding at earliest Pliocene time as reported by Hsü et al., 1973, is very likely one manifestation of the changing glacial conditions on Antarctica. This provides one dramatic illustration of the enormous impact that changes in the Antarctic environment may have had on opposite sides of the globe. Perhaps the careful examination of such topics as the precise time of flooding of the Mediterranean, late Cenozoic history of global sedimentary events recorded in the deep abyss, variations of deep circulation as evidenced by submarine erosion, changes in calcium carbonate compensation depths, and paleotemperature changes may eventually provide the more precise and detailed chronology for describing the evolution of the Antarctic icecap. The biostratigraphic and paleoclimatic information obtained at Deep Sea Drilling sites during Leg 28 and other Antarctic legs (19, 35, and 36) alone are unlikely to include enough information to firmly establish this desired chronology.

One final note of disappointment should be voiced: although the results of the Deep Sea Drilling Project in the Antarctic have been very important, they have not been all we would have wished or all they might have been. The logistics and weather requirements of being at a remote region like the Antarctic at a specific time in each of three consecutive years (Hayes and Edgar, 1972) clearly impose serious constraints on other objectives of the Deep Sea Drilling Project. When the inevitable compromises imposed by breakdowns, schedule changes, and equipment tests came, the Antarctic Program shared in these losses in spite of the fact that through the first 27 legs of the Deep Sea Drilling Project only three holes were drilled in latitudes south of 35°S.

The interests of those proponents for further Antarctic drilling have often been labeled parochial and of significance to only a small number of Antarctic scientists. Thus, even though a major charter of Phase Three of the Deep Sea Drilling Project was high-latitude Antarctic drilling, for a variety of reasons a significant portion of the proposed plans was abandoned. This is past history. What is important now is that the new generation of drilling, IPOD, has not made any provision to seriously consider drilling in the Antarctic environment in spite of the fact that this region is truly the "heart" of the world's oceans. Finally, the Antarctic continent is the last terrestrial sanctuary of open, cooperative international scientific research. The presence of trace amounts of gaseous hydrocarbons in three of the four holes drilled in the Ross continental shelf will quite obviously increase the interest in the economic potential of the offshore regions of the continent and will likely lead to exploration in the near future. The presence of these gaseous hydrocarbons adds one more element to the complicated discussions of the economic exploitation of the Antarctic continent as addressed by committees of the Antarctic Treaty Organization.

Future scientific investigations in the ocean environs of the Antarctic continent under the auspices of programs like IPOD constitutes an obvious and important scientific follow-up to many of the important questions raised during Leg 28 of the Deep Sea Drilling Project.

APPENDIX: HYDROCARBON GASES FROM THE ROSS CONTINENTAL SHELF

Shipboard observations of hydrocarbon gases through visual inspection of cores and subsequent gas chromatograph analyses led to a moderately extensive program of sampling both of gas pockets in the cores and canned sediment samples. The shore-based analysis of these samples is reported by McIver (this volume).

Hydrocarbon gases were detected at Sites 271 and 272 in the east central Ross Sea and at Site 273 in the western Ross Sea. As compared with DSDP canned samples from other sites that have been analyzed for hydrocarbons, the Ross Sea samples contained relatively large quantities of ethane and higher homologs although absolute concentrations are apparently small (McIver, this volume). The values for the ratio of total hydrocarbon gas to ethane and higher homologs are very erratic, ranging from 200 to 300 at a single site (272) and suggests the possible dilution of methane by migrating ethane both at this and other Ross Sea sites (McIver, this volume). McIver also points out that the sediment samples contain less organic carbon with respect to percent gas than similar samples from 15 other DSDP sites. The methane at Ross Sea sites is predominantly of biogenic origin as indicated by light δC^{13} values, and the ethane is probably generated by slight thermal decomposition of organic matter related to aging, burial, and associated heating (Claypool, personal communication; McIver, this volume).

At present there is no way to assess the significance of the Ross Sea hydrocarbon shows. Although the gas composition may be considered as evidence that somewhere deeper in the sections the early stages of thermal cracking are taking place, leading to the generation of light hydrocarbons (McIver, 1972, this volume), this is speculation and there is no strong reason to infer that the gaseous hydrocarbons are associated with liquid hydrocarbons or that they would be of significant economic potential even if this were the case.

It is tempting to relate the occurrence of economically important hydrocarbon production areas, such as the Gippsland Basin (Australia) and the Terinake region of western New Zealand to the Ross Sea hydrocarbons in view of the nearly contiguous nature of these areas (Hayes and Ringis, 1973) prior to rifting of New Zealand from Australia and the later rifting of Australia from Antarctica. The Ross Sea hydrocarbons were recovered from sediments of Miocene age whereas the above producing areas draw their hydrocarbons from rocks of much greater age (Eocene; Halbouty et al., 1968; Katz, 1973). Unless the hydrocarbons of the three areas have their origin in source rocks at least as old as Late Cretaceous (when the three areas were still contiguous), the presence of hydrocarbons at these areas is largely coincidental. It is extremely premature to attach any economic significance to the Ross Sea hydrocarbons at this time. Their presence in a shallow-water, thick Tertiary sedimentary sequence will logically and hopefully lead to a close examination of their potential. It may, however, lead to wishful and wild speculation regarding reserves on the Antarctic continent and new negotiations within the Antarctic Treaty Organization addressing the issues of economic exploitation of the Antarctic continent.

ACKNOWLEDGMENTS

Much of this paper is simply a summary of the site reports and shore-lab reports of this volume and thus reflects the important contributions of all these authors and particularly the shipboard scientific party. Discussions with P. Barrett, L. Kemp, A. Kaneps, and D. Piper have been especially important for this synthesis chapter. R. Houtz, A. Gordon, and A. Kaneps reviewed the manuscript and provided constructive criticisms. A. Kaneps was also responsible for major editorial improvements on the preliminary manuscript. Some portions of this synthesis are highly speculative and every effort has been made to identify them as such. The responsibility for these speculations rests entirely with the authors. Partial support for D. Hayes during the period of this study was from National Science Foundation Grant GV-40896 (Office of Polar Programs).

REFERENCES

Anderson, J.B., 1972. The marine geology of the Weddell Sea: Florida State Univ., Antarctic Res. Fac. Rept.

Bandy, O.L., Casey, R.E., and Wright, R.C., 1971. Late Neogene planktonic zonation, magnetic reversals, and radiometric dates, Antarctic to the tropics. *In* Ried, J.L. (Ed.) Antarctic oceanology I; Antarctic Res. Ser., v. 15: Washington (Am. Geophys. Union), p. 1-26.

Chriss, T. and Frakes, L.A., 1972. Glacial marine sedimentation in the Ross Sea. *In* Adie, R.J. (Ed.), Antarctic geology and geophysics: Oslo (Universitetsforlaget), p. 747-762.

Ciesielski, P.F. and Weaver, F.M., in preparation. Early Pliocene climate change: Implications for an Antarctic "interglacial."

Conolly, J.R. and Pyane, R.R., 1972. Sedimentary patterns within a continent-Mid-Oceanic Ridge-Continental profile: Indian Ocean south of Australia. *In* Hayes, D.E. (Ed.), Antarctic oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 295-315.

Damuth, J.E. and Fairbridge, R.W., 1970. Equatorial Atlantic deep-sea Arkosic sands and ice-age aridity in tropical South America: Geol. Soc. Am. Bull., v. 81, p. 189-206.

Denton, G.H., Armstrong, R.L., and Stuiver, M., 1971. The late Cenozoic glacial history of Antarctica. *In* Turekian, K.K. (Ed.), The late Cenozoic glacial ages: New Haven (Yale Univ. Press), p. 267-306.

Eittreim, S., Bruchhausen, P.M., and Ewing, M., 1972. Vertical distribution of turbidity in the South Indian and South

Australian basins. *In* Hayes, D.E. (Ed), Antarctic Oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 51-58.

Emiliani, C., 1956. Oligocene and Miocene temperatures of the equatorial and subtropical Atlantic Ocean: J. Geol., v. 64, p. 281-288.

Falvey, D.A., 1974. The development of continental margins in plate tectonic theory: APEA J., p. 96-106.

Fillon, R.H., 1972. Late Cenozoic geology, paleooceanography and paleoclimatology of the Ross Sea, Antarctica: Ph. D. Thesis, Univ. of Rhode Island.

Fillon, R.H., 1972b. Evidence from the Ross Sea for widespread submarine erosion: Nature, v. 238, p. 40-42.

Frakes, L.A., 1973. U.S.N.S. *Eltanin* core descriptions, cruises 32 to 45: Florida State Univ., Antarctic Res. Fac. Rept.

_______, in press. Sediment distributions south of Australia: Search.

Frakes, L.A. and Kemp, E.M., 1972a. Generation of sedimentary facies on a spreading ocean ridge: Nature, v. 236, p. 114-117.

_______, 1972b. Influence of continental positions on early tertiary climates: Nature, v. 240, p. 97-100.

Geitzenauer, K.R., Margolis, S.V., and Edwards, D., 1968. Evidence consistent with Eocene glaciation in a South Pacific deep sea sedimentary core: Earth Planet. Sci. Lett., v. 4, p. 173-177.

Giovinetto, M.B., 1964. The drainage systems of Antarctica: accumulation: Antarctic snow and ice studies: Antractic Res. Ser., v. 2: Washington (Am. Geophys. Union), p. 127-155.

Goodell, H.G., Watkins, N.D., Mather, T.T., and Koster, S., 1968. The Antarctic glacial history recorded in sediments of the Southern Ocean: Palaeogeogr., Palaeoclimatol., Paleoecol., v. 5: Amsterdam (Elvesier Publishing Co.), p. 41-62.

Gordon, A.L., 1971. Oceanography of Antarctic waters. *In* Reid, J.L. (Ed.), Antarctic Oceanology I, Antarctic Res. Ser., v. 15: Washington (Am. Geophys. Union).

_______, 1972. Introduction: physical oceanography of the Southeast Indian Ocean. *In* Hayes, D.E. (Ed.), Antarctic Oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 3-9.

Halbouty, M.T., Meyerhoff, A.A., King, R.E., Dott, R.H., Sr., Klemme, H.D., and Shabad, T., 1968. World's giant oil and gas fields, geologic factors affecting their formation, and basin classification. *In* Halbouty, M.T. (Ed.), Geology of giant petroleum fields: AAPG Mem. No. 14, p. 502-555.

Hamilton, W., 1972. The Hallett volcanic province, Antarctica: U.S. Geol. Surv. Prof. Paper 456C, p. C1-C42.

Hayes, D.E. and Edgar, N.T., 1972. Extensive drilling program planned for *Glomar Challenger* in Antarctic waters: Antarctic J., v. VII, p. 1-4.

Hayes, D.E., Frakes, L.A., et al., 1973. Leg 28 deep-sea drilling in the southern ocean: Geotimes, v. 18, June 1973.

Hayes, D.E. and Ringis, J., 1973. Seafloor spreading in the Tasman Sea: Nature, v. 243, p. 254-248.

Heezen, B., Tharp, M., and Bentley, C.R., 1972. Morphology of the earth in the Antarctic and Subantarctic: Folio 16 in Antarctic Map Folio Series, Am. Geograph. Soc.

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., III, and Le Pichon, X., 1968. Marine magnetic anomalies, geometric field reversals, and motions of the ocean floor and continents: J. Geophys. Res., v. 73, p. 2119-2136.

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

Houtz, R. and Markl, R.G., 1972. Seismic profiler data between Antarctica and Australia. *In* Hayes, D.E. (Ed.), Antarctic Oceanology II: the Australian-New Zealand sector: Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 147-164.

Hsü, K.J., Ryan, W.B.F., and Cita, M.B., 1973. Late Miocene desiccation of the Mediterranean: Nature, v. 242, p. 240-244.

Hughes, T., 1973. Is the West Antarctic ice sheet disintegrating? J. Geophys. Res., v. 78, p. 7884-7910.

Jacobs, S.S. Amos, A.F., and Bruchhausen, P.M., 1970. Ross Sea oceanography and Antarctic bottom water formation: Deep-Sea Res., v. 17, p. 935-962.

Kaharoeddin, F. A., Weaver, F.M., and Wise, S.W., 1973. Cretaceous and Paleogene cores from the Kerguelen Plateau, Southern Ocean: Antarctic J. U.S., v. 8, p. 297-298.

Katz, H.R., 1973. Petroleum developments in New Zealand in 1972: AAPG Bull., v. 57/lo.

Kemp, E.M., 1972. Reworked palynomorphs from the West Ice Shelf area, East Antarctica, and their possible geological palaeoclimatological significance: Marine Geol., v. 13, p. 145-157.

Kennett, J. ,and Brunner, C.A., 1973. Antarctic late Cenozoic glaciation: evidence for initiation of ice raftinng and inferred increased bottom-water activity: Geol. Soc. Am. Bull., v. 84.

Kennett, J.P., Burnes, R.E., Andrews, J.E., Churkin, M., Jr., Davies, T.A. Dumitrica, P., Edwards, A.R., Galehouse, J.S., Packham, G.H., and van der Lingen, G.J., 1972. Australian-Antarctic continental drift, palaeocirculation changes and Oligocene deep-sea erosion: Nature Phys. Sci., v. 239, p. 52-55.

Kennett, J.P., Houtz, R.E., Andrews, P.B., Edwards, A.R., Gostin, V.A., Hajos, M., Hampton, M.A., Jenkins, D.G., Margolis, S.V., Ovenshine, A.T., and Perch-Nielsen, K., 1975. Cenozoic paleoceanography in the Southwest Pacific Ocean, Antarctic glaciation and the development of the Circum-Antarctic current. *In* Kennett, J.P., Houtz, R.E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 29: Washington (U.S. Government Printing Office), p. 1155-1170.

Le Masurier, W.E., 1972. Volcanic record of Cenozoic glacial history Marie Byrd Land, Antarctica. *In* Adie, R.J. (Ed), Antarctic geology and geophysics: Oslo (Universitetsforlaget).

Lisitzin, A.P., 1971a. Distribution of siliceous microfossils in suspension and in bottom sediments: *In* Funnell, B.M. and Reidel, W.R. (Eds.), Micropaleontology of the oceans, Cambridge (Cambridge Univ. Press), p. 73-195.

_______, 1971b. Distribution of carbonate micro-fossils in suspension and in bottom sediments. *In* Funnell, B.M. and Reidel, W.R. (Eds), Microplaeontology of the oceans: Cambridge (Cambridge Univ. Press), p. 197-218.

Mandra, Y.T. and Mandra, H., 1971. Upper Eocene silicoflagellates from New Zealand: Antarctic U.S., v. 6, p. 177-179.

Margolis, S., 1975. Paleoglacial history of Antarctica inferred from analysis of Leg 29 sediments by scanning electron microscopy. *In* Kennett, J.P., Houtz, R.E., et al., Initial Reports of the Deep Sea Dri-lling Project, Volume 29: Washington (U.S. Government Printing Office), p. 1039-1048.

Margolis, S.V. and Kennett, J.P., 1971. Antarctic glaciation during the Tertiary recorded in Sub-Antarctic deep-sea cores: Science, v. 170, p. 1085-1087.

McIver, R.D., 1972. Geochemical significance of gas and gasoline-range hydrocarbons and other organic matter in a Miocene sample from Site 134—Balearic aby-sal plain. *In* Ryan, W.B.F. Hsü, K.J., et al., Initial Reports of the Deep Sea Drilling Project, Volume 13: Washington (U.S. Government Printing Office), p. 813-814.

Payne, R.R. and Conolly, J.R., 1972. Turbidite Sedimentation off the Antarctic Continent. *In* Hayes, D.E. (Ed.), Antarctic Oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 349-364.

Pimm, A.C. and Hayes, D.E., 1972. General synthesis. *In* Hayes, D.E., Pimm, A.C., et al., Initial Reports of the Deep Sea Drilling Project, Volume 14: Washington (U.S. Government Printing Office), p. 955-975.

Rutford, R.H., Craddock, C., Armstrong, R.L., and White, C., 1972. Tertiary glaciation in the Jones Mountains. *In* Adie, R.J. (Ed.), Antarctic Geology and geophysics: Oslo (Universitetsforlaget).

Shackleton, N.J. and Kennett, J.P., 1975. Late Cenozoic oxygen and carbon isotopic changes at DSDP Site 284: Implications for glacial history of the northern hemisphere and Antarctica. *In* Kennett, J.P., Houtz, R.E., et al., Initial Reports of the Deep Sea Drilling Project, Volume 29: Washington (U.S. Government Printing Office), p. 801-808.

Tchernia, P., 1974. Etude de la dérive antarctique Est-Ouest au moyen d'icebergs suivis par le satellite Eole: C.R. Acad. Sci. Paris, t. 278.

Warnke, D.A., 1970. Glacial erosion, ice rafting and glacial-marine sediments: Antarctica and the Southern Ocean: Am. J. Sci., v. 269, p. 276-294.

Watkins, N.D. and Kenne-t, J.P., 1972. Regional sedimentary disconformities and upper Cenozoic changes in bottom water velocities between australia and Antarctica. *In* Hayes, D.E. (Ed.), Antarctic Oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 273-293.

Watkins, N.D., Keany, J., Ledbetter, M.L., and Juang, T-C., 1974. Antarctic glacial history from analysis of ice-rafted deposits in marine sediments: New model and initial tests: Science, v. 186, p. 533-536.

Weaver, F.M., 1973. Pliocene paleoclimatic and paleoglacial history of East Antarctica recorded in deep-sea piston cores: Ph.D. Thesis, Dept. of Geology, Florida State University.

Weissel, J. and Hayes, D.E., 1972. Magnetic anomalies in the Southeast Indian Ocean. *In* Hayes, D.E. (Ed.), Antarctic Oceanology II: the Australian-New Zealand Sector, Antarctic Res. Ser., v. 19: Washington (Am. Geophys. Union), p. 165-196.

Wilson, A.T., 1964. Origin of ice ages: An ice shelf theory for Pleistocene glaciation: Nature, v. 201, p. 147-149.