DEPARTMENT OF MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1974/94

PALEOCLIMATIC SIGNIFICANCE OF DIACHRONOUS BIOGENIC FACIES, LEG 28, DEEP SEA DRILLING PROJECT

by

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ABSTRACT

At each of the sites 265, 266, 267 and 268, in the southeast Indian Ocean, siliceous sediments, consisting of diatom oozes or diatom silty clays, overlie calcareous nannoplankton oozes and chalks. The boundary between siliceous and calcareous sediments shows a pronounced diachronism, younging towards the north. At the southern sites, 267 and 268, the transition from a calcareous to a siliceous sedimentary regime occurred in the interval late Oligocene to early Miocene; at Site 266, the transition was gradual, and commenced in the middle Miocene; at Site 265, the most northerly, the change did not occur until probably late in the Miocene.

Back-tracking of these sites along an empirical age-depth curve for the southeast Indian Ocean suggests that the silica/carbonate boundary was stationary with respect to the crest of the Southeast Indian Ridge throughout most of the Miocene, i.e. in the period 5.5 - 22 million years BP, although some migration may have occurred along with the ridge system itself. In the early Pliocene, however, a rapid northward shift of the boundary with respect to the ridge crest occurred.

The distribution of ice-rafted detritus in these sites shows the same diachronous pattern as the biogenic facies boundary. The earliest ice-rafting is evident from the early Miocene at Site 268, from the middle Miocene at Site 267, and the late Miocene at Site 266, and is not apparent at Site 265.

Paleoclimatic interpretation of these lithofacies shifts leads us to conclude that surface waters have been cool relatively from at least the late Oligocene - early Miocene; the principal effects of this were felt only in near-continent regions. Continued gradual cooling persisted until after the early Pliocene. Upwelling may be responsible for the high diatom content of sediments at southern sites. Iceberg melting was similarly confined to extreme southern regions. In the early Pliocene, intensified, relatively sudden chilling resulted in a northward shift of the silica/carbonate facies boundary, and of the zone of iceberg melting.

INTRODUCTION

Sites 265, 266, 267 and 268 are situated in a general linear arrangement (with a spread of only 8° longitude between the four sites), from near the crest of the Southeast Indian Ridge in the north, to the Wilkes Land continental rise in the south. These sites thus provide a north-south section through a region which has experienced dominantly pelagic processes of sedimentation throughout its history (except for Site 268, the southernmost site, where terrigenous sedimentation has prevailed).

Pelagic sedimentation processes are presently controlled in the southeast Indian Ocean by those factors which determine the distribution, in surface waters, of sediment-forming pelagic organisms, and of icebergs. Oceanic circulation is the prime factor governing this distribution, and this is in turn dependent on the relationship between oceanic temperature structure and atmospheric circulation. The modern sedimentary regimes generated by this complex of factors show a pronounced latitudinal zonation, with belts of distinctive sediment type arranged in a circumpolar fashion. Latitudinally disposed oceanographic barriers such as the Antarctic Convergence give rise to this circumpolar arrangement of sediment belts; this is reinforced by a similar disposition of the major tectonic features. The Southeast Indian Ridge is aligned in an east-west direction, and controls the three-dimensional shape of sediment bodies by acting as a generative center which spreads the sea-floor to progressively greater depths both towards the north and the south. It follows that a north-south section should provide an opportunity to examine the movement of the boundaries of sedimentary facies through time, movements which ultimately have depended on fluctuations in climatic parameters such as air and ocean temperatures, but which bear some imprint of the regional tectonic picture.

The role of carbonate dissolution in delineating the boundary between calcareous and siliceous biogenic sediments on the sea floor cannot be evaluated at present because of a lack of dissolution studies on calcareous organisms in this region. For the moment, we assume that the observed lithologic changes result from deposition of pelagic debris on either side of a more-or-less vertical boundary separating different water masses which contain differing suites of micro-organisms.

MODERN SEDIMENT DISTRIBUTION, SOUTHEAST INDIAN OCEAN

The circumpolar belts evident in maps of modern sediment distribution (see Lisitzin, 1962, 1972; Hays, 1967) consist of: 1, a southern, near-continent zone of glacial marine sediments - mostly pebbly muds with some biogenic detritus - which extends across the continental shelf of Antarctica to proximal portions of the abyssal plain; 2, a more northerly belt of siliceous ooze which extends up the southern flank of the mid-oceanic ridge, and 3, further north, a belt of calcareous, largely foraminiferal oozes, with clays and muds in sea-floor areas below the calcium carbonate compensation depth.

The broad belt of siliceous oozes, chiefly composed of diatom frustules, with some radiolarian and silicoflagellate tests, reflects the surface water zone of high biologic productivity which lies between the Antarctic Divergence to the south, at approximately 62° - 65°S lat., and the Antarctic Convergence, or Polar Front Zone, to the north at 52° - 55°S latitude. The highly productive nature of this zone depends on the upwelling of relatively warm, nutrient-rich water, the Circum-Polar Deep Water, in the region of the divergence, where it replenishes Antarctic Surface Water, and flows in a general northerly direction to sink in the Polar Front Zone.

The position of the northern boundary of the siliceous ooze zone, roughly coincident with the Polar Front, is governed by the present production of cold water in Antarctic regions, which in turn governs the intensity of vertical circulation patterns in the southern ocean. A zone of mixed siliceous-calcareous oozes that presently occurs in a 600-1000 km wide belt in the mid-oceanic ridge region (Connolly & Payne 1972), reflects the short term fluctuations in the position of the northern boundary of the siliceous ooze zone. The initiation of the Polar Front Zone at some time in the past must have been marked by, or followed by, the initiation of the belt of high diatom productivity - it is with the possible motion of this boundary between siliceous and calcareous sedimentation that the present paper is concerned.

SEDIMENT DISTRIBUTION IN LEG 28 SITES

In each of the sites examined, a down-hole transition from siliceous to calcareous sediments is evident. The transition is most clearly observable in those sites where pelagic sedimentation processes have dominated. In these sites, the transition is manifested as a change from diatom oozes in the upper part of the sequence, to calcareous nannoplankton oozes below. In the sites nearer the continent, viz Sites 267 and 268, the influence of terrigenous sediment is stronger, and the transition appears as a change from diatom-bearing or diatom-rich silts and clays above, to silts and clays with nannoplankton below.

The changes in sediment type are illustrated in Figure 1. In this diagram, the percentages of the main sediment components, classified here as the diatom, calcareous nannoplankton and detrital (= terrigenous) fractions, have been averaged for each core, and are illustrated in bar form on the right hand side of the general stratigraphic columns. Although the figures on which the averages are based were derived from ship-board examination of smear-slides, they are considered to be consistent enough to show gross changes in the proportions of the main sediment fractions.

At Site 265, high on the southern flank of the mid-oceanic ridge at a water depth of 3582 m., sedimentation has been wholly pelagic. Calcareous nannoplankton oozes and chalks constitute the main sediment type up to and including Core 15. The highest nannoplankton ooze (wherein nannoplankton are the major sedimentary component, in excess of 50 percent of the total sediment) occurs in Core 15-2, and is of middle Miocene age. All of the overlying sediments, including Core 14, are diatom oozes, without appreciable carbonate content. The oldest diatom ooze, in Core 14-6, is of early Pliocene (Gilbert Magnetic Epoch) age. The change from deposition of calcareous to siliceous oozes occurred somewhere between the middle Miocene and the early Pliocene. The diatom zones identified at this site suggest that a marked time-break is present between cores 14 and 15, which represent diatom zones 6 and 9 respectively. In terms of millions of years, these intervals respectively represent sediments laid down some 2.8 - 4.0 million years BP, and 9 - 12 million years BP (see biostratigraphic correlation chart, Ch. , this volume). The radiolarian zones, which have poorer resolution in this interval, do not indicate the presence of such a time-break.

At Site 266, the change from calcareous chalks and oozes below to siliceous oozes above is not so abrupt as at Site 265. The highest calcareous ooze occurs in Core 10-1, in what are probably late Miocene sediments; this interval is, however, overlapped by the lowest diatom ooze, downhole in Core 12-2. Diatom-rich sediments occur in fact as far down as Core 16, so that probably the whole of the middle and late Miocene, as represented at this site, constitutes a transition zone of mixed calcareous and siliceous sediments. Above the base of Core 9, which is of early Pliocene to latest Miocene age (4-6 m.y.), on the basis of diatoms, radiolarians and silicoflagellates, sediments are dominantly pure diatom oozes, with little admixture of other biogenic components or of detrital material. Below Core 16, which is earliest middle Miocene in age (14-15.5 m.y.) they are dominantly calcareous nannoplankton oozes, with some clay-rich intervals.

Three holes were drilled at Site 267, situated at the edge of the deep basin to the south of the Southeast Indian Ridge, and the transition from calcareous to siliceous sedimentary regimes is more difficult to recognize because the influence of terrigenous sediment is stronger here than at the pelagic sites further north. Nevertheless, at the combined site 267-267A, a basal interval of calcareous sedimentation is clear; calcareous oozes occur as high in the sequence as Core 4-1 (with an estimated nannofossil content in excess of 75 percent of the total sediment). The youngest of these oozes is of late Oligocene age, based on nannofossil data. Above this level, in Core 3, of early Miocene age, diatoms are the dominant biogenic fraction, although the sediment is largely detrital. True diatom oozes, with diatoms in excess of 50 percent of the total sediment, occur in Core 3A-2. The basic change between calcareous and siliceous biogenic regimes, however, can be broadly ascertained as having occurred in the interval late Oligocene - early Miocene, i.e. at an older date than at Site 266.

In Hole 267B, middle Miocene sediments are similarly dominated by a diatomaceous biogenic component. The late Eocene or early Oligocene sediments at the base of the sequence are nannofossil chalks; the middle and late Oligocene is missing.

Site 268, the southernmost in the line of sites between the crest of the southeast Indian Ridge and the Antarctic continental margin, has been influenced by terrigenous sedimentation to an even more marked degree than was Site 267. Sediments throughout the sequence penetrated are mainly silty clays, but the admixture of biogenic debris is sufficient to enable a change to be detected from a lower calcareous biogenic regime to a siliceous one in the upper part of the section. Calcareous nannofossil oozes occur in sediments as young as early Miocene (in Core 8-2) although the proportion of nannofossils in the cherty sequence in the deeper parts of the hole is extremely low. The upper limit of calcareous nannofossil deposition at this site lies broadly within the same time interval (late Oligocene - early Miocene) as that observed at Site 267. However, the presence of a substantial time-break between the youngest calcareous sediments and the oldest diatom ooze (early Pliocene, in Core 7-2) at Site 268 precludes precise identification of the time at which the change in biogenic sediment type occurred.

FACIES GEOMETRY

An overview of the sites on this north-south section suggests that, within the relatively broad limits of paleontological control, the boundary between calcareous and siliceous biogenic facies is diachronous, being older in the southern sites than in those to the north. At Sites 267 and 268 the change from nannofossil ooze deposition to a diatom depositional regime occurs within the late Oligocene - early Miocene interval; at Site 266, some 300 km to the north of 267, the transition begins in the middle Miocene and is complete by the earliest Pliocene. At Site 265, still further north, meagre evidence suggests that the late Miocene is a time of full-scale carbonate deposition; again, however, by the early Pliocene, the change to a siliceous sedimentary regime was complete at this site.

A first examination of such a situation might suggest that the diachronous form of the facies boundary is a result of a south to north migration of some factor which controlled the type of sediment accumulation on the sea-floor. Such a boundary might be envisaged as a kind of ancient Antarctic Convergence migrating northward in response to climatic cooling. However, interpretation in these relatively simple terms would have validity only in relation to a stable, immobile sea-floor. The same geometric situation, that of a facies boundary becoming older and deeper away from an active mid-oceanic ridge, could arise by the horizontal or vertical passage of the sea-floor itself through an oceanographic boundary which had remained relatively fixed through time (Frakes and Kemp, 1972).

In order to determine whether the observed diachronism can be ascribed to movement of an oceanographic boundary or alternatively, to sea-floor spreading motions with respect to a stationary boundary, it is necessary to remove the effects of spreading. Any apparent displacement remaining must reflect relative motion between the boundary and the ridge. Spreading effects can be removed by replotting each of the sites in its geographic or depth position for any particular point in time, that is, by "back-tracking" (Berger, 1972) the sites along the appropriate age-depth curve and thus depicting the sites in their respective positions at that time.

The construction of such a curve is made possible by the widespread correlation between sea-floor age and depth in widely separated oceanic areas (Sclater et al., 1971; Hays and Pitman, 1973). In Figures 2-5, Sites 265 to 267 have been plotted on an age-depth curve constructed using data from the published bathymetry (Hayes and Conolly, 1972), magnetic lineation ages (Weissel and Hayes, 1972), sediment isopachs (Houtz and Markl, 1972) and the leg 28 site results. Data for the longitudinal corridor from 105 E to 115 E were combined in arriving at the epirical curve of basement age vs depth for both the north and south flanks of the Southeast Indian Ridge and as shown in Figures 2-5. The basement depths are shown with estimates of the error bars at locations corresponding to well identified and dated sea-floor magnetic lineations. A smooth curve was then fitted by eye to the entire data set. The empirical curve is in general agreement with that derived by Hayes and Weissel (in prep.) using a much more rigorous mathematical approach, but it differs significantly from the average global age-depth relationship determined by Sclater et al. (1971).

In Figures 2-5, the present positions of Sites 265, 266 and 267 have been plotted in accordance with the age of the basal sediment. Age determinations based on magnetic lineations are all slightly older. Site 268 is not shown because paleontological control is very poor; this site is expected to occupy a position on the curve near 50 m.y., from magnetic lineation data. For Sites 265 and 266, the expected depth, the "A depth" of Berger (1972), as determined from this curve, is somewhat less than the real one, probably because of regional conditions. At Site 267, for instance, strong local basement relief is evident. Additionally, the error in terms of dating the sediment immediately above basement is not well known.

In order to evaluate any movement of the silica/carbonate facies boundary through time, several discrete intervals of time have been selected, and the sites have been back-tracked along the ridge profile to their paleodepositional depths for those particular intervals. Examination of the type of sediment being deposited at those points in space and time should then indicate the relative position of the facies boundary with respect to points on the ridge flank. The time intervals selected were based on radiolarian zones 5, 6 and 8, which correspond, approximately, to time intervals of 3.5 - 5.5 million years BP, 5.5 - 12 m.y. BP, and 13 - 14 m.y. BP respectively. In addition to the time intervals represented by these zones, the sites were also back-tracked for a paleontologically less-well-defined early Miocene interval, i.e. 16 - 22 m.y. BP. Time intervals defined by radiolarian zones were selected in preference to those defined by other fossil groups because contiguous zones could be recognized at all three sites plotted.

When back-tracking of Sites 267 and 266 is carried out for the oldest time intervals considered, i.e. for the periods 16 - 22 m.y. and 13 - 14 m.y., (Site 265 was not in existence at this time) it becomes evident that the boundary separating siliceous and calcareous ooze deposition intersects the ridge flank between the back-tracked positions of the two sites in each case. Taking the mid-point of the depth ranges of the back-tracked sites as an arbitrary estimate of the limits of the lithological boundary position, then the depth range of the facies boundary lies between 3360 m and 4250 m for the older positions (Fig. 2, spanning a time interval of some six million years), and 3620 m and 4420 m for the younger interval (Fig. 3).

When Sites 265, 266 and 267 are back-tracked to their range of position for the interval 5.5-12 m.y. BP (Fig. 4, Radiolarian zone 6), it is evident that the facies boundary is still positioned between Sites 267 and 266. The time interval at Site 266 is represented by a transition zone of mixed diatom and nannofossil deposition, so it is possible that there were small fluctuations of the boundary across the site during that period - that is, Site 266 lay near the boundary. For the boundary, the possible depths on the ridge flank range from 3980 m (the back-tracked depth of the youngest nannofossil ooze) to 4380 m. Considered together with the depth ranges for the older time intervals, this suggests that the boundary was positioned near bottom depth of about 3980 m, and about 300 km south of the ridge crest. Little movement of the boundary with respect to the ridge crest appears to have taken place within the interval 5.5-22 million years BP, although this observation implies an absolute northward migration of the boundary of about 450 km.

When the drillsites are back-tracked along the ridge profile to their early Pliocene positions (Fig. 5, Radiolarian Zone 5, 3.5 - 5.5 m.y.), then clearly, the silica/carbonate facies boundary lies to the north of Site 265, as diatom oozes are being deposited at all three sites during this interval. The boundary lies above Site 265 on the ridge flank i.e. between the ridge crest at 3000 m (or even to the north of it), and 3360 m. This represents a significant motion of the boundary with respect to the ridge crest, when compared with positions for the earlier time intervals. Because all sediments younger than early Pliocene are dominated by their diatom fraction, it appears that there has been no significant regression of this facies boundary in a southerly direction since that date - at least not in this particular sector of the southeast Indian Ocean.

All of the boundary motion discussed above refers to movement of the boundary with respect to the ridge crest only. A further complication remains, in that the Southeast Indian Ridge has almost certainly been migrating in a northerly direction, away from Antarctica (Weissel and Hayes, 1972). Available evidence suggests that Antarctica has remained relatively fixed with respect to the earth's spin axis since the Cretaceous (McElhinny, 1973; Lowrie and Hayes, this vol.), and thus Australia has migrated steadily northward since the early Tertiary. The ridge system itself probably maintained a near median position with respect to the Australian and Antarctic continents; its migration speed thus equalling approximately half the rate of separation of those continents, or about 2.5 - 3 cm per year. This being the case, it seems likely that the silica/carbonate facies boundary, which appears, on the evidence of back-tracking, to have maintained a constant depth position with respect to the ridge crest during the Miocene (5.5 - 22 m.y. BP), must have undergone a steady northward migration during that interval, moving at a rate comparable to that of the entire ridge system (2-3 cm/yr). In the early Pliocene the northward movement of the facies boundary appears to have accelerated abruptly with respect to the ridge; the relative northward displacement of the boundary was greater than 50 km and probably exceeded 300 km. The Polar Front zone now coincides roughly with the ridge crest whereas during the Miocene its ancient counterpart apparently lay about 300 km south of it.

PALEOCLIMATIC INTERPRETATION

Interpretation of the shift of the facies boundary in terms of climatic changes affecting the southeast Indian Ocean must be undertaken with caution in view both of the scarcity of data points offered by the present study, and inadequacies in our understanding of the physical factors presently controlling sedimentation in high southern latitudes. Whilst it is tempting to equate the factors which have in the past determined the siliceous/calcareous sediment boundary with the present Polar Front or Antarctic Convergence, the parallel is not exact, since the modern oceanic boundary separates diatomaceous ooze from calcareous foraminiferal ooze; through much of the Neogene, however, the ancient boundary separated diatomaceous sediment and calcareous nannoplankton ooze with only a few foraminifera.

The presence of nearly pure, deepwater carbonate sediments in high southern latitudes does indicate, however, that much warmer temperatures than those of the present day prevailed in these regions from at least the late Eocene until perhaps sometime in the middle Miocene. The presence of nannofossil chalks of late Eocene age in the base of Hole 267B and of early Miocene nanno oozes at Site 268 provides evidence for this.

At Site 268, the presence of ice-rafted sediment is firmly established back into the early Miocene (Piper, this vol., Chapt.); there is a possibility that it may be even older, extending back into the late Oligocene. Farther north, at Site 267, the presence of ice-rafted sand has been established in the middle Miocene. At Site 266, the presence of sand in wholly pelagic sequences testifies to ice-rafting processes which are evident only from the late Miocene onwards. The distribution of ice-rafted sediment in this sector thus shows the same diachronism as does the silica/carbonate boundary, with both becoming significantly younger towards the north. In the three sites mentioned, it is significant that ice-rafting begins in sediments in which a calcareous biogenic component is dominant; icebergs appear to have been present in the area and dropping sediment loads <u>before</u> the change to a siliceous sedimentary regime occurred.

The overall picture, then, appears to be one in which oceanic conditions were warm enough, up till the early to middle Miocene, to allow deposition of calcareous nannofossils at Sites 267 and 268, and in which, simultaneously, the earliest icebergs were melting and rafting debris. The change to deposition of diatom oozes or diatom-dominated sediments probably reflects a change to a cooler water regime, as evinced by fairly rapid changes in the probable early Miocene at Site 267, and by more gradual transition beginning in the middle Miocene at Site 266. This cooling followed after the initiation of iceberg sediment-rafting at each site.

Back-tracking of sites along an empirical age-depth curve suggests that the effects of this cooling were expanding outward from the continent at a relatively constant rate, from before the latest Miocene to the earliest Pliocene. The silica/carbonate boundary appears to have been maintained in a relatively constant position with respect to the ridge crest, while undergoing a systematic northward migration along with the ridge system itself. The distribution of ice-rafted debris suggests that iceberg melting first took place in a nearshore zone; this zone migrated steadily northward from the Antarctic continent before the late Miocene. Conditions even after the initiation of a siliceous biogenic regime at the southern sites appear to have been warm enough to allow melting of icebergs, with release of their sediment loads, before they reached localities as far north as Site 266.

A relatively rapid motion of the diatom ooze/nannoplankton ooze boundary appears to have taken place sometime in the interval 3.5 - 5.5 m.y. BP. This dating is as precise as present paleontological studies on Leg 28 sites permit. Whether or not this rapid northward boundary movement in fact represents the initiation of the Antarctic Convergence in its present form is unknown. Evidence bearing on the history of the boundary between diatom oozes and foraminiferal oozes awaits further drilling in areas to the north of Leg 28 drillsites.

In any case it seems reasonable to assume that the relatively sudden early Pliocene boundary shift to the north represents a sudden intensified chilling osfsurface waters. The suggestion of rapid cooling in the early Pliocene draws support from other sources. The truncation of seaward-dipping sequences in the Ross Sea appears to have occurred at about this time, probably from the erosive action of a grounded Ross Ice Shelf, which extended much beyond its present limits (Hayes et al., 1973). Furthermore, from observations of the northward movement of the siliceous ooze/glacial-marine sediment boundary offshore from the Adelie and George V Coasts, and from radiolarian and silicoflagellate data, Weaver (1973) suggested that a regional cooling occurred about 4.0 million years ago, with the initiation of an oceanic thermal structure similar to that of modern polar seas. Correlation of these events with that suggested by the present study of facies distributions in Sites 265 - 268 remains tentative in view of the broadness of paleontological dating.

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Text-figure explanations

Figure 1 : Stratigraphic and sedimentological record of sites making up a ridge flank to continental rise profile in the 105° - 110°E longitudinal corridor. The proportion of various sediment types is shown on the right of each column (see text for further explanation).

Figures 2 - 5 : Age-depth curve for the southeast Indian Ocean, with drill sites back-tracked to their paleodepths on the ridge flank for their early Miocene, middle Miocene, late to late middle Miocene and early Pliocene positions. Depth corrections are based on distance of interval under consideration above basement. (See text for derivation of curve and explanation of back-tracking process).

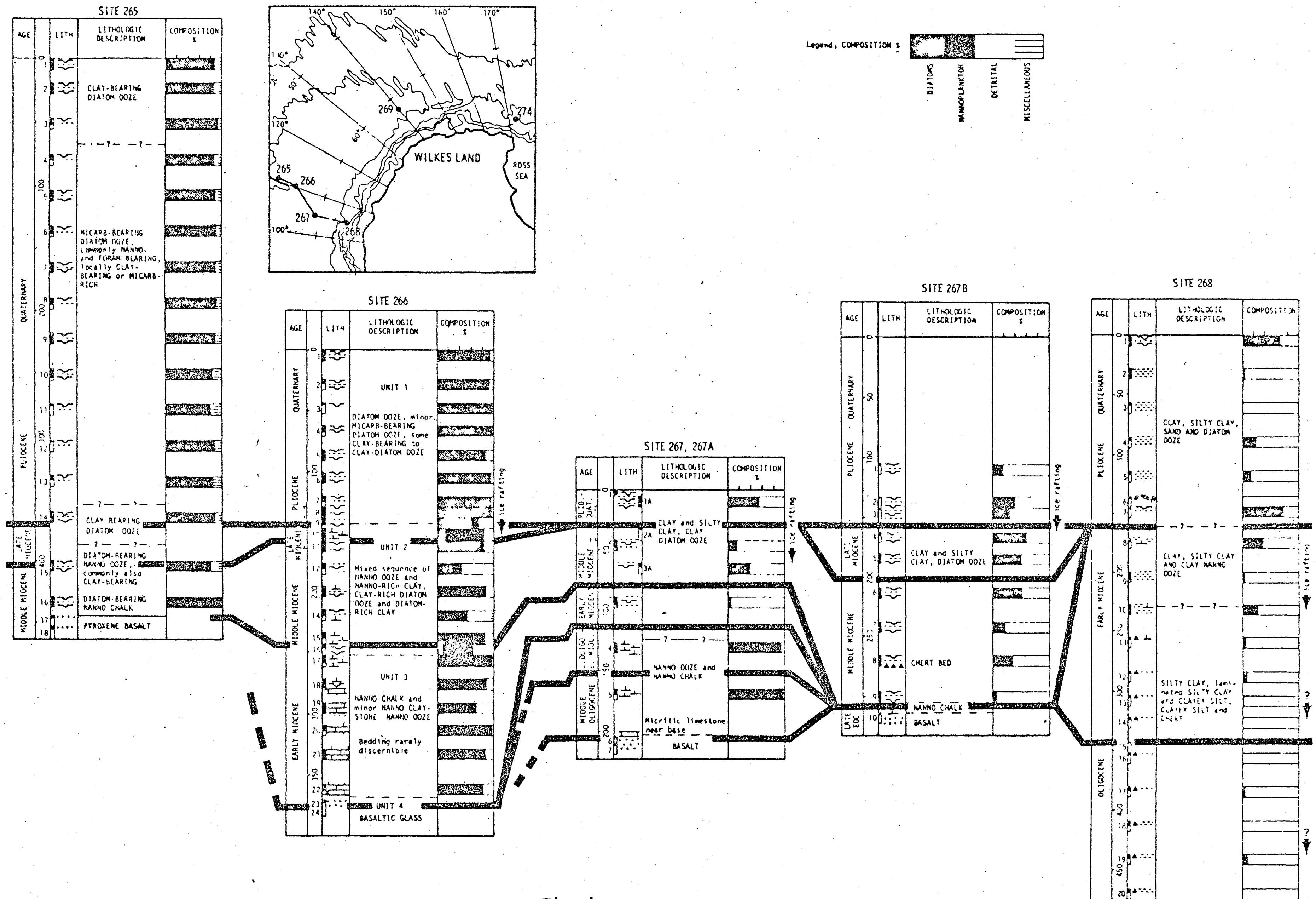
SITE 265
SITE 266
SITE 267, 267A
SITE 267B
SITE 268
AGE
LITH
LITHOLOGIC DESCRIPTION
COMPOSITION %
CLAY-BEARING DIATOM OOZE
MICARB-BEARING DIATOM OOZE, commonly NANNO- and FORAM BEARING, locally CLAY-BEARING or MICARB-RICH
CLAY BEARING DIATOM OOZE
DIATOM-BEARING NANNO OOZE, commonly also CLAY-BEARING
DIATOM-BEARING NANNO CHALK
PYROXENE BASALT
UNIT 1
DIATOM OOZE, minor MICARB-BEARING DIATOM OOZE, some CLAY-BEARING to CLAY-DIATOM OOZE
UNIT 2
Mixed sequence of NANNO OOZE and NANNO-RICH CLAY, CLAY-RICH DIATOM OOZE and DIATOM-RICH CLAY
UNIT 3
NANNO CHALK and minor NANNO CLAYSTONE NANNO OOZE
Bedding rarely discernible
UNIT 4
BASALTIC GLASS
CLAY and SILTY CLAY, CLAY DIATOM OOZE
NANNO OOZE and NANNO CHALK
Micritic limestone near base
BASALT
CLAY and SILTY CLAY, DIATOM OOZE
CHERT BED
NANNO CHALK
CLAY, SILTY CLAY, SAND AND DIATOM OOZE
CLAY, SILTY CLAY AND CLAY NANNO OOZE
SILTY CLAY, laminated SILTY CLAY and CLAYEY SILT, CLAYEY SILT and CHERT
QUATERNARY
PLIOCENE
LATE MIOCENE
MIDDLE MIOCENE
EARLY MIOCENE
MIDDLE OLIGOCENE
OLIGOCENE
LATE EOC
ice rafting
WILKES LAND
ROSS SEA
Legend, COMPOSITION %
DIATOMS
NANNOPLANKTON
DETRITAL
MISCELLANEOUS

Fig. 1

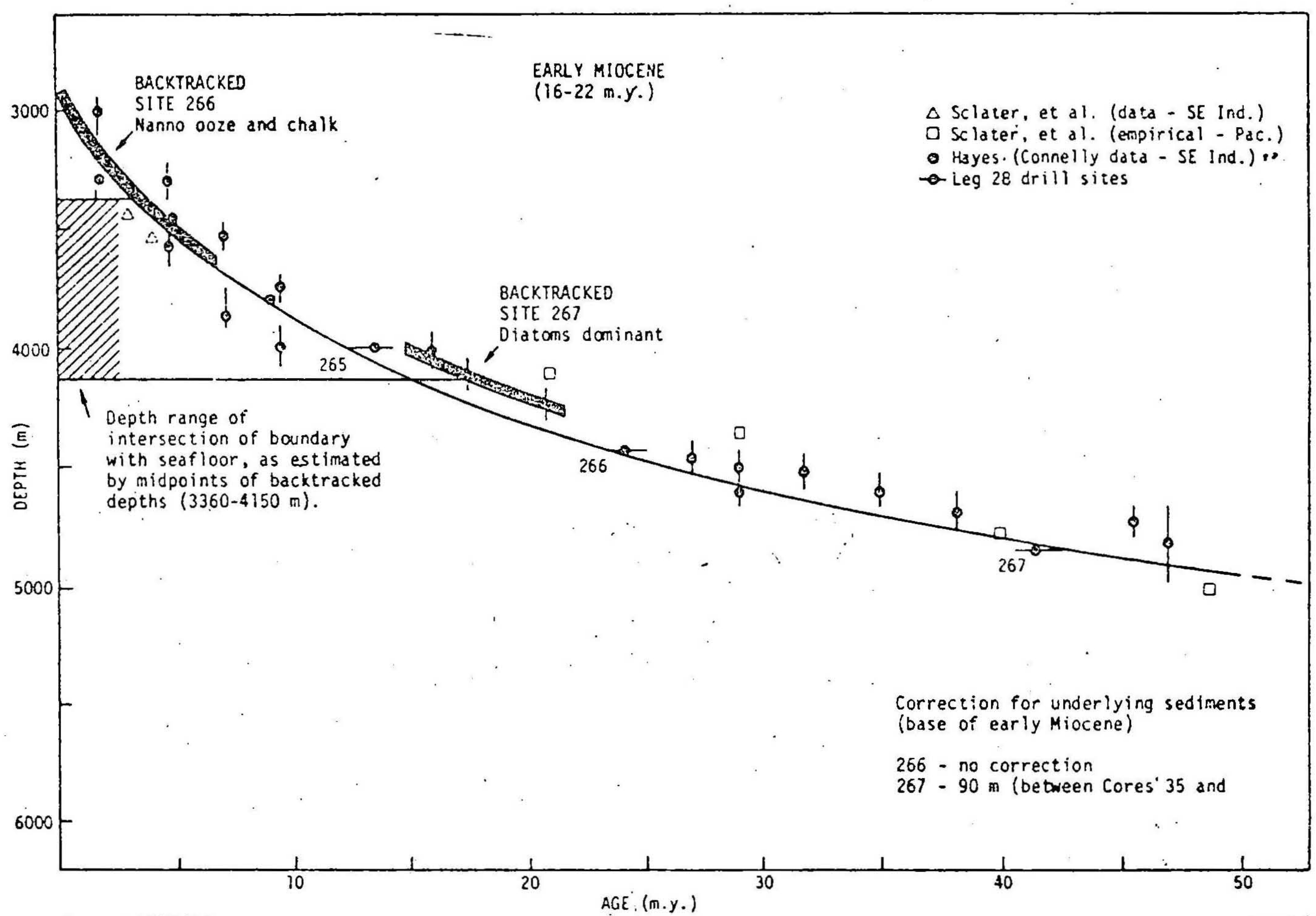

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Fig. 2

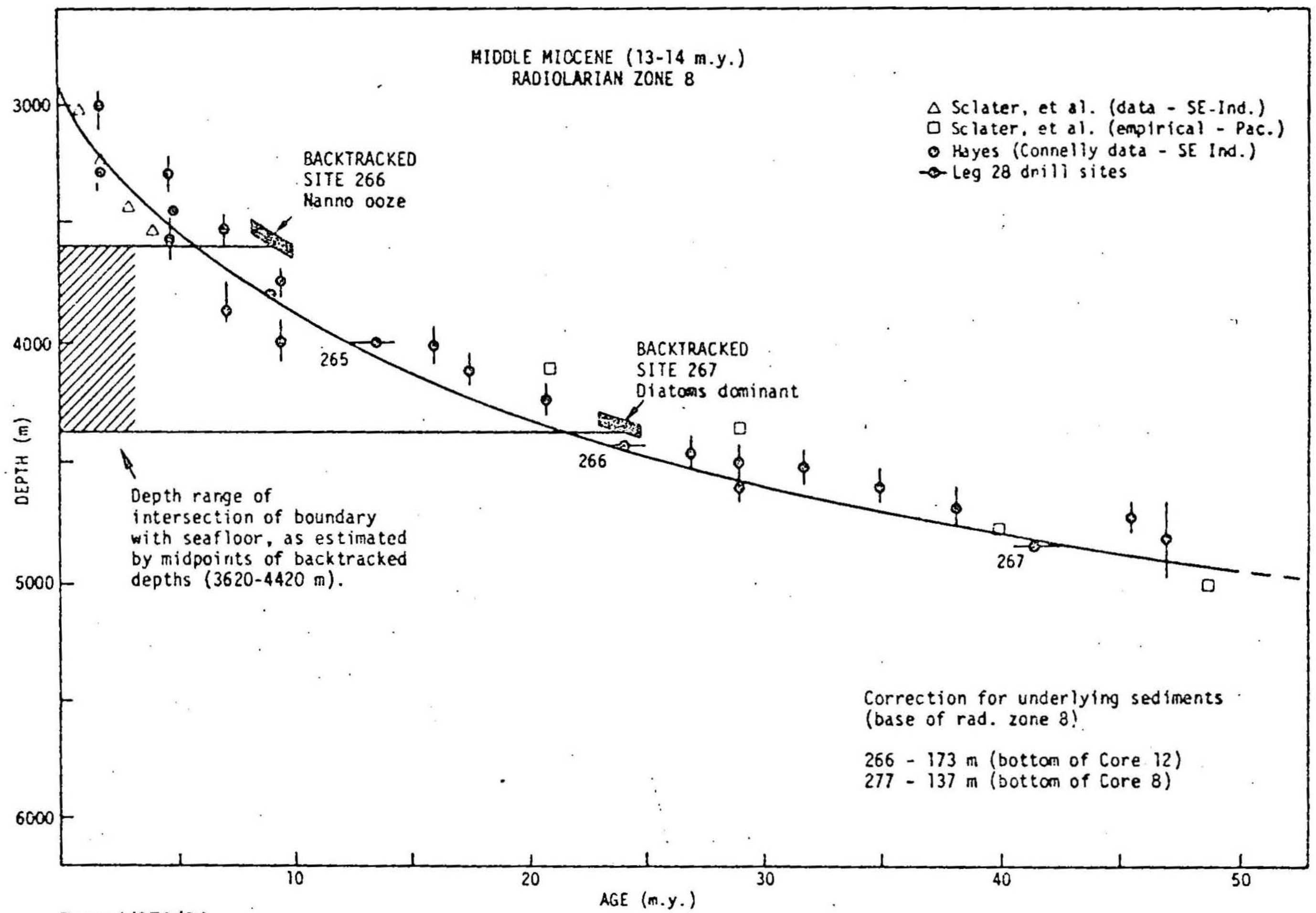
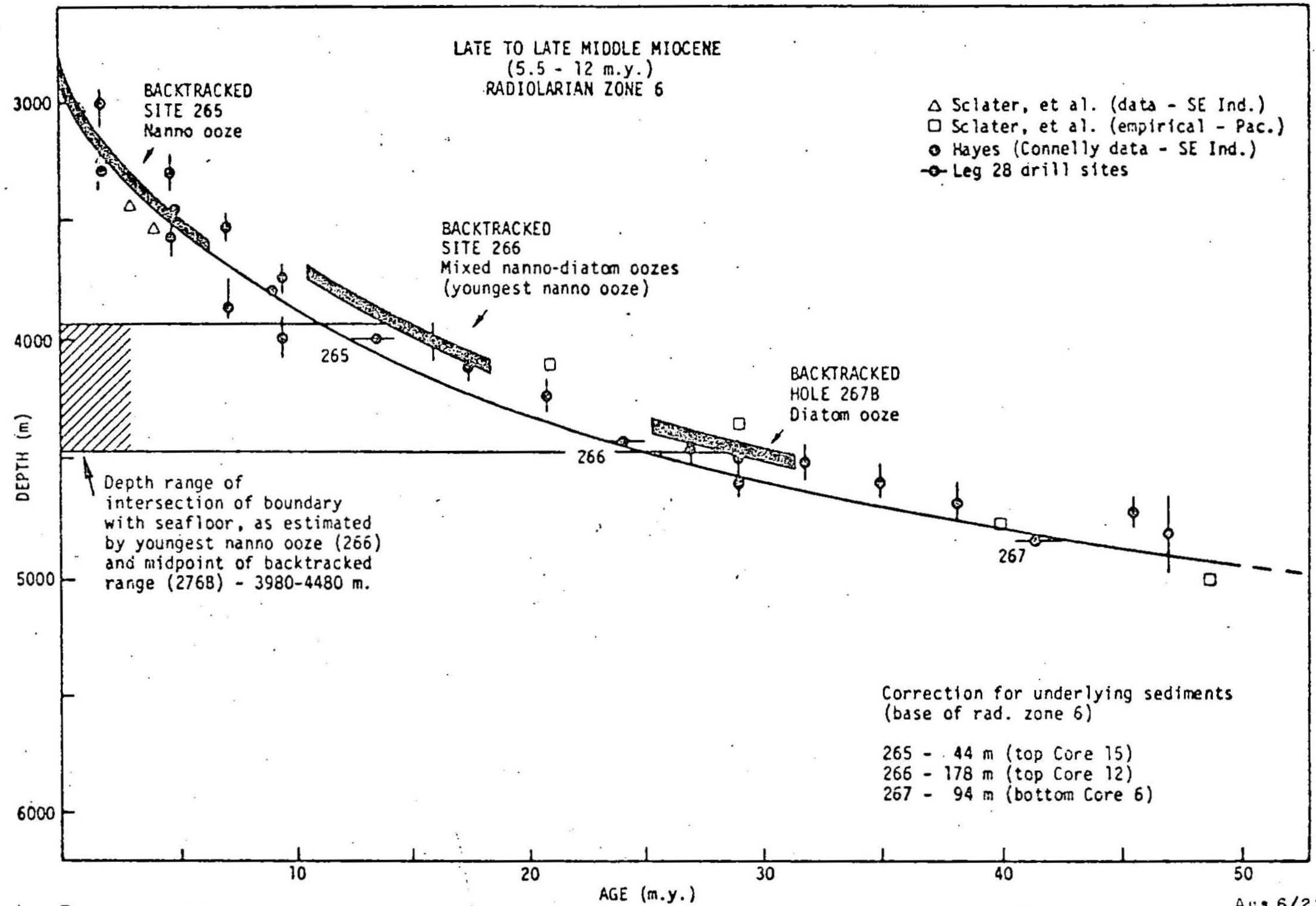

MIDDLE MIOCENE (13-14 m.y.)
RADIOLARIAN ZONE 8
△ Sclater, et al. (data - SE-Ind.)
□ Sclater, et al. (empirical - Pac.)
⊙ Hayes (Connelly data - SE Ind.)
-⊙- Leg 28 drill sites
BACKTRACKED
SITE 266
Nanno ooze
BACKTRACKED
SITE 267
Diatoms dominant
265
266
267
Depth range of intersection of boundary with seafloor, as estimated by midpoints of backtracked depths (3620-4420 m).
Correction for underlying sediments (base of rad. zone 8)
266 - 173 m (bottom of Core 12)
277 - 137 m (bottom of Core 8)
DEPTH (m)
3000
4000
5000
6000
10
20
30
40
50
AGE (m.y.)

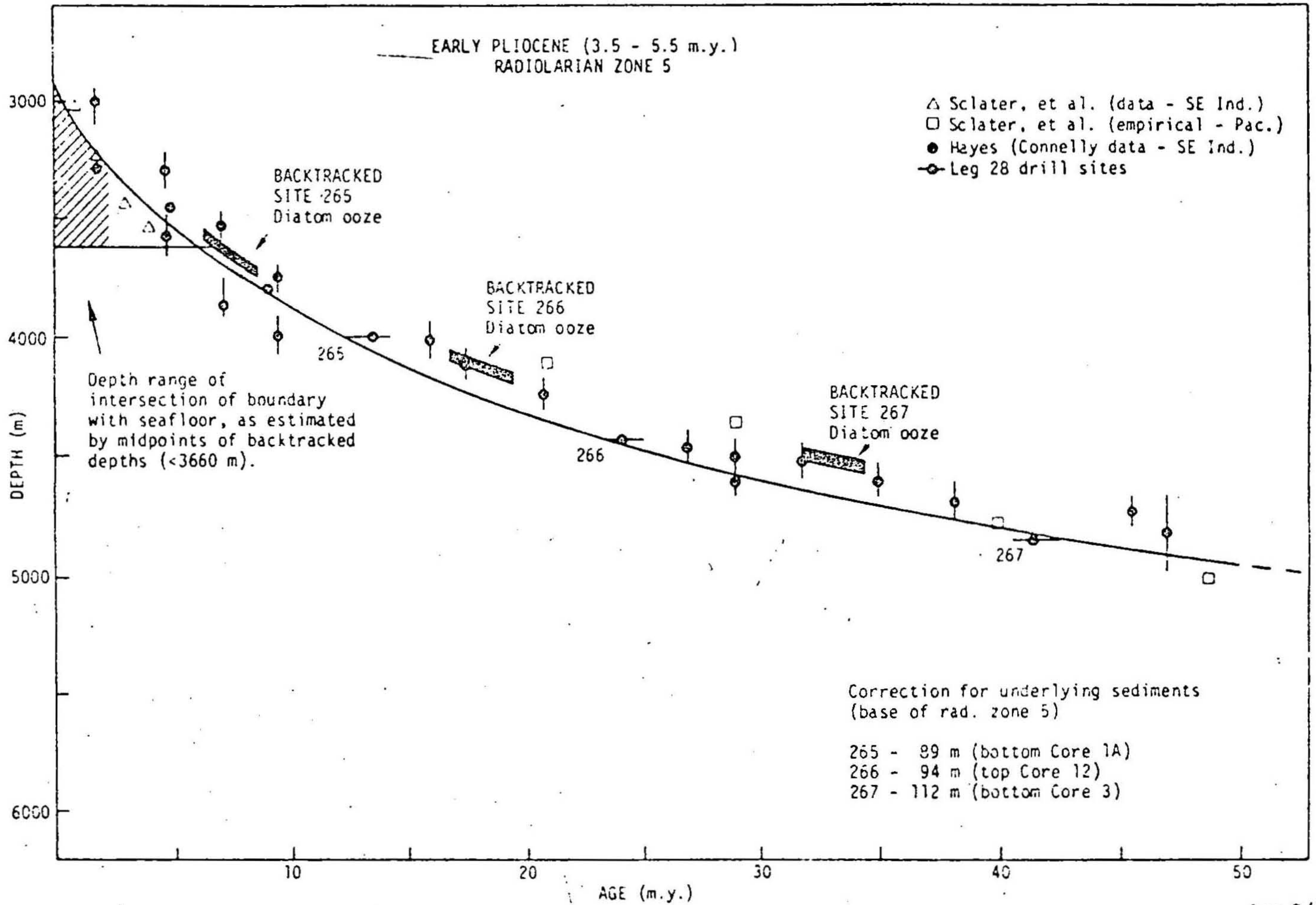
Fig. 3



Record 1974/94

Aus 6/220

Fig.4



Record 1974/94 Aus 6/221

Fig. 5