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PROBING THE LIMITS OF NANNOFOSSIL STRATIGRAPHIC RESOLUTION IN THE SOUTHERN HIGH LATITUDES

CONTENTS

Key words: calcareous nannofossils, biostratigraphy, high southern latitudes.

ABSTRACT

The recovery of two nearly 300 m-long Maastrichtian to Miocene carbonate sections at 65° South Latitude cored at water depths between 2100 and 3000 m on Maud Rise in the Weddell Sea has provided an unprecedented opportunity to assess the extent to which commonly used low to mid latitude calcareous nannofossil zonations can be extended into the high southern latitudes. Previous studies of abbreviated sections at 50° South (Falkland Plateau) in the South Atlantic had indicated that lower latitude Cenozoic zonations might have quite limited application at such high latitudes, but this is not the case for those intervals characterized by equitable, non-glacial global climates, particularly the Paleocene through lower Eocene intervals.

On Maud Rise, all of the Paleocene zones of MARTINI (NP1-NP9) can be recognized or approximated, but there are some problem intervals. As in most deep sea sections, *Ellipsolithus macellus* (basal marker for NP4) is not present, and an alternate marker, *Prinsius martinii*, is used to roughly approximate that datum level. *Discoaster mohleri* and *Heliolithus riedelii* are sporadic in their occurrences, and the boundaries of Zone CP6 are difficult to delineate. All other zonal markers are present, and discoaster reach their maximum diversity of about 5 species during warm intervals in Zone NP9, despite the fact that the overall assemblage has a distinctly cool water, high latitude composition.

The base of the earliest Eocene Zone NP10 is delineated by rare *Tribrachiatus bramlettei*, an unexpected find at this deep sea locality, which is located 700 km north of the East Antarctic continental margin. The distribution of this taxon is apparently limited more by paleo-water-depth than by the proximity of land. Zones NP14-15 are combined due to the sporadic occurrences of *Discoaster sublodoensis*, *D. lodoensis* and *Nannotetrina fulgens*. At this point, the low to mid latitude zonation begins to break down due to the apparent absence of taxa such as *Chiasmolithus gigas*, which is present in the region of the northern Antarctic Peninsula. Also absent are *Rhabdosphaera inflata*, *R. gladius* and *Discoaster saipanensis*.

The remainder of the middle Eocene, the upper Eocene and the Oligocene at Maud Rise can be subdivided using a broad zonal concept, but only by using temperate markers supplemented by additional datums. Nine provincial zones are recognized for the in-

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terval from NP16 to NP23 using first or last occurrences of various species of *Reticulofenestra* and *Chiasmolithus* plus *Isthmolithus recurvus*. No discoasters were present in this interval, thus the Eocene/Oligocene boundary could not be delineated; nor was *Clausicoccus fenestratus* useful as it was rare or absent at this latitude. Last, the Oligocene/Miocene boundary could not be approximated by the LO of *Reticulofenestra bisecta*, which was rarely present in the upper Oligocene. The LO and the least common occurrence of this taxon are strongly time transgressive from the mid to the extreme high latitudes, and cross the LO of *Chiasmolithus altus* between the Falkland Plateau and Maud Rise. As on the Falkland Plateau, no useful zonation of the Miocene is possible in the extreme high latitudes, due to the very low diversity (less than 3 or 4 species throughout). Despite such difficulties, the middle Eocene to Oligocene zonation is sufficient to allow the nannofossil assemblages to be used for paleoenvironmental analysis, and Maud Rise will serve as the southern anchor for all such studies in the South Atlantic.

Elsewhere in the Weddell Sea, thin upper Oligocene nannofossil oozes were discovered on the margin of East Antarctica at ODP Site 693. These occurrences plus those at Maud Rise and the presence of reworked Eocene nannofossils in glacial tills on the Antarctic continent and elsewhere suggest that nannofossils or even nannofossil ooze deposition may well have occurred within the intracratonic basins of Antarctica at times during the Paleogene.

RIASSUNTO

Il recupero sul Maud Rise del Mare di Weddell, a 65° di latitudine Sud, di due sezioni carbonatiche, potenti circa 300 metri, ed estese cronologicamente dal Maastrichtiano al Miocene, ha fornito la prima opportunità di stabilire fino a che punto le zonazioni a nannofossili standard delle basse e medie latitudini si possano estendere alle alte latitudini meridionali. Studi precedenti su sezioni del Falkland Plateau (50° Sud) ne avevano dimostrato la scarsa applicabilità a latitudini così elevate, se non durante periodi di tempo caratterizzati da condizioni non glaciali, con bassi gradienti climatici, come, in particolare, il Paleocene e l'Eocene inferiore.

Tutte le zone del Paleocene di Martini (NP1-NP9) si possono individuare in maniera più o meno precisa sul Maud Rise, seppure con alcuni intervalli problematici. Come avviene nella maggior parte delle sezioni di mare profondo, non è presente *Ellipsolithus macellus* (*marker* per la base della Zona NP4) ed in sua vece viene usato un *marker* alternativo, *Prinsius martinii*, per approssimare questo *datum level*. *Discoaster mohleri* e *Heliolithus riedelii* sono presenti sporadicamente e i limiti della Zona CP6 sono difficili da tracciare. Tutti gli altri *marker* zonali sono presenti ed i discoasteridi raggiungono il massimo di diversità, con circa cinque specie, durante gli intervalli caldi nella Zona NP9, nonostante l'associazione abbia complessivamente una composizione di acqua fredda e di alta latitudine

La base della prima zona dell'Eocene (Zona NP10) è contraddistinta dalla presenza di rari *Tribrachiatus bramlettei*, ritrovamento inatteso in questa località di mare profondo, 700 Km a Nord del margine continentale orientale dell'Antartide. La distribuzione di questo *taxon* sembra limitata più dalla paleoprofondità dell'acqua che dalla vicinanza del continente. Le zone NP14-15 sono combinate a causa della presenza sporadica di *Discoaster sublodoensis*, *D. lodoensis*, e *Nannotetrina fulgens*. A questo punto la zonazione di bassa e media latitudine inizia a non funzionare più per l'apparente assenza di forme quali *Chiasmolithus gigas*, presente nella Penisola Antartica settentrionale. Anche *Rhabdosphaera inflata*, *R. gladius* e *Discoaster saipanensis* sono assenti.

Il resto dell'Eocene medio, l'Eocene superiore e l'Oligocene nel Maud Rise possono essere suddivisi con un concetto zonale ampio, soltanto usando *markers* temperati coadiuvati da eventi addizionali. Nell'intervallo da NP16 a NP23 sono state riconosciute nove zone regionali usando la prima o ultima comparsa di varie specie di *Reticulofenestra* e di *Chiasmolithus* oltre ad *Isthmolithus recurvus*. In questo intervallo risultano mancanti i discoasteridi, e pertanto non è stato possibile riconoscere il limite Eocene/Oligocene; neppure *Clausicoccus fenestratus* risulta utilizzabile in tal senso in quanto raro od assente a queste latitudini. Infine, non è stato possibile riconoscere il limite Oligocene/Miocene mediante la LO di *Reticulofenestra bisecta*, rara nell'Oligocene superiore. La LO e l'ultima presenza comune di questo *taxon* sono fortemente tempotrasgressive fra le medie ed alte latitudini ed intersecano la LO di *Chiasmolithus altus* tra il Falkland Plateu e il Maud Rise. Analogamente a quanto riscontrato nel Falkland Plateau, non è possibile suddividere biostratigraficamente il Miocene alle alte latitudini estreme a causa della bassissima diversità tassonomica (meno di 3 o 4 specie in tutto). Nonostante queste difficoltà, la zonazione dall'Eocene medio all'Oligocene consente di utilizzare le associazioni a nannofossili per analisi paleoambientali, ed il Maud Rise potrà essere il punto di riferimento meridionale per gli studi di questo tipo nel Sud Atlantico.

In un'altra località del Mare di Weddell, nel Site 693 dell'ODP sul margine dell'Est Antartide, sono stati recuperati sottili livelli di fanghi a nannofossili dell'Oligocene superiore. Questi ritrovamenti, insieme a quelli del Maud Rise, e la presenza di nannofossili eocenici rimaneggiati nelle tilliti del continente Antartico e di altre località, suggeriscono che durante il Paleogene possa essersi a volte verificata deposizione di nannofossili o perfino di fanghi a nannofossili nei bacini intracratonici dell'Antartide.

INTRODUCTION

Two nearly 300 m-long Maastrichtian to Miocene carbonate sections cored at 65° South Latitude on Maud Rise in the Weddell Sea (ODP Sites 689 and 690; Figs. 1 and 2) comprise the southern anchor of a latitudinal transect of DSDP/ODP drill holes through the South Atlantic basin. This provides an unprecedented opportunity to assess the extent to which commonly used low to mid latitude calcareous nannofossil zonations can be traced into the high southern latitudes. The acquisition of such complete and extensive carbonate sections during ODP Leg 113 in January, 1987, was something of a surprise. Previous efforts at 50° South (Falkland Plateau) during two drilling campaigns (DSDP Legs 36 and 71) had recovered only fragmentary Cenozoic carbonate sections for which the application of lower latitude zonations had been rather limited (Fig. 3). Although the DSDP Leg 71 results indicated that more extensive Paleogene carbonate sections were present in the region, the drilling capabilities of the D/V GLOMAR CHALLENGER used for that expedition did not allow successful coring of longer sections given the prevailing weather and current conditions (WISE *et al.*, 1985).

With the conclusion of the DSDP phase of ocean drilling in 1983, the presence of appreciable nannofossil oozes and chalks adjacent to or on the margins of the Antarctic continent remained a matter of some doubt. Early drilling in the Pacific sector of the Southern Ocean at 59°S had indicated that nannofossil ooze accumulated at ridge crest depths within 600 km of the continent at Site 267 until at least the late Eocene, but that at some time thereafter calcareous phytoplankton had migrated northward as surface waters cooled to inhospitable temperatures, as indicated by the presence of upper Oligocene, glacial-marine sediments devoid of nannofossils in the Ross Sea (KEMP *et al.*, 1975).

Maud Rise is a large, isolated volcanic feature located 700 km off the coast of East Antarctica. Drill Sites 689 and 690, situated near the crest and on the flank of the rise at water depths of 2080 and 2914 m respectively, accumulated pelagic sediments deposited above the regional CCD until latest Miocene time, at which point the full glaciation of the Antarctic continent and the establishment of a true Antarctic surface water mass drove nannoplankton from the area. This event was preceded by a long term deterioration of climate that began around the beginning of middle Eocene time and caused a generally progressive decrease in diversity of nannofossil assemblages. Beyond the early/middle Eocene transition, major drops in diversity occurred during

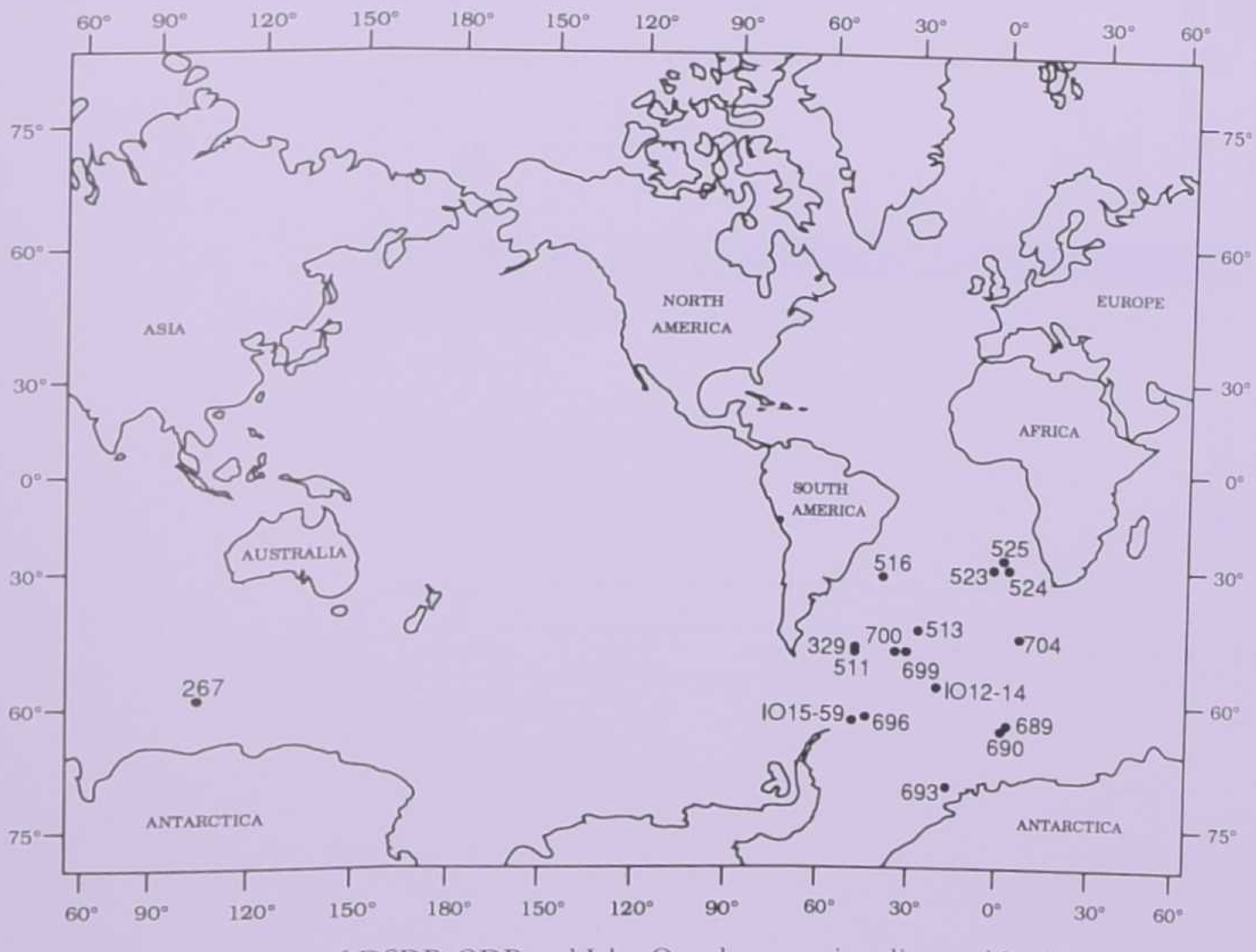

FIG. 1 - Locations of DSDP, ODP and Islas Orcadas core sites discussed in this paper.

FIG. 2 - Lithologic columnar sections for ODP Sites 689 and 690 on Maud Rise, Weddell Sea.

FIG. 3 - Cenozoic calcareous nannofossil zones recognized in the region of the Falkland Plateau following the completion of DSDP Legs 36 and 71 (after WISE, 1988, fig. 11).

the late Eocene, near the early/middle Oligocene boundary, and at the end of the Oligocene. Each drop served to eliminate low to mid latitude zonal markers until insufficient "standard" markers are left to zone the Miocene sediments in the region (WISE *et al.*, 1985). We do not review the attendant record of Cenozoic climatic deterioration here, but for the Southern Hemisphere region under discussion, refer the reader to summaries by KENNETT (1977, 1978) and KENNETT and BARKER (1990).

The purpose of this paper is to outline the nannofossil zonation for the Maud Rise sites and to compare it with those for the lower latitudes of the South Atlantic as a means of predicting where one can expect to find datable nannofossil oozes in the high southern latitudes and the degree of zonal resolution one might expect to achieve for such sediments. The detailed nannofossil biostratigraphies for these sequences are given by POSPICHAL and WISE (1990a, b, c), who used primarily the OKADA and BUKRY (1980) zonal compilation, and by WEI and WISE (1990a), who adopted a highly modified version of that and other zonal schemes. A calibration of nannofossil datum levels with the geomagnetic polarity time scale for the South Atlantic region is given by WEI and WISE (1989, 1990a), and an analysis of mid Cenozoic nannofossil biogeographic gradients across this basin is given by WEI and WISE (this volume and 1990b).

COMPARISON OF ZONES BY LATITUDE

Zonal subdivisions recognized by various authors for Maastrichtian to Holocene DSDP/ODP drill sites across the South Atlantic are given in Figures 4 and 5. Sites were selected that provide the most complete, representative sections with moderate to good preservation at mid (30°S), high (50°S), and extreme high (65°S) latitudes. To facilitate comparison, all zones reported regardless of the schemes originally used by the authors cited in the figure captions, are normalized to the SISSINGH (1977) and MARTINI (1971) zonal compilations for the Mesozoic and Cenozoic respectively, because these are the schemes that have been most commonly used in this region. Those compilations are assumed to define complete, ideal equatorial to mid latitude sections, and thus provide a general standard based on a maximum diversity of taxa and datum levels.

The actual number of nannofossil zones recognized at any given site for a particular time inter-

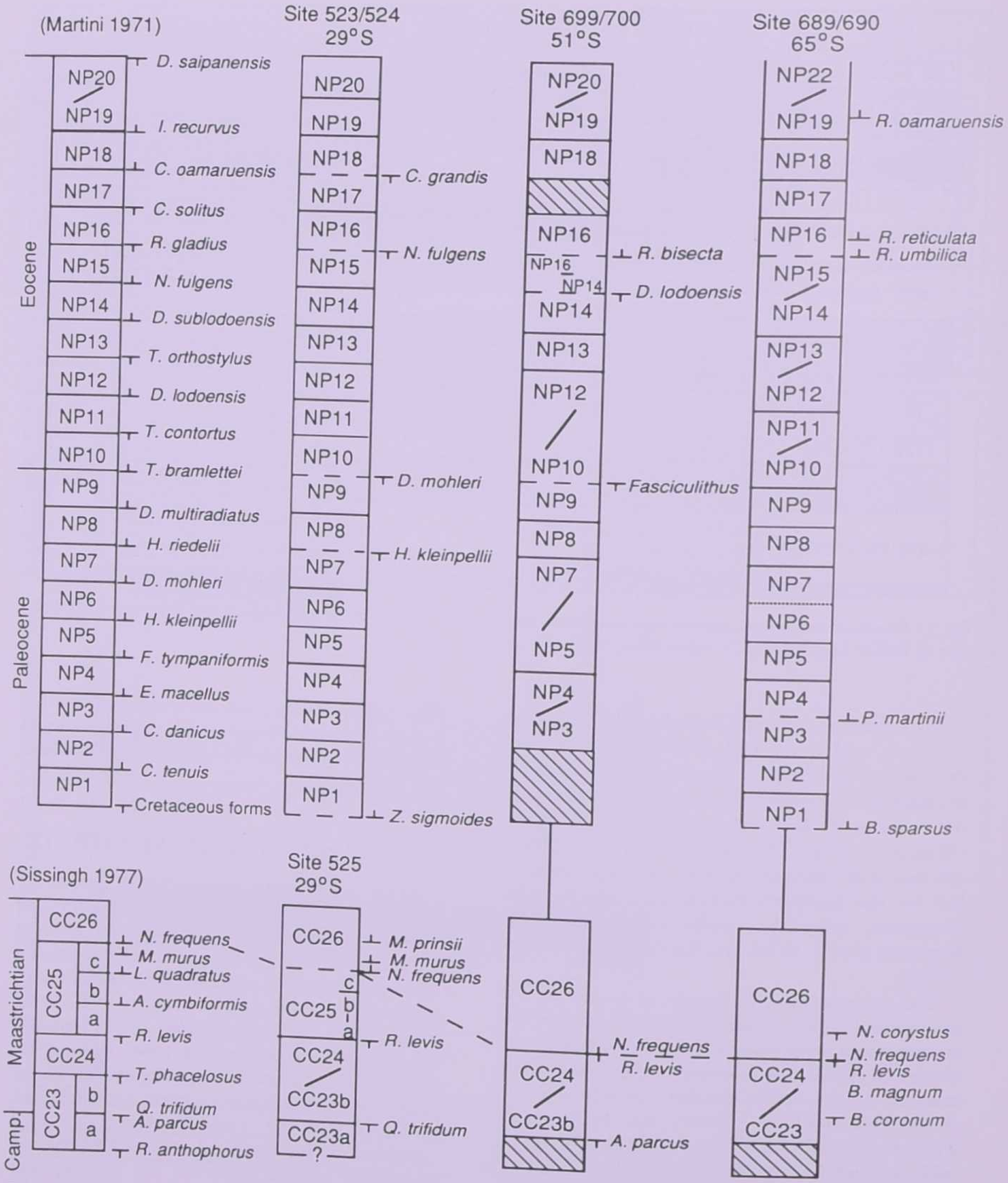

FIG. 4 - Latitudinal transect across South Atlantic DSDP/ODP drill sites illustrating the uppermost Cretaceous and lower Cenozoic nannofossil in zones distinguished in terms of the MARTINI (1971) zonal compilation. Zonal boundaries are dashed where an author has substituted a secondary marker species for the defining taxon. A dotted boundary indicates uncertainty because the zonal marker was very rare or sporadic in its occurrence. From left to right, data for the sites indicated were taken from the following sources: Sites 523/524, PERCIVAL (1984); Site 525, MANIVIT (1984); Sites 699/700, CIESIELSKI, *et al.* (1989); Sites 689/690, POSPICHAL and WISE (1990a, b, c) and WEI and WISE (1990a).

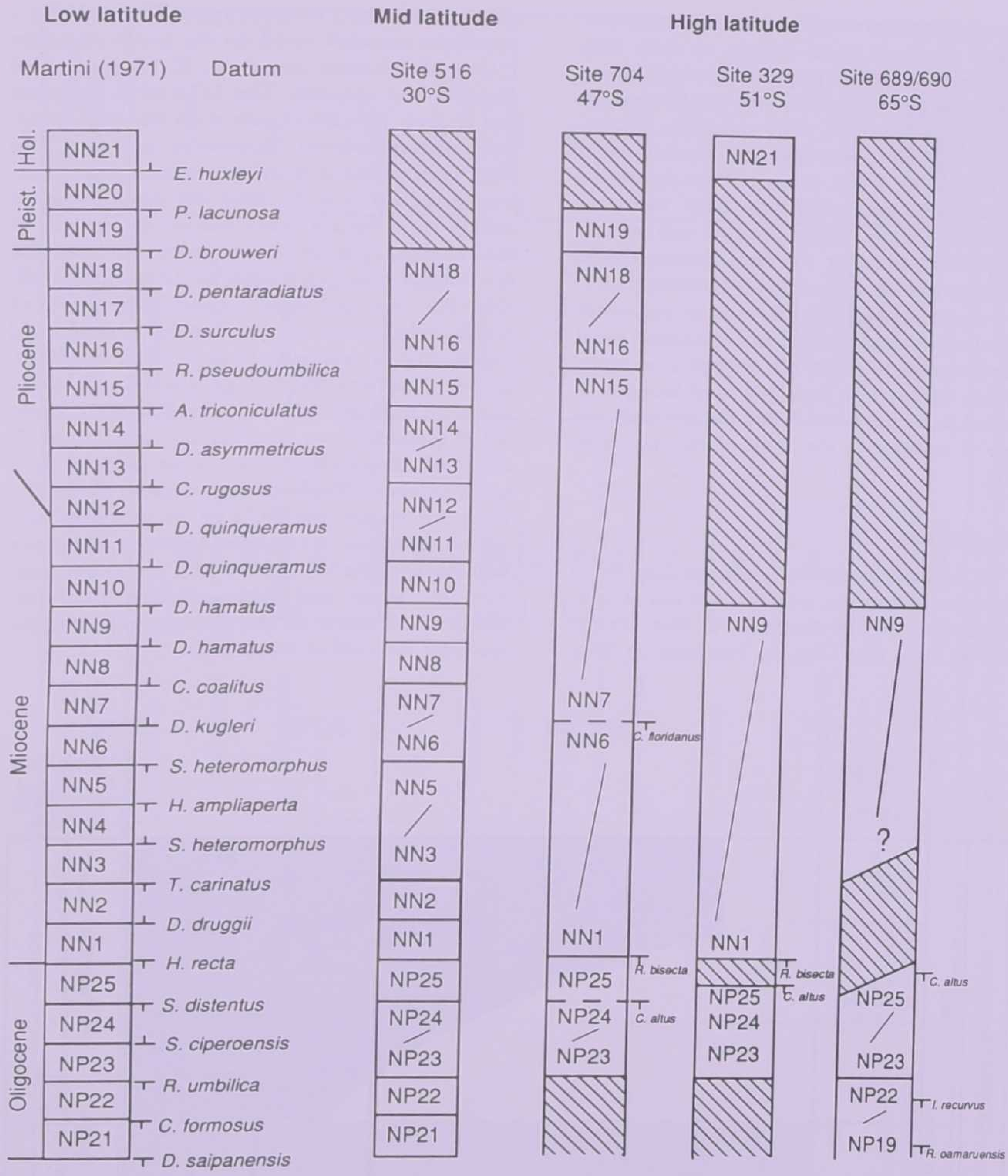

FIG. 5 - Latitudinal transect across South Atlantic DSDP/ODP drill sites illustrating the upper Cenozoic nannofossil zones distinguished in terms of the MARTINI (1971) zonal compilation. Zonal boundaries are dashed where an author has substituted a secondary marker species for the defining taxon. From left to right, data for the sites indicated were taken from the following sources: Sites 516, BERGGREN *et al.* (1984); Site 704, CIESIELSKI, KRISTOFFERSEN *et al.* (1989); Site 329, WISE and WIND (1977); Sites 689/690, WEI and WISE (1990a).

val is dependent on paleolatitude, paleo-water depth, degree of preservation, completeness of the section, and perhaps the proximity to continental margins where diversities may be higher (see ROTH and BERGER, 1975, and WISE, 1982, for discussions of these factors). As the sites shown in Figures 4 and 5 are all oceanic and represent similar water depths (all above 3000 m), the primary factor that would have controlled diversity and density of zonal datums at these sites would have been paleotemperature, which for any given time interval at these sites can be approximated by paleolatitude (WEI and WISE, this volume and 1990b). As summarized for this region by WISE (1981, 1988), in general the number of identifiable zones, particularly those based on tropical index taxa, should decrease with increasing latitude, and after the early Eocene, should decrease, with the progression of Cenozoic time.

It should be noted that investigators sometimes substitute different index taxa for standard zonal markers while retaining the original zone name. Where this has been done, the zonal boundary is dashed in Figures 4 and 5, and the substitute datum is indicated to the right of that boundary line.

MAASTRICHTIAN

Of the six Maastrichtian zones and subzones of the SISSINGH zonation, only two intervals of combined zones could be recognized at Sites 689 and 690 on Maud Rise (Fig. 4). POSPICHAL an WISE (1990a), therefore, adapted from WIND (1979) a provincial zonation based on the last occurrences (LO's) of *Biscutum coronum, B. magnum,* and *Nephrolithus corystus*. The LO's of *B. magnum* and *R. levis* coincide closely with the first occurrence of *Nephrolithus frequens* at the Maud Rise sites, perhaps due to missing or incompletely recovered section (Fig. 6), thus the exact sequence among these datums could not be determined at this locality. It is apparent, however, from the few magnetostratigraphically dated sections available (POSPICHAL and WISE, 1990a), that the FO of *Nephrolithus frequens* transgresses time toward the equator as originally hypothesized by WORSLEY and MARTINI (1970) (Figs. 4 and 6). Thus SISSINGH's *Arkhangelskiella cymbiformis* Zone (CC25), which is an interval or "gap" zone, is displaced completely in the higher latitudes by a much expanded *Nephrolithus frequens* Zone. For the same reason, the FO's of *N. frequens* and *Micula murus* are transposed between the lower latitudes and Site 525 (29°S). The low to mid latitude *M. murus* and *Lithraphidites quadratus*, which are common in the low to mid latitudes, were not observed at Maud Rise.

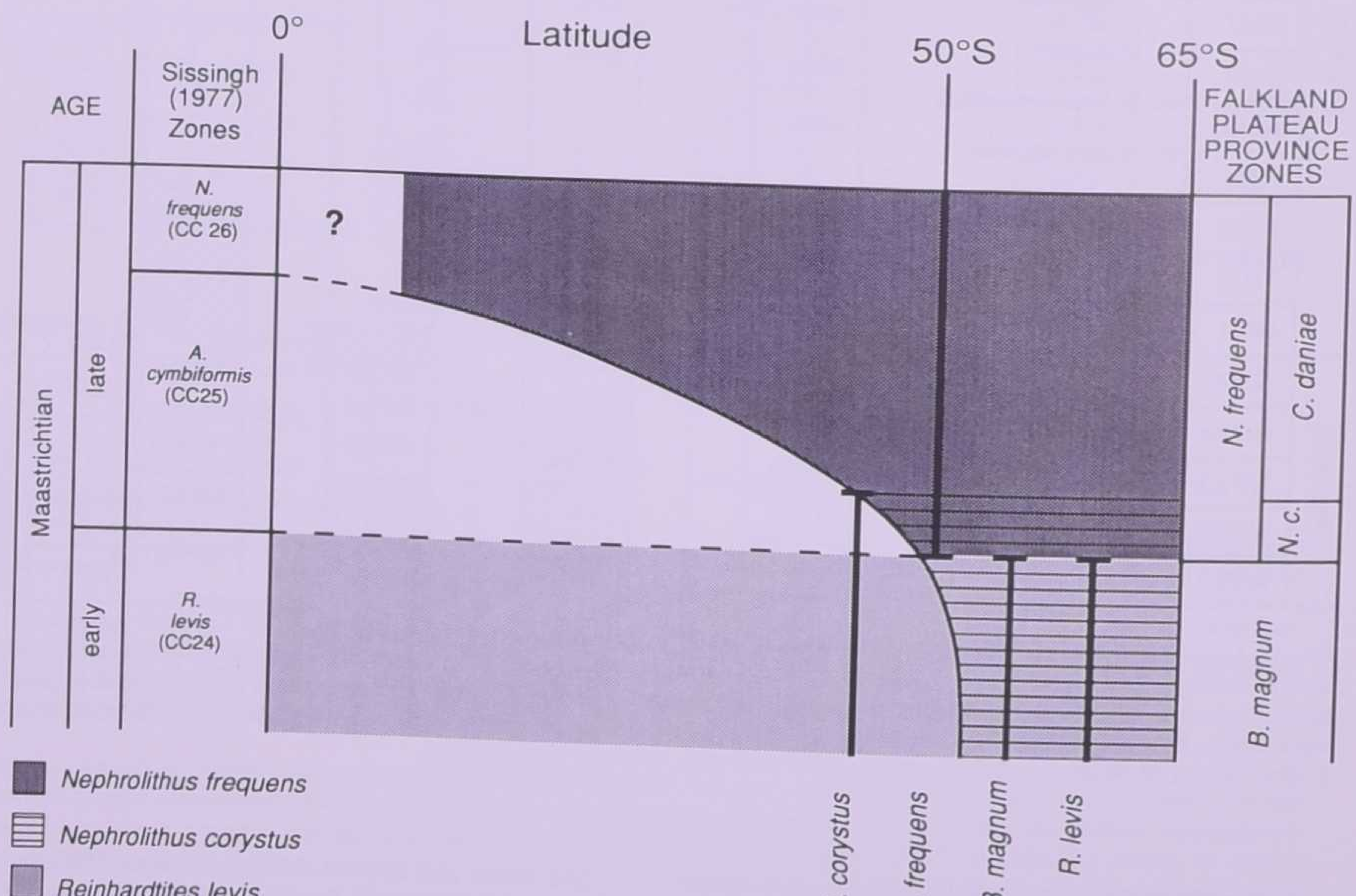

FIG. 6 - Idealized depiction of the stratigraphic relationships among *Nephrolithus frequens, N. corystus* and other selected taxa correlated to latitude and age (from POSPICHAL and WISE, 1990a, fig. 7).

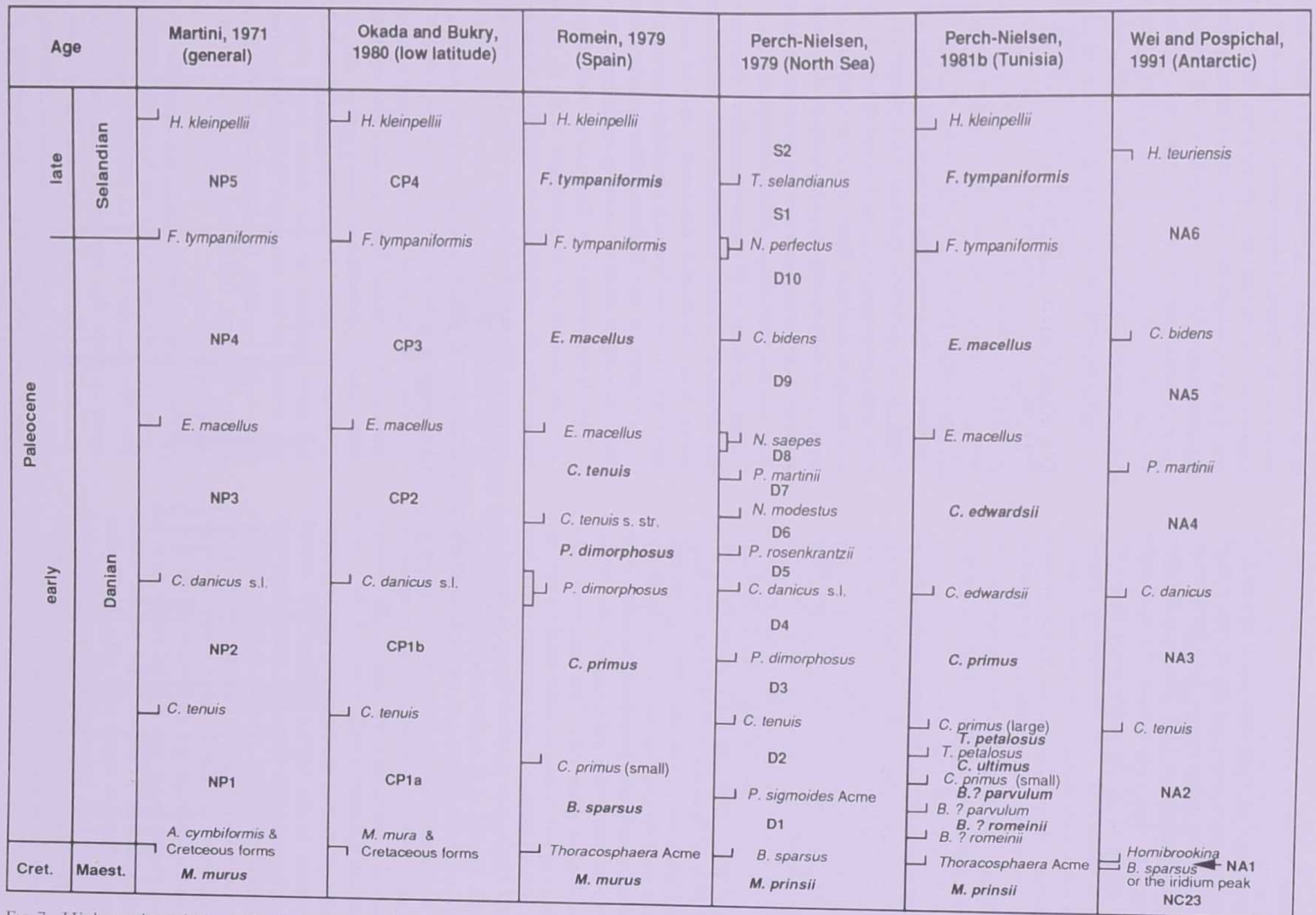

FIG. 7 - High southern latitude Danian nannofossil zonation developed by WEI and POSPICHAL correlated with other zonations (from WEI and POSPICHAL, 1991, fig. 2).

Paleocene

The succession of Paleocene zonal markers is remarkably uniform across the entire spectrum of latitudes, and few substitutions have been made. The loss of resolution at 51°S (Fig. 4) is attributed to less than ideal preservation of the sections because nearly all of the zones could be distinguished at Maud Rise. The cosmopolitan aspect of these zones is attributed to the generally equitable climates of the Paleocene, which became warmer toward the end of that epoch (Stott *et al.*, 1990), in time to ensure the widespread distribution of the warm water loving discoasters, which had evolved by NP7 time.

Although rare, the FO of *Biantholithus sparsus* is useful for delimiting the K/T boundary in the high latitudes of both the northern and southern hemispheres (Pospichal and Wise, this volume and 1990b). The FO of the delicate *Ellipsolithus macellus*, however, is seldom a useful datum in oceanic sites; the time transgressive nature of this datum at different sites has been clearly shown by Wei and Wise (1989). In the high latitudes, the FO of *Prinsius martinii* may be used as a rough approximation for this datum. Although present, discoasters are far less common in the higher latitudes, and their sporadic occurrences make it difficult to determine the evolutionary first or last appearances of these taxa. This depreciates the reliability of such forms as zonal markers and because of this uncertainty, the boundary at the base of NP7 (*Discoaster mohleri* Zone) is dotted in Figure 4. The FO of *D. multiradiatus* proved to be a more consistent datum and the peak in Paleogene discoaster diversity occurs within this zone, coincident with a peak in isotopic temperature values and a strong negative shift in δC^{13} values (Stott and Kennett, 1990).

Although most of the Paleocene zonal markers are present in the higher latitudes, the overall compositions of the attendant assemblages are significantly different relative to those of the lower latitudes (Haq and Lohman, 1976). Thus Wei and Pospichal (1991) found it useful to erect a provincial zonation for the Danian of the Kerguelen Plateau based the FO's of forms such as *Hornibrookina* and *Chiasmolithus bidens*, which are quite abundant above 50°S (Fig. 7). Further details of the high latitude Danian assemblages of Maud Rise and the Kerguelen Plateau are given in Pospichal and Wise (1990b and this volume).

Eocene

The basal Eocene marker, *Tribrachiatus bramlettei*, could not be distinguished at all mid to high latitude sites, and the LO's of *Discoaster mohleri* and *Fasciculithus* have been used to approximate that datum at various sites (Fig. 4; see Wei [this volume] for a detailed discussion of these datums and others related to the Paleocene/Eocene boundary). Originally reported from former active margin basins of Austria and Switzerland, *Tribrachiatus bramlettei* has been noted in mid latitude South Atlantic sediments deposited near the then emergent Walvis Ridge by Backman (1986) and Manivit (1984) and, surprisingly, at Maud Rise where it was rare. The latter finding not only allowed an approximation of the Paleocene/Eocene boundary at Site 690, but demostrated that this form is clearly not confined to continental margin environments or emerged promontories (there is no evidence that any portion of Maud Rise was emergent at this time). The succeeding marker species, *T. contortus* and *T. orthostylus*, are also present at Maud Rise, but are sporadic in their occurrences.

The numbers of discoasters decline sharply in the lower to middle Eocene at Maud Rise. The index taxa *Discoaster lodoensis* and *D. sublodoensis* occur in such small numbers there and in the environs of the Falkland Plateau that their FO's can only be used tentatively to delimit zones.

The disappearance of *Discoaster sublodoensis* and the absence of assemblages with *D. barbadiensis* and *D. saipanensis* in middle Eocene sediments at Maud Rise coincides with a further step in the deterioration of Antarctic climate. The beginning of a global cooling trend at this time is documented by Shackleton an Kennett (1975) and Oberhänsli *et al.* (1984). The percentage of sphenoliths in Maud Rise samples also declines at this time. *Sphenolithus moriformis* are quite abundant in lower Eocene Zones NP10-NP13, but their numbers decline above these zones. In the middle to low latitudes, sphenoliths diversified to six species by NP14 and NP15 time (Perch-Nielsen, 1985), but failed to do so in the region of Maud Rise.

Nannotetrina fulgens was too sporadic to delimit the base of NP15 at Sites 689/690 and 699/700, and the LO of *D. lodoensis* was substituted to mark the top of the zone at the latter site. In Islas Orcadas piston core 15-59 taken off the northern Antarctic Peninsula, however, *N. fulgens* co-occurred with *Chiasmolithus gigas* (Toker *et al.*, 1991), a subzonal marker of Bukry (1973).

The neritic marker species, *Rhabdosphaera gladius*, is generally not found beyond the continental margins, and numerous datums have been used in the South Atlantic to approximate its LO at the top of Zone NP 15, including the LO of *Nannotetrina fulgens* and the FO's of *Reticulofenestra bisecta* and *R. umbilicus* (Fig. 4). The next datums within the zonation, *Chiasmolithus solitus, C. oamaruensis*, and *Isthmolithus recurvus*, can all be found at the mid to extreme high latitudes. Well acclimated to cooler climates, these are all temperate species first described from California and New Zealand.

The FO of *Sphenolithus pseudoradians* is no longer employed in the Martini compilation to subdivide Zones NP19 and NP20 (MARTINI and MÜLLER, 1986). The FO of *Reticulofenestra oamaruensis* can be used instead to help subdivide this interval at high latitudes.

As mentioned previously, *Discoaster saipanensis* is not observed in the uppermost Eocene at Maud Rise. It is rare and somewhat sporadic in the Falkland Plateau region, but its LO can still be used there to mark the nannofossil Eocene/Oligocene boundary. At this point in geologic time, Antarctic climates were deteriorating further, leading to the establishment of a sizable though possibly short lived ice sheet on the Antarctic continent (BARRON, LARSEN, *et al.*, 1989; WISE, SCHLICH *et al.*, 1989; BARRETT *et al.*, 1989).

To summarize the data in Figure 4, most Paleocene-Eocene zones of the MARTINI (1971) zonal compilation can be recognized at mid latitudes (around 30°S), and most of the Paleocene zones can be extended as far as 65°S. Resolution in the high latitudes, however, is considerably diminished in the lower to middle Eocene, but is restored for most of the upper Eocene because the zonation employs temperate species as zonal markers.

OLIGOCENE-HOLOCENE

The Oligocene zonation works reasonably well in the mid latitudes although the dependence on the warm water sphenoliths presents problems even at 30° S. These problems become critical by 47°S where the sphenolith markers are absent (Fig. 5). In the region of the Falkland Plateau, even the lower Oligocene markers such as *Coccolithus formosus* are sporadic, and WISE (1983) found it advantageous to erect an essentially local zonation for the entire Oligocene which retained only the LO of *Reticulofenestra umbilicus* as a "standard" marker (Fig. 3). As done previously in the mid latitudes of the Northern Hemisphere (WISE, 1973), the LO of *Reticulofenestra bisecta* was used to approximate the Oligocene/Miocene boundary (Fig. 3). This datum was followed up-

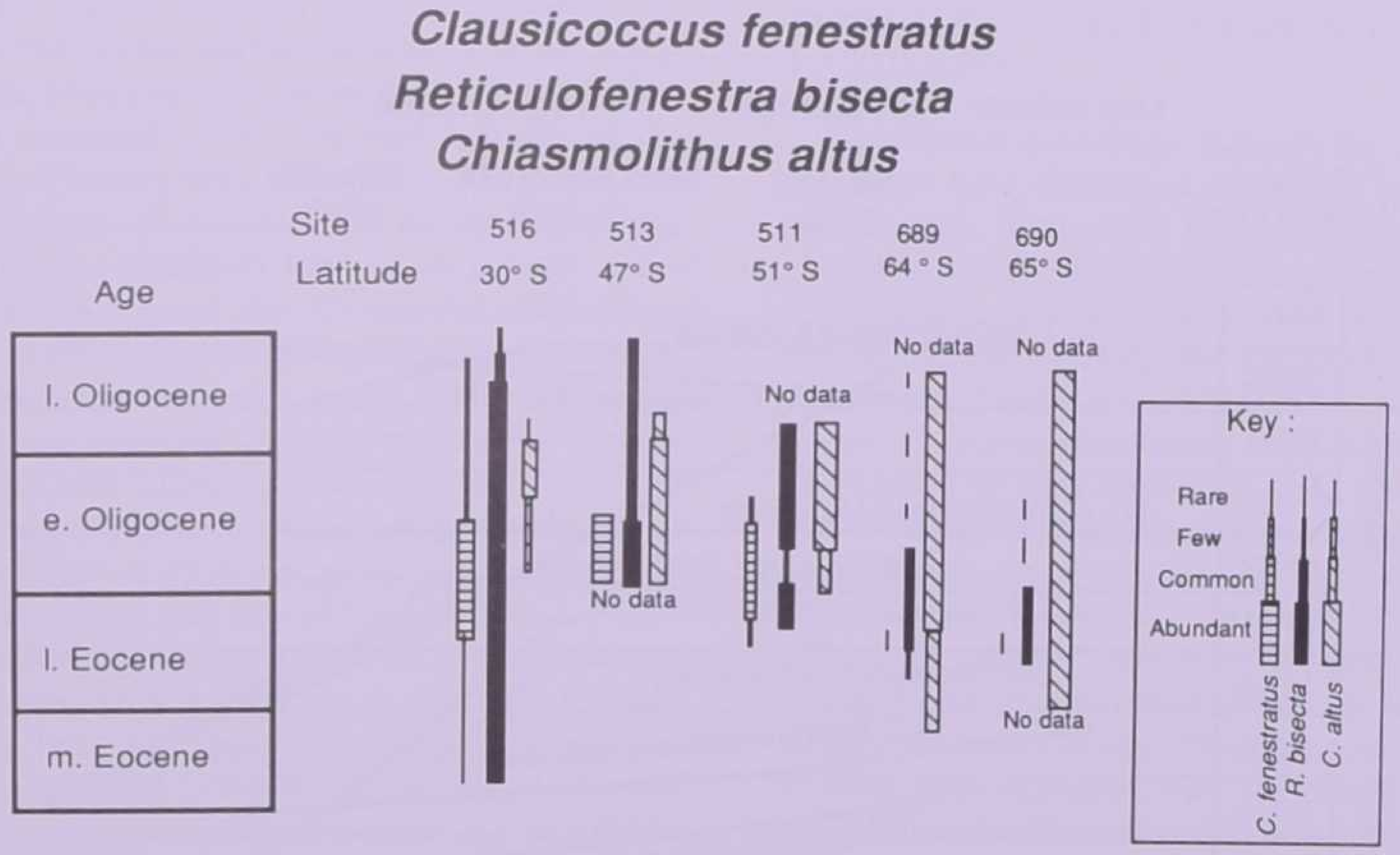

FIG. 8 - Simplified stratigraphic distribution patterns of *Chiasmolithus altus, Clausicoccus fenestratus*, and *Reticulofenestra bisecta* along a latitudinal transect from the mid to extreme high latitudes of the South Atlantic (data from WEI and WISE, 1990a). Note the strong diachroniety for the LO's of *Clausicoccus fenestratus* and of common *Reticulofenestra bisecta*, both of which trend down section toward the pole. Conversely, the LO of *Chiasmolithus altus* transgresses time toward the pole.

section by the LO of *Chiasmolithus altus*, which is a dominant form in the high southern latitudes. Of the other markers, the LO of *Isthmolithus recurvus* has proven reliable over a broad region (WEI and WISE, 1989, 1990a). The LO of *Clausicoccus fenestratus* occurred considerably lower in the Falkland Plateau section than in the tropics, where ROTH (1971) traced it essentially to the top of the Oligocene. No distinct acme of this species was present near the base of the Oligocene as reported by BUKRY (1973) for the tropics.

Although WISE's 1983 Oligocene zonation was applied to other South Atlantic sites subsequently drilled by ODP Leg 114 at the same latitude as the Falkland Plateau (CIESIELSKI, KRISTOFFERSEN *et al.*, 1988), it proved quite unworkable further south at Maud Rise. Only the LO's of *Isthmolithus recurvus* and *Reticulofenestra umbilicus* proved useful because *Clausicoccus fenestratus* and *Cyclicargolithus abisectus* were virtually absent at these extreme high latitudes. Furthermore, the LO of *Reticulofenestra bisecta* proved to be diachronous. Whereas it occurred 33 m above the LO of *Chiasmolithus altus* at Site 699 (52°S), these datums were reversed at Site 690 with a minimum separation of nearly 20 m. The diachroniety of *R. bisecta* appears even more pronounced if rare occurrences of this taxon at Maud Rise are discounted or if the last common occurrence of this taxon is traced. The diachronous nature of *R. bisecta* and some of the other provincial markers used by WISE (1983) for the Falkland Plateau is illustrated in Figures 8 and 9. Figure 8 summarizes some of the abundance and occurrence data complied by WEI and WISE (1990a) on which Figure 9 is based. Figure 9 is a schematic portrayal of how the key datums "behave" across latitude. Because of the problem with *R. bisecta* and the lack of other markers, the upper Oligocene could not be zoned using the low latitude zonal compilations, and MARTINI's Zones NP23-25 have been combined (Fig. 5). To account for these problems and similar difficulties with the existing middle to upper Eocene zonations in the extreme high latitudes, WEI and WISE (1990a) strongly modified the existing zonations to produce a scheme applicable for Maud Rise (Fig. 10). Their scheme is also useful for the Kerguelen Plateau in the Southern Indian Ocean (WEI and THIERSTEIN, 1991; WEI *et al.*, in press).

The Oligocene was a time of significant cooling and the initiation of the psychrosphere on a permanent basis (KENNETT and SHACKLETON, 1976) as a moderate-sized ice cap developed, waxed and waned through several cycles over the Antarctic continent (MILLER *et al.*, 1987; see summary by WISE *et al.*, 1991). Toward the end of that epoch, the Drake Passage opened, allowing the development of a deep water circum-Antarctic current. The initiation of this current accounts for the hi-

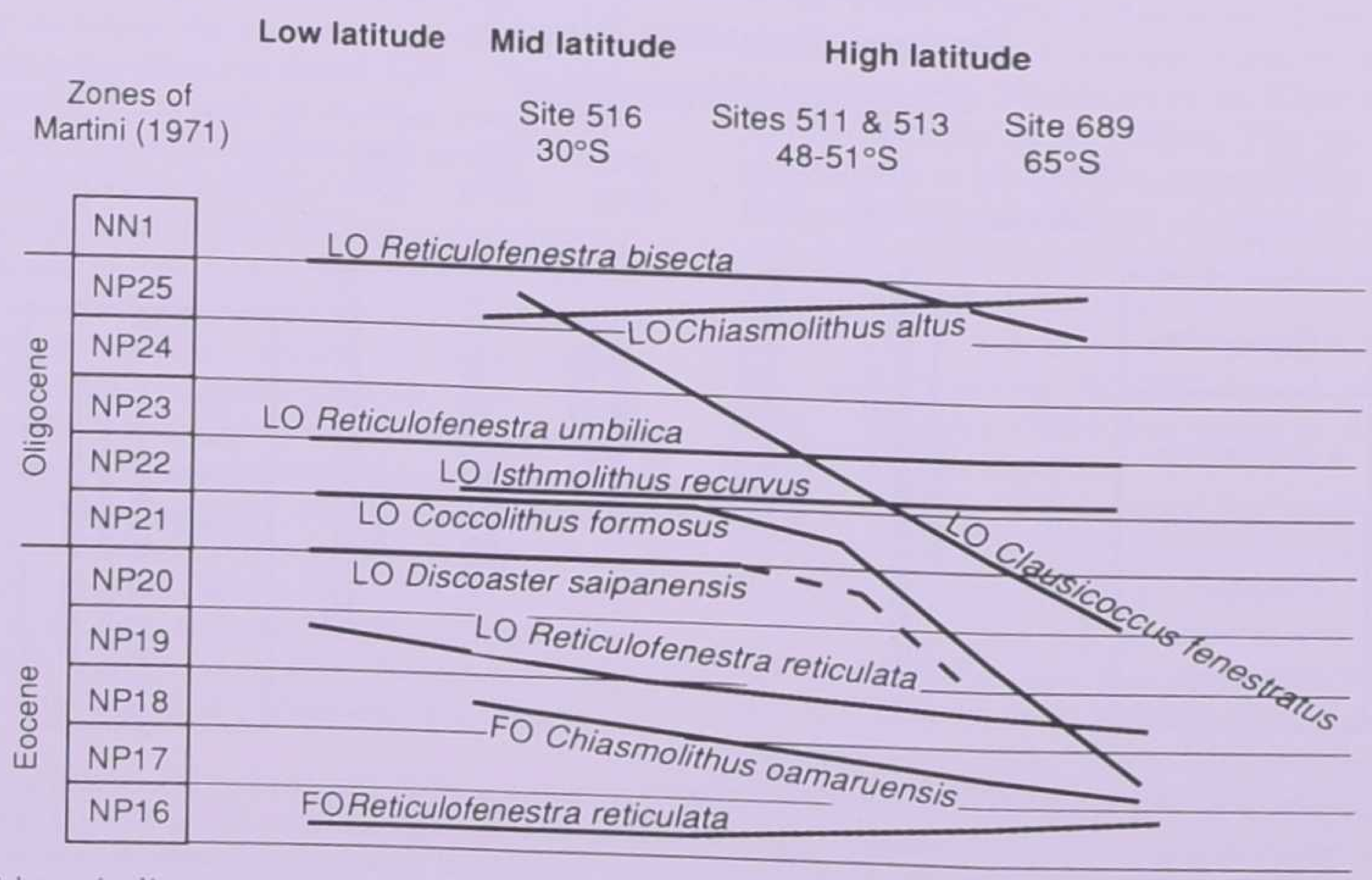

FIG. 9 - Schematic diagram summarizing the data of WEI and WISE (1989, 1990a) for selected middle Eocene to Oligocene zonal markers illustrating the diachroniety of some of these taxa and the synchroniety of others.

Age	Zones of Wei and Wise (1990a)	Datums	Zones of Martini (1971)	Zones of Wise (1983)
late Oligocene	No data		NP25	*Cyclicargolithus abisectus*
			NP24	*Reticulofenestra bisecta*
		Last common *Chiasmolithus altus*		
	Chiasmolithus altus		NP23	*Chiasmolithus altus*
early Oligocene		LO *Reticulofenestra umbilica*		
	Reticulofenestra daviesii		NP22	*Reticulofenestra daviesii*
		LO *Isthmolithus recurvus*		*Clausicoccus fenestratus*
	Blackites spinosus			
		LO *Reticulofenestra oamaruensis*		
	Reticulofenestra oamaruensis		NP21	*Blackites spinosus*
late Eocene		FO *Reticulofenestra oamaruensis*		
	Isthmolithus recurvus		NP20	*Reticulofenestra oamaruensis*
		FO *Isthmolithus recurvus*	NP19	No data
	Chiasmolithus oamaruensis		NP18	
middle Eocene		FO *Chiasmolithus oamaruensis*		
	Discoaster saipanensis		NP17	
		LO *Chiasmolithus solitus*		
	Reticulofenestra reticulata		NP16	*Discoaster bifax*
		FO *Reticulofenestra reticulata*		
	Reticulofenestra umbilica			
		FO *Reticulofenestra umbilica*	— — —	

FIG. 10 - Nannofossil zones used by WEI and WISE (1990a) for the middle Eocene to Oligocene of the extreme high latitude ODP Sites 689 and 690 on Maud Rise, Weddell Sea. The zones are compared against the zonal compilation of MARTINI (1971).

atus across the Oligocene-Miocene boundary at Site 329 and perhaps directly or indirectly for the one at Maud Rise (Fig. 5).

The isolation of the Antarctic continent by the Circumpolar Current eventually led to further climatic cooling and the development of highly restricted nannofossil assemblages in the higher latitudes. These assemblages were dominated during the early Miocene by *Coccolithus pelagicus*, which during the middle and late Miocene alternated with and finally gave way completely to *Reticulofenestra perplexa* (see detailed discussion by WEI and WISE, in press). The latter species represents the colder surface waters. The net result is that the Miocene cannot be zoned in the higher latitudes although, as in the mid latitudes of the Northern Hemisphere (WISE, 1973), the LO of *Cyclicargolithus floridanus* can be used up to the latitude of the Falkland Plateau to provide a datum near the top of the *Discoaster exilis* Zone (Fig. 5). Although rare Miocene discoasters have been detected as far south as the Falkland Plateau, they did not provide consistently useful datums beyond the mid latitude sites.

Discoasters and ceratoliths are generally useful to zone the lower Pliocene as far south as the mid latitude sites, but not beyond (Fig. 5). *Reticulofenestra pseudoumbilicus* provided a useful datum to subdivide the Pliocene up to the high latitude Site 704, but the upper Pliocene could not be further subdivided using the extinction of discoasters. Sharp global cooling at about 3.2 to 3.0 Ma and the initiation of Northern hemisphere continental glaciation at about 2.4 to 2.5 Ma marked the further deterioration in Pliocene climate (example, CIESIELSKI and WEAVER, 1983). Further north, Pliocene nannoplankton are absent on the Falkland Plateau, having been driven north beyond the plateau by the northward migration of the Polar Front (CIESIELSKI and WISE, 1977; WISE *et al.*, 1981). Only in the Holocene sediments of this region do significant accumulations of nannofossil oozes reappear (NN21), a testament to the strong warming of the present day interglacial combined with the sharp global Plio/Pleistocene descent of the carbonate compensation level.

EXTENT OF NANNOFOSSIL OOZE DEPOSITION IN THE HIGH SOUTHERN LATITUDES

Geophysical soundings through the Antarctic Ice Sheet have delineated a series of subglacial, intracratonic basins that extend below sea level (DREWRY, 1983). These may have been interior seaways prior to the establishment of ice sheets during the mid Tertiary (see discussion, both pro and con, by TOKER *et al.*, 1991). The discovery of oceanic Cenozoic microfossils in glacial tills dated as Pliocene at high elevations along the present day Transantarctic Mountains, including a well preserved specimen of what is probably *Chiasmolithus solitus* (HARWOOD, 1984), led WEBB *et al.* (1984) to suggest that the microfossils were eroded by the ice sheet from within the subglacial Wilkes-Pensacola Basins. The fossils are thought to have been deposited with the tills as the ice passed over the Transantarctic Mountains during glacial maxima. If so, and if there were sufficient connections to the sea through these basins, then it is possible that nannofossils or even nannofossil oozes may have been deposited within the vicinity of the South Pole. Following this reasoning,

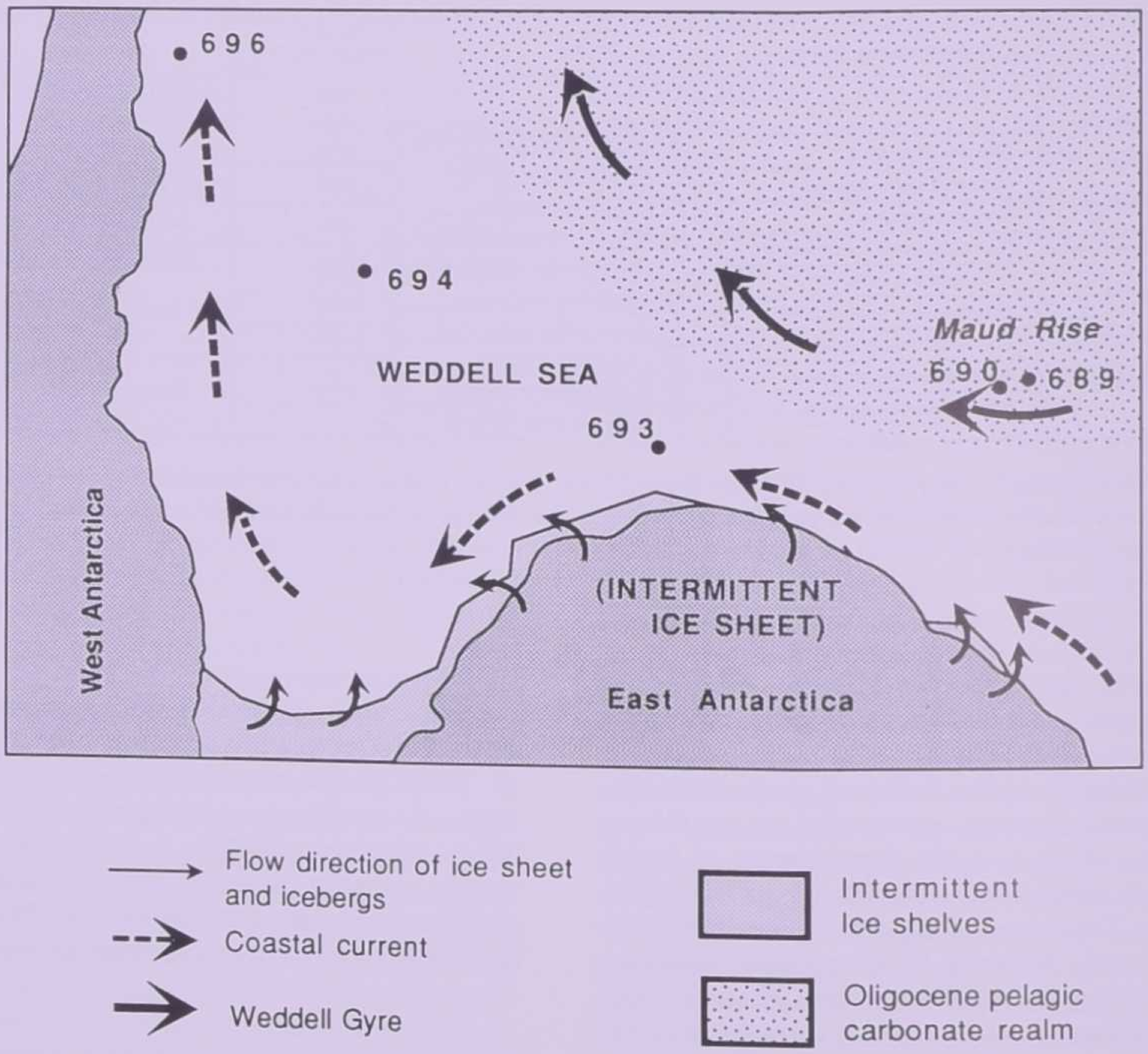

FIG. 11 - Sketch map showing the suggested disposition of continental ice and of oceanic surface circulation in the Weddell Sea region for Oligocene glacial episodes. The pelagic carbonate realm covers those areas that would receive nannofossil ooze at water depths above 3000 m (from WEI and WISE, 1990a, fig. 16).

BIRKENMAJER (1987) (see also BIRKENMAJER, 1985, BIRKENMAJER and GAZDZICKI, 1986) suggested that remnants of middle Eocene nannofossil chalk found on planktonic foraminifers in Oligocene tills from the northern Antarctic Peninsula may have even been ice-rafted from the interior basins of Antarctica.

The results of ODP drilling on Maud Rise, at DSDP Site 267, and the recovery of Paleocene nannofossils from ISLAS ORCADAS piston core 12-14 taken at 58°S along the southwest Indian Ridge (WISE *et al.,* 1991), show that coccolith oozes accumulated at paleodepths down to 3000 m in the seas around Antarctica until at least Oligocene times. During the Oligocene, however, glacial activity chilled the surface waters immediately surrounding the Antarctica. This inhibited nannoplankton production along the continental margin and, in the Weddel Sea area, produced cold, corrosive bottom waters that prevented the accumulation of nannofossil ooze along the shelves and slopes (Fig. 11) except for brief intervals of climate amelioration during the late Oligocene and late Miocene (WEI and WISE, 1990a; Fig. 12). Several thin beds (about 10 cm or less) of Oligocene ooze were cored at a water depth of 2359 m on the continental slope at ODP Site 693. These consisted of monospecific assemblages of *Chiasmolithus altus*. The upper Miocene assemblage consisted solely of *Reticulofenestra perplexa*, but these nannofossils were mixed with the biosiliceous ooze that dominated that portion of the section. A similar occurrence was found over a short interval at Site 696 in a very shallow hole (water depth = 650 m) drilled off the northern Antarctic Peninsula.

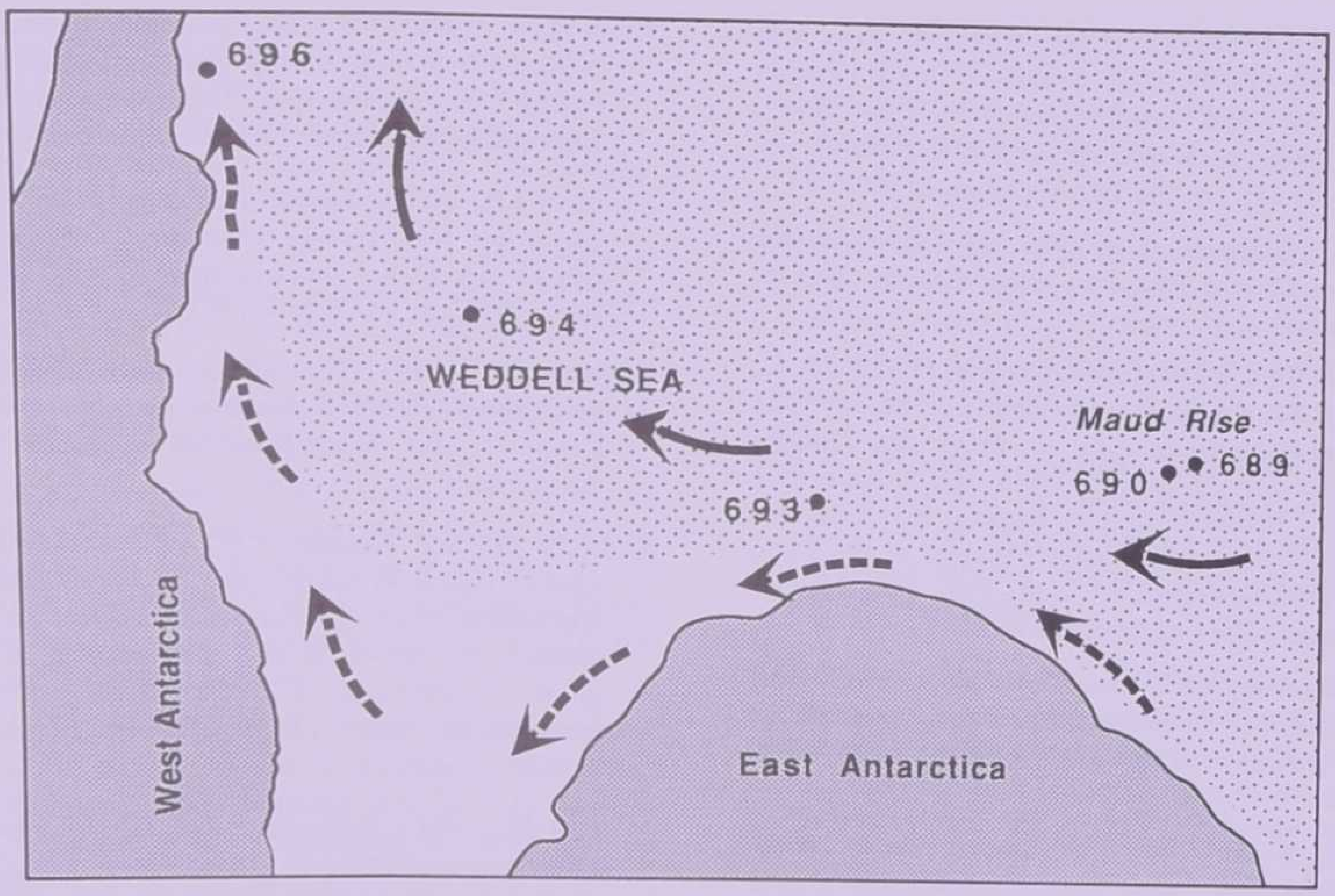

FIG. 12 - Sketch map showing the suggested disposition of continental ice and of oceanic surface circulation in the Weddell Sea region for a late Oligocene interglacial event during which nannofossil ooze was deposited along the margin of Antarctica (from WEI and WISE, 1990a, fig. 17).

Other than the above situations, there are no other records, direct or indirect, of nannofossil ooze deposition on the Antarctic continent. Scattered nannofossils have been found, however, within thick (up to 350 m) lower Oligocene and possibly upper Eocene glacial marine sequences in drill cores from the Ross Sea (EDWARDS and WAGHORN, 1989) and Prydz Bay, Antarctica (WEI and THIERSTEIN, 1991). These consist of limited assemblages with up to a dozen species in at least one interval (WEI, 1989, in press), which is a surprisingly high diversity considering the intermittent glacial or periglacial conditions under which the sediments were deposited. Key taxa in the CIROS-1 hole include the marker species *Isthmolithus recurvus*, as well as *Chiasmolithus altus*, *C. oamaruensis*, *Reticulofenestra bisecta*, and *Reticulofenestra umbilicus* (WEI, 1989, in press).

In summary, three lines of evidence can be cited to argue for the presence of nannofossils and possibly nannofossil oozes within the interior seaways of Antarctica during nonglacial Cenozoic and Mesozoic times:

1. The reworked marine microfossils in tills dated as Pliocene in the Transantarctic Mountains.

2. The presence, although limited, of nannofossil and nannofossil-rich oozes as young as late Oligocene and late Miocene in age along the margins of Antarctica.

3. The presence of surprisingly diverse assemblages within lower Oligocene glacial marine sequences of the marginal seas and embayments of Antarctica.

Direct sampling of such deposits, should they exist, will require drilling and sampling through the ice cap, a project which has been recommended for future exploration during the coming decade (HAYES *et al.*, 1986).

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