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# SOUTHERN HIGH LATITUDE K/T BOUNDARY CALCAREOUS NANNOFOSSILS

## CONTENTS



K e y w o r d s : *calcareous nannofossils, Cretaceous/Tertiary boundary, high southern latitudes, provinciality, Ocean Drilling Program.*

## ABSTRACT

Recent drilling in the Southern Oceans by the Ocean Drilling Program has produced several Cretaceous/-Tertiary boundary sections. Before these excursions to the Southern Hemisphere, little was known about calcareous nannofossils across the K/T boundary in the austral high latitudes. In the Weddell Sea of the South Atlantic, a complete but heavily bioturbated Maastrichtian-Danian section was recovered at ODP Leg 113, Site 690 (65° S). Leg 119 recovered a complete, laminated K/T sequence at Site 738 (63° S) on the southern end of the Kerguelen Plateau in the Indian Ocean. And, Leg 121 cored a biostratigraphically complete K/T section in an ash-chalk sequence of Site 752 (paleolatitude 50-55° S) on Broken Ridge in the Indian Ocean.

Calcareous nannofossils are displaced up to 1.3 m in burrows of the heavily bioturbated sediments of the K/T boundary of Site 690. A strong color change between light colored Cretaceous chalks and dark orange-brown Tertiary clay-rich chalks aids in the identification of the K/T boundary horizon along with the first occurrence of *Biantholithus sparsus* and a distinct iridium anomaly.

The highly expanded K/T boundary of Site 752, on the Broken Ridge is located at the base of a 6 m volcanic ash unit which overlies indurated ash-rich Maastrichtian chalks. The initial Danian subzone, CP1a, is 5 m thick at this location, which is quite thick when compared to Site 690 (40 cm) and other deep sea drilling locations. The presence of the unique series of ash deposits above the boundary is not attributed to a large increase in volcanic activity but to the greatly diminished $CaCO_3$ production and accumulation associated with the K/T event. The K/T boundary itself is located in an interval of drilling disturbed chalk, ash, and chert. The first occurrence of *B. sparsus* is found approximately 20 cm above the last occurrence of Cretaceous foraminifera and a distinct iridium anomaly, which marks the geochemical K/T boundary (MICHEL *et al.*, in press).

Moderate to poorly preserved nannofossil assemblages of the uppermost Maastrichtian *Nephrolithus frequens* Zone of Site 690 contain about 20 to 25 species, and are completely dominated by a small species, *Prediscosphaera stoveri*. In addition to this form, the Cretaceous assemblage, which is typical of higher latitudes, is predominantly composed of *Nephrolithus*

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*frequens frequens, Arkhangelskiella cymbiformis, Kamptnerius magnificus, Cribrosphaerella daniae*, and *Acuturris scotus*. The assemblage of Site 752 is similar but with much fewer *P. stoveri*. The uppermost Maastrichtian at this site is characterized by lower diversity due to dissolution and poor preservation, and the assemblage is dominated by the solution resistant, *Micula decussata*.

The nannofossil assemblage of the lowermost Danian Subzone CP1a at both Sites 690 and 752, is dominated by a mixture of reworked Cretaceous taxa along with species which escaped the terminal Cretaceous extinction. The "opportunistic" or "survivor" assemblage is composed of about 5 or 6 species similar to those found at northern high latitude K/T boundaries. These include *Zygodiscus sigmoides, Biscutum castrorum, Markalius inversus, Neocrepidolithus* spp., *Thoracosphaera* spp. and *Cyclagelosphaera* spp.

The first species to appear in the lowermost Danian sediments is *Biantholithus sparsus*. At Site 690 this is followed shortly by the first occurrence and abundance bloom of *Hornibrookina* just below the CP1a/CP1b Subzone boundary. This is the first observed bloom of this taxon, and it was later noted in sediments of the same age from Sites 738 and 750 on Kerguelen Plateau, but not at Broken Ridge Site 752.

Quantitative studies reveal that the K/T boundary nannofozssil assemblages of the high southern latitudes display a unique provinciality in respect to high boreal latitude and low latitude assemblages. The high abundance of *P. stoveri* appears to be limited to extremely high southern latitudes although the form does show an increase in abundance in the uppermost Maastrichtian of mid and lower latitudes. Austral Maastrichtian assemblages are of lower diversity and lack the markers *Micula murus* and *M. prinsii*. Above the boundary, "survivor" forms such as *Z. sigmoides* and *Biscutum castrorum* (=*B. constans*) are most dominant in the austral sections, while *Thoracosphaera* species are less abundant than in other sections. Another "survivor" form, *Braarudosphaera*, is rare to absent in the austral deep sea sections studied here. In the lowermost Danian, blooms of *Hornibrookina* species appear to be restricted to the extreme high southern latitudes. *Biantholithus sparsus*, is not latitudinally restricted, however, other lower Danian species such as *Neobiscutum romeinii* and *N. parvulum* are absent and *Futyania petalosa* extremely rare in high southern latitude sections.

## RIASSUNTO


Le perforazioni recenti dell'Ocean Drilling Program negli oceani dell'emisfero meridionale hanno recuperato molte sezioni del limite Cretaceo/Terziario. Precedentemente le conoscenze dei nannofossili calcarei al limite K/T delle alte latitudini australi erano limitate. Nel mare di Weddell (Sud Atlantico) è stata recuperata una sezione completa, ma fortemente bioturbata di Maastrichtiano — Daniano [ODP Leg 113, Site 690 (65°S)]. Nella parte meridionale del Kerguelen Plateau (Oceano Indiano) è stata recuperata una sequenza completa, laminata del limite K/T [Leg 119, Site 738 (63°S)]. Infine nella Broken Ridge (Oceano Indiano) è stata carotata una sequenza a cineriti e carbonati, biostratigraficamente completa, del limite K/T [Leg 121, Site 752 (paleolatitudine 50° - 55°S)].

Al Site 690 intorno al limite K/T i nannofossili calcarei sono spiazzati da intensi fenomeni di bioturbazione fino a 1.3 m. Un forte contrasto di colore, tra i carbonati cretacei chiari e quelli terziari scuri, oltre alla prima comparsa di *Biantholithus sparsus* e ad una anomalia marcata dell'iridio servono ad identificare il limite K/T.

Al Site 752, sulla Broken Ridge, una successione espansa al limite K/T è situata alla base di una unità di ceneri vulcaniche, dello spessore di 6 m, sovrapposta a calcari maastrichtiani induriti ricchi di cenere. La zona basale del Daniano, CP1a, in questa località è potente 5 m, il che rappresenta uno spessore notevole in confronto al Site 690 (40 cm) e ad altre perforazioni di mare profondo. La presenza di questa serie di depositi di cenere sopra il limite non è da attribuire tanto ad un aumento dell'attività vulcanica, quanto ad una forte diminuzione nella produzione ed accumulo di $CaCO_3$ legata all'evento K/T. Il limite K/T si trova, a sua volta, in un intervallo di carbonati, cenere e selce fortemente disturbato dalle operazioni di perforazione. La prima comparsa di *B. sparsus* avviene circa 20 cm sopra all'ultimo ritrovamento di foraminiferi planctonici cretacei e alla anomalia dell'iridio che caratterizza il limite K/T geochimico (MICHEL *et al.*, in stampa).

Le associazioni a nannofossili della Zona a *Nephrolithus frequens* del Maastrichtiano sommitale del Site 690 hanno preservazione da moderata a povera e contengono circa 20-25 taxa fra cui predomina nettamente una specie, di piccole dimensioni, *Prediscosphaera stoveri*. Oltre a questa forma, l'associazione cretacea, tipica di alte latitudini, è prevalentemente composta da *Nephrolithus frequens frequens, Arkhangelskiella cymbiformis, Kamptnerius magnificus, Cribrosphaerella daniae* e *Acuturris scotus*. L'associazione del Site 752 è simile, seppur con *P. stoveri* meno frequente. In questa località il Maastrichtiano sommitale è caratterizzato da una più bassa diversità a causa della dissoluzione e della cattiva conservazione e l'associazione è dominata da *Micula decussata*, specie resistente alla dissoluzione.

L'associazione a nannofossili del Daniano basale, Sottozona CP1a, è dominata, sia al Site 690 che al 752, da una mescolanza di taxa cretacei rimaneggiati e specie "sopravvissute" all'estinzione terminale del Cretaceo. L'associazione "sopravvissuta", costituita di specie "opportuniste" è composta da circa 5-6 taxa ed è simile a quelle trovate al limite K/T delle alte latitudini boreali. Essa include *Zygodiscus sigmoides, Biscutum castrorum, Markalius inversus, Neocrepidolithus* spp., *Thoracosphaera* spp. e *Cyclagelosphaera* spp.

La prima specie che compare nei sedimenti del Da-

niano basale è *Biantholithus sparsus*. Al Site 690 essa è seguita a breve distanza dalla prima comparsa e dal "bloom" di *Hornibrookina* subito sotto il limite di sottozona CP1a/CP1b. Questo è stato il primo "bloom" osservato di tale taxon, in seguito notato in sedimenti coevi del Site 738 e 750 sul Kerguelen Plateau, ma non al Site 752 sulla Broken Ridge.

Analisi quantitative dimostrano che le associazioni a nannofossili del limite K/T delle alte latitudini australi hanno una caratteristica provincialità rispetto alle associazioni di alta latitudine boreale e a quelle di bassa latitudine. La grande abbondanza di *P. stoveri* sembra limitata alle estreme latitudini meridionali, per quanto la forma manifesti un aumento di frequenza nel Maastrichtiano terminale alle medie e basse latitudini. Le associazioni maastrichtiane australi hanno una minore diversità e mancano dei markers *Micula murus* e *M. prinsii*. Sopra al limite, i "sopravvissuti", quali *Z. sigmoides* e *Biscutum castrorum*, (= *B. constans*) sono dominanti nelle sezioni australi, mentre le *Thoracosphaera* sono meno abbondanti che in altre sezioni. Un'altra forma "sopravvissuta", *Braarudosphaera*, è rara o assente nelle sezioni australi di mare profondo qui studiate. Nel Daniano basale i blooms di *Hornibrookina* sembrano limitati alle estreme latitudini meridionali. *Biantholithus sparsus* non è ristretto, latitudinalmente, mentre altre specie del Daniano inferiore, come *Neobiscutum romeini* e *N. parvulum*, mancano nelle sezioni meridionali di alta latitudine e *Futyania petalosa* è estremamente rara.

## INTRODUCTION

Until a number of recent ODP drilling legs in the southern Indian and Atlantic oceans, little was known about the change in calcareous nannofossils across the Cretaceous/Tertiary (K/T) boundary in the austral high latitudes. Drilling on the Maud Rise in the Weddell Sea during Leg 113 (Site 690) produced the first continuous K/T section at the extremely high latitude of 65°S (Fig. 1). The heavily bioturbated muddy nannofossil chalks of the Maastrichtian-Danian interval shown in Figure 2 contain nannofossil assemblages similar to those of well studied boreal sections but unique in many ways (POSPICHAL and WISE, 1990a). Noted surprises in this section included the first observation of a bloom of *Hornibrookina* just above the K/T boundary within OKADA and BUKRY Subzone CP1a. Also noted here was an overwhelming dominance of uppermost Maastrichtian assemblages by *Prediscosphaera stoveri*, a phenomenon observed to a much lesser degree in the low and mid latitude sections of El Kef and Brazos River by JIANG and GARTNER (1986).

The question that remained after the study of the K/T sequence of Maud Rise was whether or not the above mentioned events were purely provincial, exclusive to the Atlantic sector of the Southern Ocean, or whether they could be observed elsewhere. Six legs later, a laminated, continuous K/T sequence was cored on the southern tip of the Kerguelen Plateau (Site 738, 63° S) in the Indian Ocean (Fig. 1). Nannofossil assemblages studied by WEI and THIERSTEIN (1991) and WEI and POSPICHAL (1991) revealed results similar to those of Leg 113. A *Hornibrookina* bloom, in the upper portion of Subzone CP1a was noted, as well as a complete dominance of the uppermost Maastrichtian assemblage by *Prediscosphaera stoveri*. Fortunately, this section was not complicated by intense bioturbation as was the case at Site 690, thus a more accurate picture of the sequence of nannofossil turnover across the K/T boundary could be ascertained.

From Sites 690 and 738, it is obvious that a distinct biogeographic province can be constructed for the high austral latitudes for K/T time. The next question then is just how far north did this biogeographic province extend? The answer to this came during the next two ODP legs following Leg 119. Leg 120 drilled sites on the central portion of the Kerguelen Plateau and Leg 121 took cores from Broken Ridge, which had constituted the northernmost part of the plateau until it was rifted and moved north during the middle Eocene.

A complete boundary sequence was not cored during Leg 120. Subzone CP1a was missing in

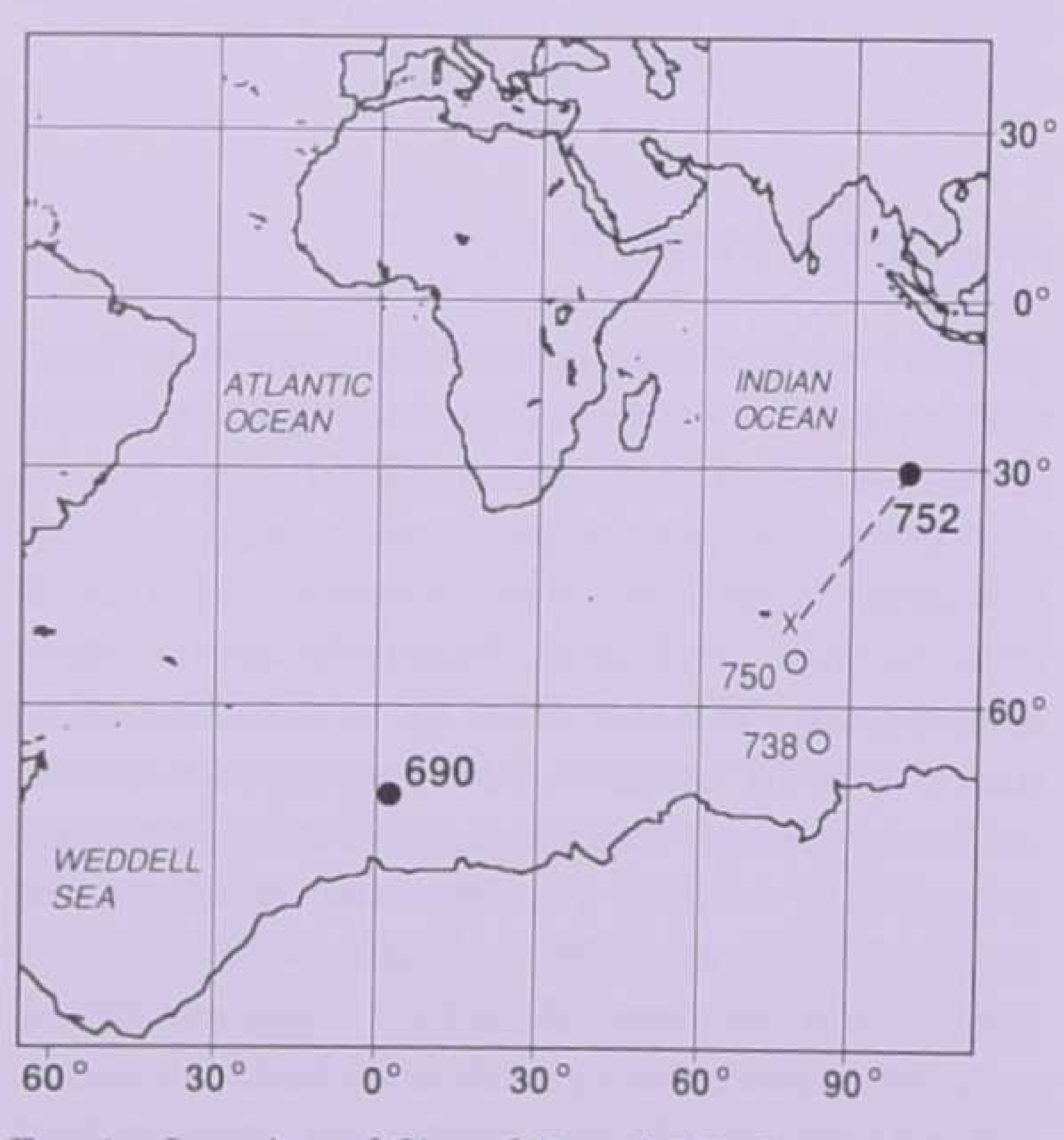


FIG. 1 - Location of Sites 690 and 752. Site 738 of Leg 119 and Site 750 of Leg 120 are indicated with an open circle. The paleo-position of Site 752 is indicated by an "X".

cores of Site 750 (58° S) (SCHLICH, WISE *et al.*, 1989). An abundance bloom of *Hornibrookina* was noted (EHRENDORFER and AUBRY, in press) in the lowermost Tertiary samples (CP1b). WATKINS (in press) also noted abundant *Prediscosphaera stoveri* in the uppermost Maastrichtian sediments.

During Leg 121, a biostratigraphically complete K/T boundary was cored at Site 752 (paleolatitude 50-55° S) on Broken Ridge, which completed the northern end of the Kerguelen Plateau transect (Fig. 1). The K/T boundary sediments were disturbed by drilling and the section is composed of numerous drilling "biscuits' produced by the rotary coring process (Fig. 3). Since all the nannofossil zones are present, it is difficult to tell how much, if any, section was lost between these "biscuits". Nevertheless, this section is the most expanded deep sea K/T sequence yet recovered by ODP/DSDP. At this site, a constant supply of volcanic ash through the late Maastrichtian and early Danian produced sedimentation rates slightly higher than those normally found at other deep sea sites. This, despite the commensurate drop in $CaCO_3$ flux associated with the collapse in surface productivity at the end of the Maastrichtian, resulted in an expanded boundary sequence extremely valuable for paleontologicals study.

This paper briefly summarizes quantitative studies of calcareous nannofossils from the K/T boundary interval at Sites 690 on the Maud Rise and Site 752 on the Broken Ridge. Detailed descriptions, range charts, and systematic paleontology can be found in POSPICHAL and WISE (1990a), POSPICHAL *et al.* (1990) and POSPICHAL (in press).

## PREVIOUS WORK

Initial work on calcareous nannofossils in Cretaceous/Tertiary boundary sections was conducted by BRAMLETTE and MARTINI (1964). Important stratigraphic studies were later carried out by EDWARDS (1966) in New Zealand, HAY and MOHLER (1967) in France, PERCH-NIELSEN (1969) in Denmark, WORSLEY (1974) in Alabama, ROMEIN (1977) in Spain, and PERCH-NIELSEN (1981) in Tunisia. A high latitude South Pacific sequence from DSDP drilling was described by EDWARDS (1973). THIERSTEIN (1981), PERCH-NIELSEN *et al.* (1982), and SMIT and ROMEIN (1985) published comprehensive reviews with information on calcareous nannofossils and planktonic foraminifers compiled from a geographically wide range of K/T boundary sites.

The studies mentioned above are primarily works of a qualitative nature. Quantitative methods for which the studies described here have been patterned were done by PERCIVAL and FISHER (1977), THIERSTEIN and OKADA (1979), and JIANG and GARTNER (1986). Quantification and statistical analysis permits a more accurate assessment of the assemblage turnover across the boundary which can then be easily used for comparison on a regional or global basis. However, regardless of the accuracy of these methods, problems still remain when comparing quantitative analyses by different workers as individual methods and species concepts vary to a certain extent.

## METHODS

Aboard ship during Legs 113 and 121, toothpick samples were taken at 1 cm increments across the boundary interval and at additional intervals where deemed necessary. Regular 3 cc samples were taken at 4 cm increments across the boundary and at successively thicker intervals after that. For the section at Site 690, individual burrows were sampled above and below the boundary.

Smear slides of raw sediment were analyzed under the light microscope at 1600X and at least 500 specimens per sample were counted. The count of 500 is designed to ensure that infrequent taxa are included. Most samples were examined beyond this count, however, to uncover any additional species present and to assure that no stratigraphic information was lost. Such is the case with *Biantholithus sparsus*, which was not observed during the counting of Sample 121-752B-11R-3, 72-73 cm, but was observed during routine shipboard examination of the same slide. For the compiled data charts for Site 690 see POSPICHAL and WISE (1990a) and POSPICHAL (in press) for Site 752.

Individually counted specimens were placed in one of three categories: Tertiary, Cretaceous or "survivor". The procedure is similar to that used by THIERSTEIN and OKADA (1979) on DSDP Site 384 and PERCIVAL and FISCHER (1977) on the Zumayan section of Spain. The definition of these three assemblages follows that of PERCH-NIELSEN *et al.* (1982) where Cretaceous forms are those species considered to have become extinct before or at the end of the Maastrichtian. "Survivor" species are those which were present in the Cretaceous and survived into the Tertiary or had direct descendants surviving into the Danian. Tertiary forms are those which evolved starting at or above the K/T boundary.

Biostratigraphic zonations used in this report are that of OKADA and BUKRY (1980) for the Danian and a recent scheme of POSPICHAL and WISE (1990b) for the Maastrichtian. Several provincial schemes have been proposed for the Danian. PERCH-NIELSEN (1979) provided a high resolution scheme for sections in Denmark and van HECK and PRINS (1987) for the North Sea. These schemes are highly detailed and do not appear to work well at the high southern latitude sites. WEI and POSPICHAL (1991) provide a provincial scheme for the Danian of the Southern Oceans; however for the purpose of this paper, we will refer to the more commonly used numbered zonation of OKADA and BUKRY (1980).

## K/T BOUNDARY DESCRIPTIONS

### SITE 690, MAUD RISE

Ocean Drilling Program Leg 113, Site 690 was cored on Maud Rise (65°S) in the Weddell Sea off East Antarctica (Fig. 1). A biostratigraphically continuous, but intensely bioturbated, Cretaceous/Tertiary boundary sequence was recovered, the first from the high latitudes of the South Atlantic sector of the Southern Ocean.

The K/T boundary lies just within Chron 29R and is placed at ODP Sample 113-690C-15X-4, 41.3 cm (Fig. 2). An iridium anomaly was independently noted at about this level as well (MICHEL, *et al.,* 1990). Upper Maastrichtian-lower Paleocene sediments consist mostly of light-colored nannofossil chalks. Dark brown sediments at the base of the Danian (Zone CP1a) are characterized by an increased clay content attributed to a drop in calcareous microplankton productivity following the terminal Cretaceous event.

Although delineation of the boundary is hampered by intense bioturbation, the sharp color contrast between overlying clay-rich, dark brown chalks of the Tertiary and light cream colored chalks of the Cretaceous aids in the selection of the K/T horizon. Several dark colored burrows sampled at intervals as far as 1.3 m below the boundary and within the light colored Cretaceous chalk were found to contain up to 17% Tertiary nannofossils (Fig. 2). The problems of bioturbation are discussed in further detail in POSPICHAL *et al.* (1990).

### SITE 752, BROKEN RIDGE

Site 752 was cored on Broken Ridge which has a present latitude of about 30°S in the Eastern Indian Ocean. Broken Ridge did not always lie at this latitude. It had once constituted the northern end of the Kerguelen Plateau before rifting and subsequent northward movement by sea-floor spreading, which began in the middle Eocene. The estimated paleolatitude for Broken Ridge at K/T time is approximately 50° to 55° S (marked by an "X" in Figure 1).

The Cretaceous/Tertiary boundary is located within a unit of well indurated, ash-rich chalk between 72 cm and 94 cm in ODP Core 11R, Section 3, or at approximately 358.50 to 358.75 mbsf (meters below sea floor) (Fig. 3). These two sample levels denote biostratigraphic events with the first occurrence (FO) of the Tertiary calcareous nannofossil *Biantholithus sparsus* in the sample at 72 cm and the last occurrence (LO) of Cretaceous planktonic foraminifers in the sample at 94 cm (Fig. 3). An iridium anomaly was also noted at approximately 94 cm (MICHEL *et al.,* in press). The boundary lies within a sequence of ash, chert, and chalk which immediately underlies a 5.5 to 6.5 m ash layer. More precisely, the lithology of the boundary interval is described as follows (PEIRCE, WEISSEL *et al.,* 1989). The ash layer present between 90-95 cm overlies light gray, mottled, and well indurated uppermost Maastrichtian chalk containing the last Cretaceous foraminifers. Immediately above this, in the interval from 85-90 cm, is a light colored chalk with soft sediment deformation structures. The overlying interval between 75-85 cm is composed of gray chert and porcellanite which underlies chalk containing *B. sparsus*. The chalk grades upward into ash at about 60 cm. This is overlain by 25 cm of chalk which lies just below the approximately 6 m thick ash layer (discussed below).

The entire K/T sequence described above, and especially the cherty interval, is composed of numerous drilling "biscuits" produced by twisting and breaking during the rotary coring process (Fig. 3). All interpretations through this interval must then be made with caution since much sediment can be and probably is missing from between these "biscuits". Recovery in Core 121-752B-11R was only 52% of the 9.6 m cored. However, logging data (PEIRCE, WEISSEL *et al.,* 1989) suggest that most of the overlying 6 m ash was recovered, and recovery in the overlying core, Core 121-752B-10R, was 100%.

The striking 6 m ash unit present between the chalks at Site 752 does not represent a tremendous increase in volcanic activity at K/T time but is an artifact of the drastic drop in $CaCO_3$ accumulation associated with the events of the terminal Cretaceous. Ash flux at Site 752 was on the de-

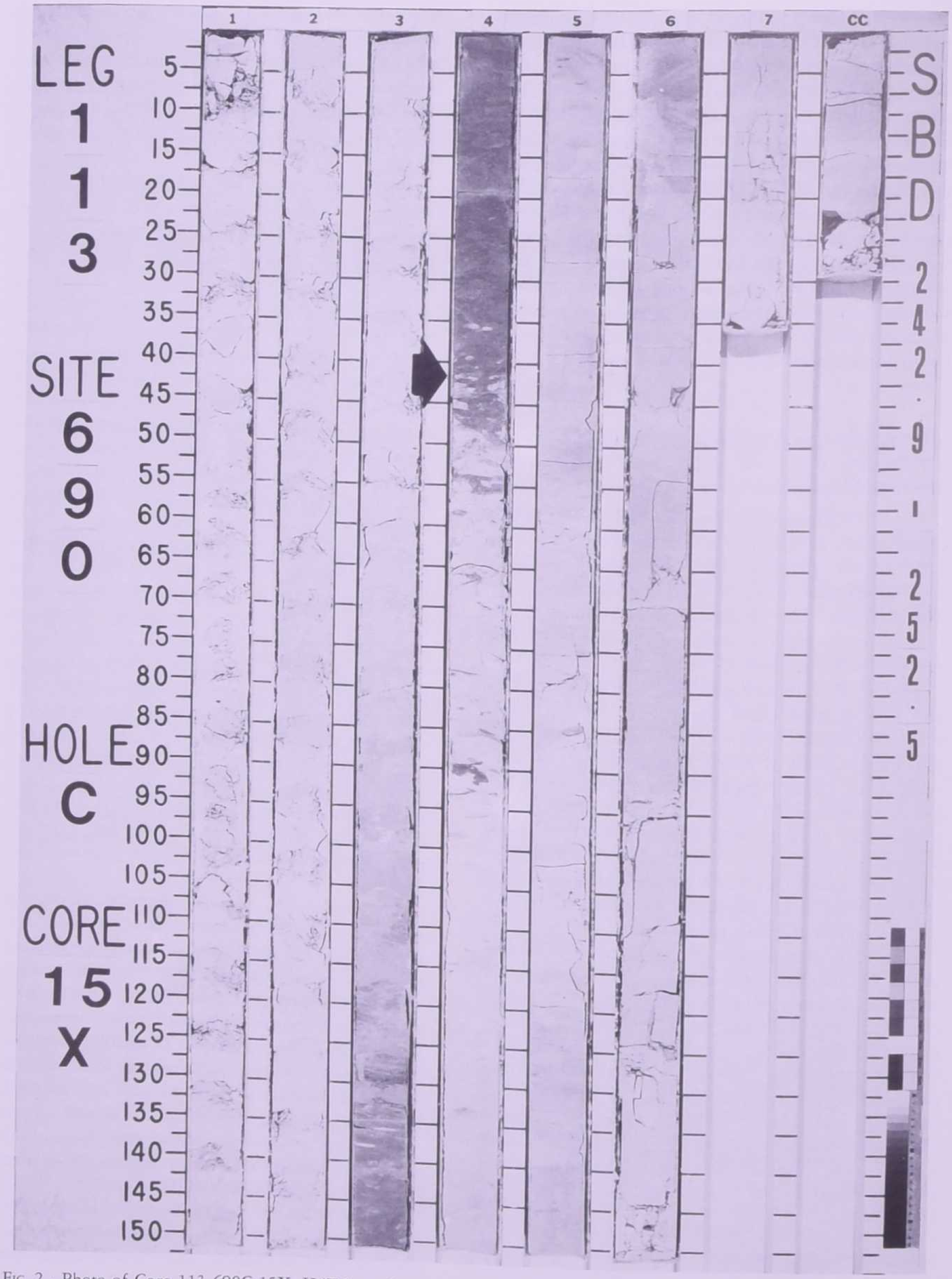


FIG. 2 - Photo of Core 113-690C-15X. K/T boundary at 41.5 cm in section 4 is indicated by an arrow. Dark blebs within the light colored chalk below the boundary are burrows.

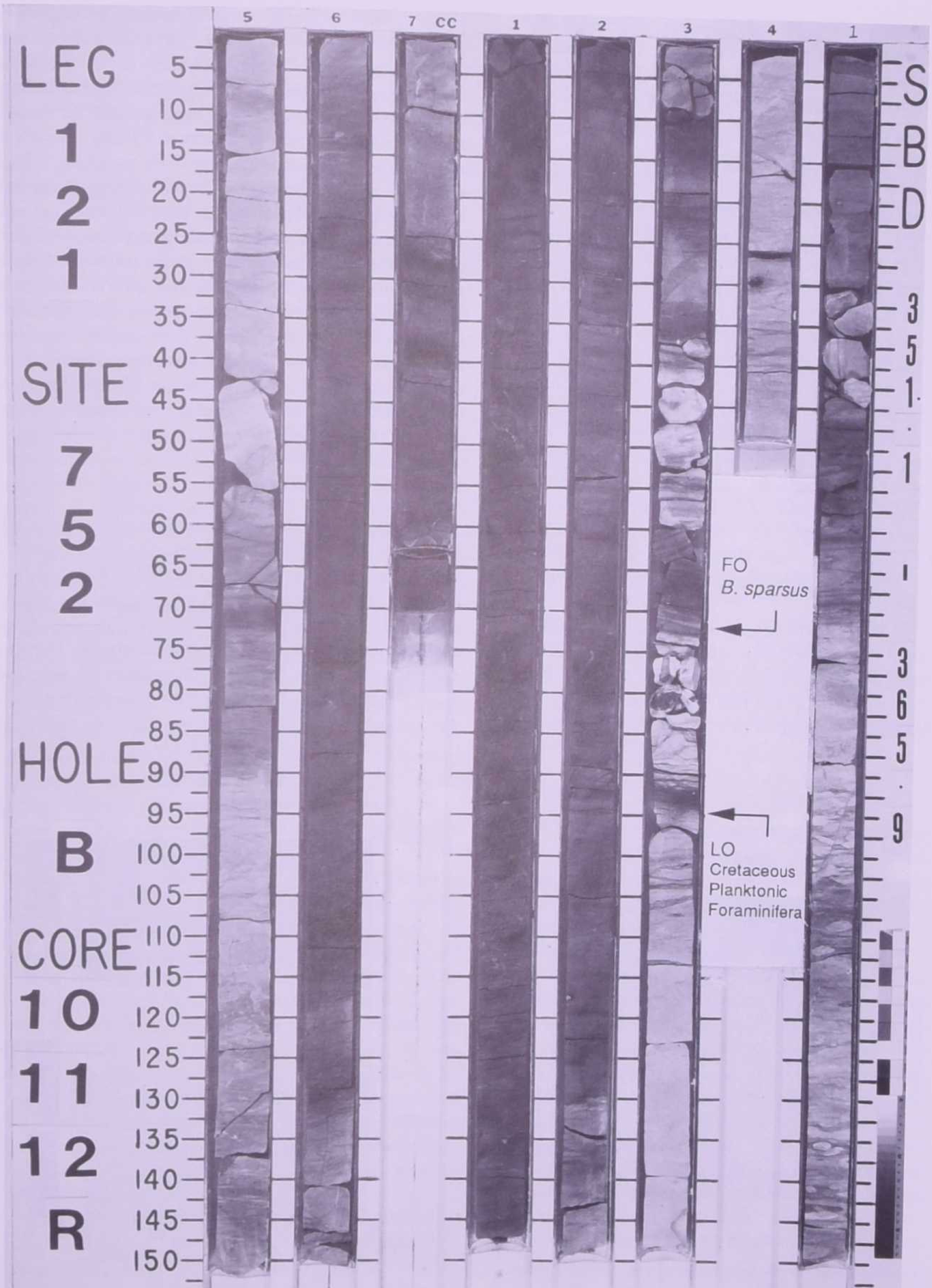


FIG. 3 - Photo of Core 121-752B-11R. The first occurrence of *Biantholithus sparsus* at 72 cm in section 3 and the last occurrence of Cretaceous foraminifera at 94 cm are indicated by arrows. The dark sediment in layers below the boundary and in the sections above is volcanic ash. An iridium anomaly is present in section 3 at 94-95 cm and 12-13 cm.

cline through the Maastrichtian and Tertiary and showed only a slight increase at the boundary while carbonate flux declined by a factor of four (PEIRCE, WEISSEL *et al.*, 1989; REA *et al.*, 1990).

## CALCAREOUS NANNOFOSSIL RESULTS

### BIO-MAGNETOSTRATIGRAPHY

The biostratigraphy and magnetostratigraphy for Sites 690 and 752 are summarized in Figures 4 and 5 respectively. As mentioned previously, at Site 690, the first occurrence of *Biantholithus sparsus* worked well to help delimit biostratigraphically the K/T boundary at 247.81 mbsf, although the intense bioturbation hampered boundary selection. Fortunately, the presence of highly contrasting colors between Cretaceous and Tertiary sediment greatly aided in boundary placement. The magnetostratigraphy of HAMILTON (1990) shows that this level falls just within Chron 29R (Fig. 4). The initial Danian Subzone, CP1a is about 45 cm thick at this site while the underlying *Nephrolithus frequens* Zone is quite thick at 23 m.

At Site 752, the selection of a precise boundary level is more difficult due to the presence of nannofossil-poor cherts and porcellanites in addition to drilling disturbance. Aboard ship, the boundary was located in a 20 cm interval between the last occurrence of Cretaceous foraminifera and the first occurrence of *B. sparsus* (PEIRCE and WEISSEL *et al.*, 1990). Subsequent nannofossil investigations revealed that the abundance of survivor forms increases sharply within this 20 cm interval and the boundary is most likely closer to the lower end of this interval or at about 358.7 mbsf. As shown in Figure 5, this level falls well within Chron 29R (PEIRCE and WEISSEL *et al.*, 1990). Much higher sedimentation rates prevailed at Site 752 as the section is more expanded than at Site 690 as illustrated by the vertical axes of Figures 4 and 5 which depict depth. The scale for Site 752 is in meters while that shown for Site 690 is in centimeters. The thickness of Subzone CP1a is about 5 m compared to 45 cm for Site 690. The underlying *N. frequens* Zone is over twice as thick at 58 m.

### QUANTITATIVE RESULTS

The results of the quantitative study for K/T boundary at Site 690 are summarized in Figures 4 and 6 and in Figures 5 and 7 for Site 752. Figures 4 and 5 show a comparison of the percent abundance of the three subassemblages, Tertiary, Cretaceous, and "survivor", described above. Figures 6 and 7 show the percent abundance of selected individual species from each of the three subassemblages. Counts were made on samples

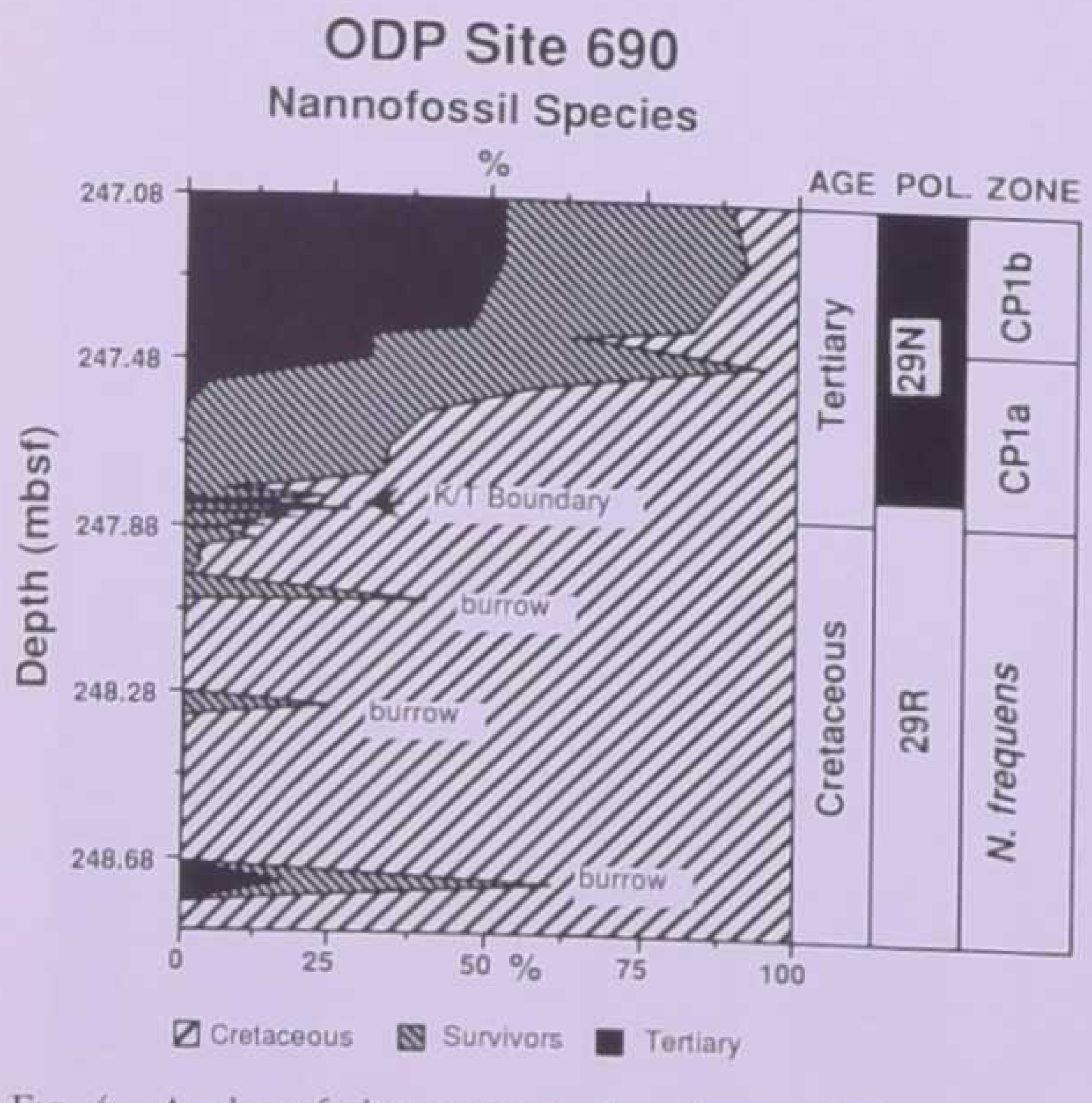


FIG. 4 - A plot of the percent abundance of Cretaceous vs. Tertiary vs. "survivor" nannofossil species at Site 690 along with the biostratigraphic nannofossil zones correlated with the magnetostratigraphy of HAMILTON (1990). Note burrows below boundary.

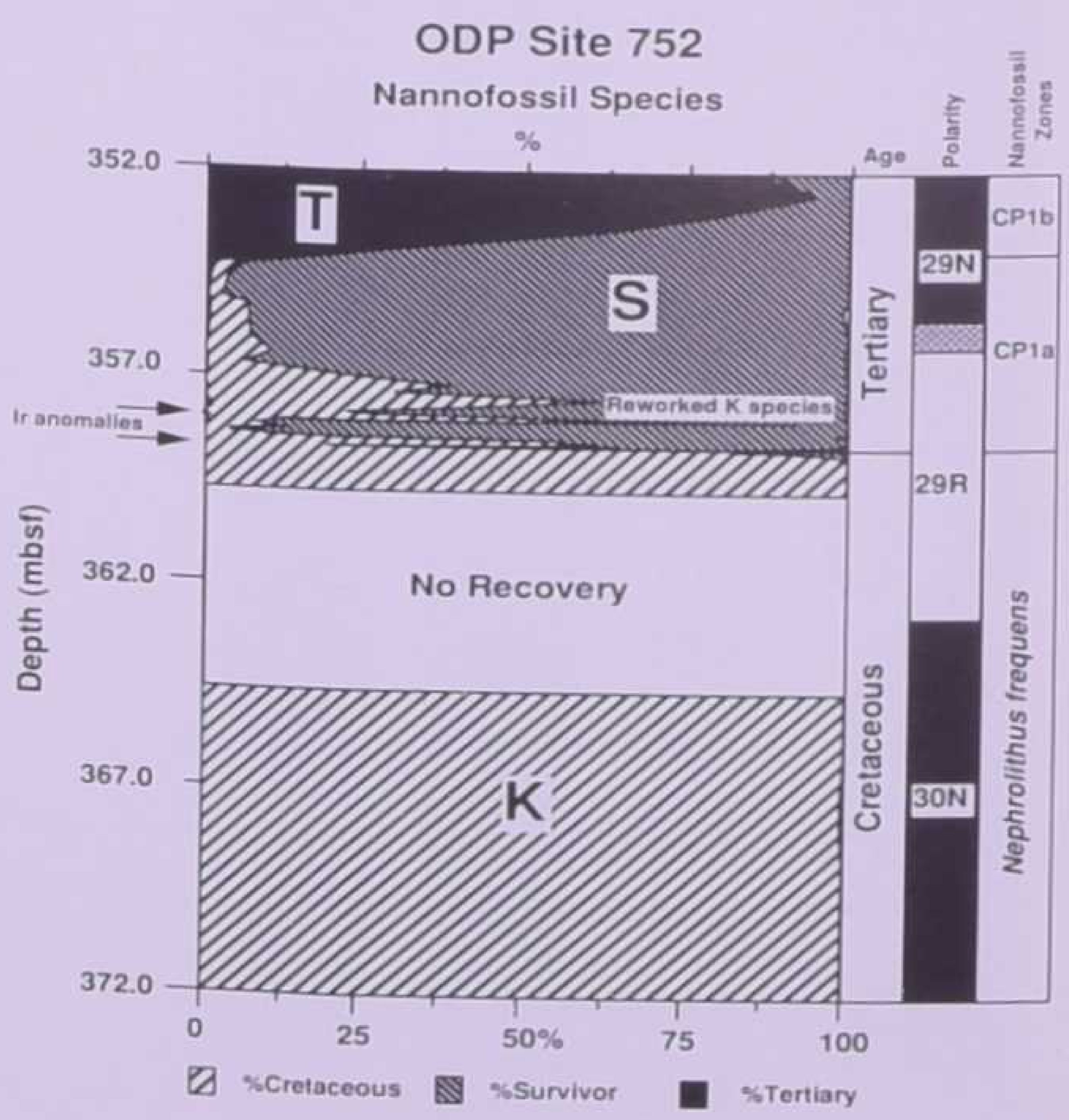


FIG. 5 - A plot of the percent abundance of Cretaceous vs. Tertiary vs. "survivor" nannofossil species correlated with the bio-and magnetostratigraphy across the K/T boundary, Site 752.

through Subzone CP1b at Site 752 and to about the middle of CP1b at Site 690. The K/T boundary at Site 690 is located at approximately 247.81 mbsf. The graph clearly shows the dominance of Cretaceous forms below and up to at least 30 cm above the boundary. The Cretaceous assemblage at this point is then replaced by an assemblage of "survivor" taxa, which dominate for a short interval and are quickly replaced by a rapidly evolving Tertiary assemblage at about 247.47 mbsf. Thus, the entire turnover from a Cretaceous to a Tertiary dominated assemblage at Site 690 occurs within about 40 cm of sediment or within the interval of Subzone CP1a. The turnover is similar at Site 752, but occurs over a much larger interval of about 5 m, which roughly corresponds to the thick basal Danian ash unit. The evolution and dominance of Tertiary forms marks the return to normal carbonate accumulation. As shown in Figure 5, the dominance of Cretaceous forms is abruptly interrupted at the K/T boundary at about 358.7 mbsf and the assemblage is replaced by "survivor" forms, which dominate for the next 5 m until being replaced by a Tertiary dominated assemblage. A short interval within the "survivor" dominated sequence is present between about 356.0 mbsf and 358.0 mbsf where Cretaceous forms return in high abundance (92%) at 12-13 cm (357.92 mbsf). This phenomenon can probably be attributed to a large increase in reworking. Coincident with this level, MICHEL *et al.* (in press) and SCHURAYTZ *et al.* (in press) note a secondary peak in iridium abundance, which appears to confirm an explanation of redeposition.

For Site 690, a striking feature of the graph in Figure 4 is the numerous peaks representing anomalously high abundances of "survivor" and Tertiary species below the K/T boundary. As noted, these correspond to large burrows. The most surprising is the lowest burrow sampled, which contains 17% Tertiary forms. This burrow is nearly 1.3 m below the first estimated *in situ* occurrence of these Tertiary forms. This illustrates well the problems one may encounter when performing a study of this nature on a section where there is little color change between Cretaceous and Tertiary sediments and burrows cannot be differentiated.

Among other things, these quantitative studies have illustrated, by direct correlation with the nannofossil data, the susceptibility of iridium to movement up and down section via the physical processes of bioturbation and reworking. The consequences of these observations are obviously important to interpretations that additional iridium anomalies are indicators of multiple impacts or extended intense volcanic events.

### CRETACEOUS

At Site 690, the uppermost Maastrichtian assemblage of the *Nephrolithus frequens* Zone consists of about 20 to 25 species. The basic assemblage is typical of high latitudes (THIERSTEIN, 1981) and includes abundant *Acuturris scotus, Arkhangelskiella cymbiformis, Cribrosphaerella daniae, Kamptnerius magnificus, Prediscosphaera cretacea, Nephrolithus frequens frequens* and *N. f. miniporus*. The most dominant form is the tiny *Prediscosphaera stoveri* (Fig. 6). The basic assemblage does not change much through the uppermost Maastrichtian *N. frequens* Zone, however, the base of this zone at Site 690 is marked by the disappearance of several forms.

The uppermost Maastrichtian assemblage at Site 752 is poorly preserved and is dominated for the most part by the dissolution resistant forms, especially *Micula decussata* (Fig. 7). The basic assemblage is essentially the same as at Site 690 although less diverse because of the poor preservation. Near the very top of the Maastrichtian, however, nannofossils from several of the ash layers exhibit better preservation and a more diverse assemblage is present. The delicate *P. stoveri* is dominant along with *N. f. frequens* and *A. cymbiformis* (Fig. 7).

### "SURVIVORS"

The "survivor" subassemblage of the lowermost Danian CP1a Subzone at Site 690 is dominated by *Zygodiscus sigmoides*, which ranges around 25% of the total nannofossil assemblage including reworked Cretaceous forms. Its peak abundance is about 45% (Fig. 6). This form is even more abundant at Site 752, ranging around 50% of the assemblage and peaking at nearly 80% (Fig. 7). The remaining assemblage consists of *Biscutum castrorum* (=*B. constans* of some authors), *Markalius inversus, Neocrepidolithus* spp. (mostly *N. cruciatus*), *Thoracosphaera* spp., and *Cyclagelosphaera reinhardtii*. An additional constituent, *Lapideacassis*, is extremely rare at both sites. At Site 752, *"Zygolithus" crux* (forms possibly related to *Chiastozygus ultimus*) are present as members of the "survivor" group.

After *Z. sigmoides, B. castrorum* and *M. inversus* are the most dominant "survivor" forms at Site 690. *Neocrepidolithus, Thoracosphaera*, and *Cyclagelosphaera reinhardtii* are minor components peaking at no more than 6% of the assemblage. At Site 752, there is a more equal dis-

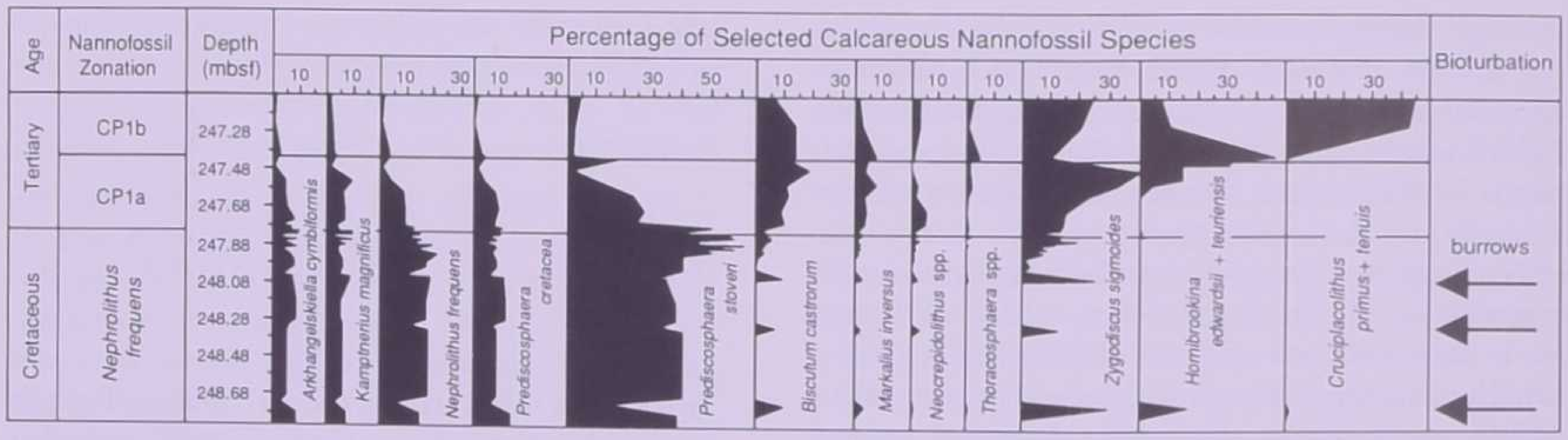


FIG. 6 - Percent abundance of selected individual nannofossil species across the K/T boundary, Site 690.

tribution of *M. inversus, B. castrorum, Neocrepidolithus* and *Thoracosphaera*, which is much more abundant at this site. Only 3 specimens of *Braarudosphaera* were observed in samples from Site 752 and none at Site 690.

In Figure 7, a peak abundance for *Thoracosphaera* of about 40% is shown just above the K/T boundary. This peak is probably misleading in that several samples from this interval contained very few nannofossils, and it was necessary to use counts totaling less than 500 (see POSPICHAL, in press). Although included in the construction of Figure 7, the data from the sample consisting of 40% *Thoracosphaera* can not be taken as a true statistical representation of the assemblage.

TERTIARY

The first Tertiary species to appear at Sites 690 and 752 is *Biantholithus sparsus*. This form first occurs at the boundary at Site 690 and about 20 cm above the K/T horizon at 752. It is very rare at each site and is never more than one specimen per 500.

At Site 690, the next taxa to appear is *Hornibrookina*, which first occurs about 15 centimeter above the boundary within Subzone CP1a. Surprisingly, this form rapidly becomes the most abundant with a peak of about 50% around the CP1a/CP1b boundary (Fig. 6). Shortly above this, *Cruciplacolithus primus* and *C. tenuis* first occur at about the same level and become the most dominant forms. The small *Prinsius tenuiculum/dimorphosus* and *Coccolithus cavus* also occur at about this level but are rare at first. In most sections, *C. primus* occurs below the first *C. tenuis* and the coincidental first occurrences here are probably due to either bioturbation or possibly a slight hiatus around the CP1a/CP1b Subzone boundary.

The much more expanded, less bioturbated sequence at Site 752 permits a more accurate assessment of the evolution of Tertiary species. At this site, the first species to occur above *B. sparsus* are small (≤5μm) *C. primus*, which are rare at first, beginning at about 2 m above the boundary. At about 5 m above the boundary, larger forms (5-7 μm) of *C. primus* appear along with *C. tenuis* (≥ 7 μm), which is the most abundant form (Fig. 7). *Prinsius tenuiculum/dimorphosus* also appears about at this level but is rare at first. *Coccolithus cavus* appears shortly above this along

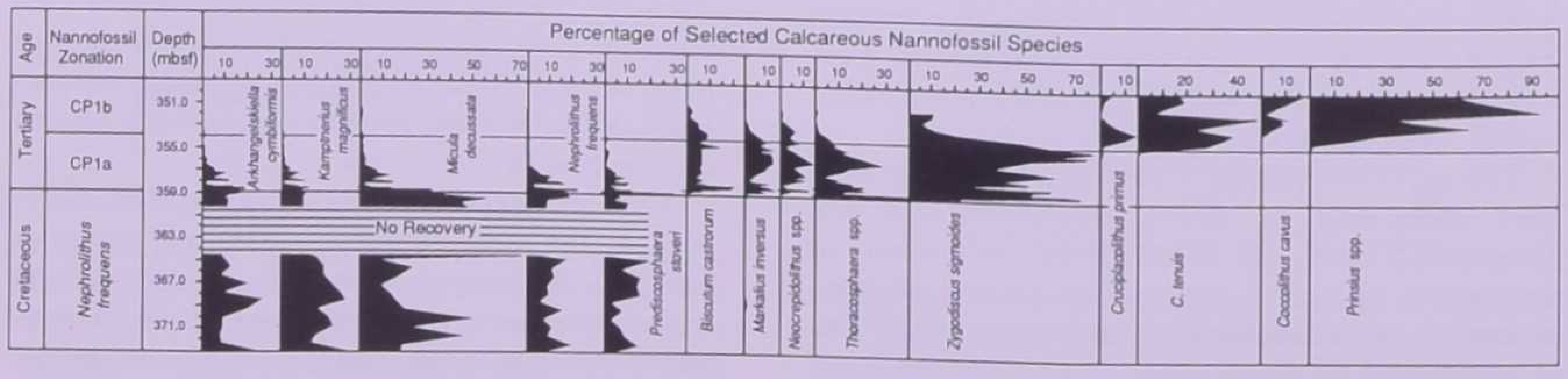


FIG. 7 - Percent abundance of selected individual nannofossil species across the K/T boundary, Site 752.

with one observed specimen of *Futyania petalosa*. Starting at about a meter above the first occurrence of *C. tenuis* (CP1a/CP1b boundary), *P. tenuiculum/dimorphosus* is the most dominant form ranging from 50% to 80% of the assemblage within Subzone CP1b.

## BOUNDARY COMPARISONS AND DISCUSSION

As expected, the uppermost Maastrichtian assemblages of Sites 690 and 752 are much less diverse than those of middle and lower latitudes. Marker taxa such as *Micula murus* and *M. prinsii* are absent and assemblages are dominated by *Nephrolithus frequens frequens, Arkhangelskiella cymbiformis, Kamptnerius magnificus* and *Prediscosphaera stoveri* (discussed below).

*Wartznaueria barnesae*, an abundant constituent of low latitude sediments, is rare to few at these higher latitude localities.

The Cretaceous/Tertiary transitional nannofossil assemblage consisting of the environmental generalist "survivor" forms appears to be controlled by a variety of paleoceanographic, environmental, and latitudinal factors. In comparison to low latitude sections as reported by PERCH-NIELSEN *et al.* (1982), forms such as *Markalius inversus, Biscutum castrorum, Neocrepidolithus*, and especially *Zygodiscus sigmoides* appear to be more prevalent in higher latitudes. Conversely, *Cyclagelosphaera, Thoracosphaera* and *Braarudosphaera* are more abundant in lower latitude sections. The distribution of *Thoracosphaera* is more complex than first thought. It did not bloom at Site 690 and at Site 752, although abundant, did not reach the same abundances as reported at K/T boundary localities such as El Kef and Brazos River (JIANG and GARTNER, 1986) or Site 384 in the North Atlantic (THIERSTEIN and OKADA, 1979). *Braarudosphaera* also did not bloom in the austral high latitude sections, although its distribution may be controlled more by water depth and salinity than temperature (for discussion see THIERSTEIN, 1981).

The distribution of newly-evolving Tertiary taxa such as *Biantholithus sparsus* is also complex. This species is rare in most sections and absent in others. Its presence at a high latitude of 65°S at Site 690, as well as in the Tethyan sections exemplifies its broad latitudinal range. What factors govern its distribution are not known, although they are clearly not latitudinally dependent.

The early Danian assemblages of Sites 690 and 752 lack *Neobiscutum romeinii, N. parvulum*. A single specimen of *Futyania petalosa* was observed at Site 752, and very rare specimens were noted in samples from Site 750 (POSPICHAL, unpubl.) These taxa were not reported from Site 738 (WEI and THIERSTEIN, 1991). The distribution of these forms appears to be latitudinally dependent, however, not all of these species or their blooms are present at all localities of the lower latitudes as illustrated by the well studied Tethyan sequences. PERCH-NIELSEN *et al.* (1982) note that *N. romeinii* is present at El Kef but not at Caravaca. *Neobiscutum parvulum* and *Futiyania petalosa* are present at both localities. *Futiyania petalosa* appears to have the broadest latitudinal distribution of the three. As mentioned before it was noted at Sites 750 and 752, although extremely rare. It is also rare in the mid latitude sections of DSDP Site 356 and in Denmark (PERCH-NIELSEN *et al.*, 1982). Local paleoceanographic conditions appear to control the occurrences of these forms and their blooms. The bloom of *Hornibrookina* noted at Sites 690 (65°S) and 738 (63°S) may be strongly controlled by latitudinal factors in addition to local paleo-environmental factors as discussed in more detail below.

### *Prediscosphaera stoveri*

According to PERCH-NIELSEN *et al.* (1982), the uppermost Maastrichtian of most all K/T sections is not dominated by any single nannofossil species. This is not the case for the extremely high southern latitudes where *P. stoveri* is highly abundant. This form reaches nearly 60% of the assemblage just below the boundary at Site 690 (Fig. 6), an abundance not previously reported possibly due to the species' small size. JIANG and GARTNER (1986) noted an uppermost Maastrichtian peak abundance of about 15% for *P. quadripunctata* (a synonymous form?) from the Brazos River, Texas and El Kef, Tunisia sections. Samples from the boundary interval of Site 738 from the southern Kerguelen Plateau contain abundant *P. stoveri*, possibly as abundant as at Site 690 (WEI and THIERSTEIN, 1991). The species is also abundant in samples from Site 750 on the Central Kerguelen Plateau (WATKINS, in press; EHRENDORFER and AUBRY, in press). At Site 752, *P. stoveri* is abundant, but only to a maximum of about 30%, although poor preservation may have affected the true percentage at this site.

It is obvious that the distribution of abundant small forms of *Prediscosphaera* is latitudinally dependent. The taxon apparently prefers cooler waters, however, since acmes have not been reported from high northern latitudes, this assertion can only be made for the austral realm. In addition, their migration into lower latitudes may reflect a latest Maastrichtian cooling trend, although much more data are needed to support this assumption.

*Hornibrookina*

*Hornibrookina (H. edwardsii* in POSPICHAL and WISE, 1990a) achieves an unexpected abundance of nearly 50% of the assemblage near the CP1a/CP1b subzonal boundary at Site 690 (65°S) in the Weddell Sea. At Site 738 (63°S) on the southern end of the Kerguelen Plateau, WEI and THIERSTEIN (1991) note a similar bloom of *Hornibrookina* (*H. teuriensis*) at the same stratigraphic level. Just to the north of this site on the Kerguelen Plateau, abundant *Hornibrookina* have been reported in samples of Subzone CP1b at site 750 (57°S) (EHRENDORFER and AUBRY, in press). The abundance of *Hornibrookina* at this site appears to be lower than at the equivalent level at either Site 690 or Site 738. Furthermore, at Site 752 (paleolatitude 55°S), which would have been situated just north of Site 750, *Hornibrookina* does not first appear until Zone CP2 and is only rare to few in this section.

For the southern Indian Ocean, one may postulate that a latitudinal gradient in the abundance of *Hornibrookina* may exist with this form being most abundant on the south end of the Kerguelen Plateau and much less so on the northern end. Further detailed studies will be necessary to verify this, however, it is clear that the highest abundance of *Hornibrookina* yet reported is at the highest latitude site, Site 690 in the Atlantic sector of the Southern Ocean. This bloom is not noted at any other Atlantic, or Pacific locality. PERCH-NIELSEN (1977) noted only rare *Hornibrookina* in the South Atlantic sites of DSDP Leg 39 (Rio Grande Rise) and specimens were not reported from any of the Walvis Ridge sites of

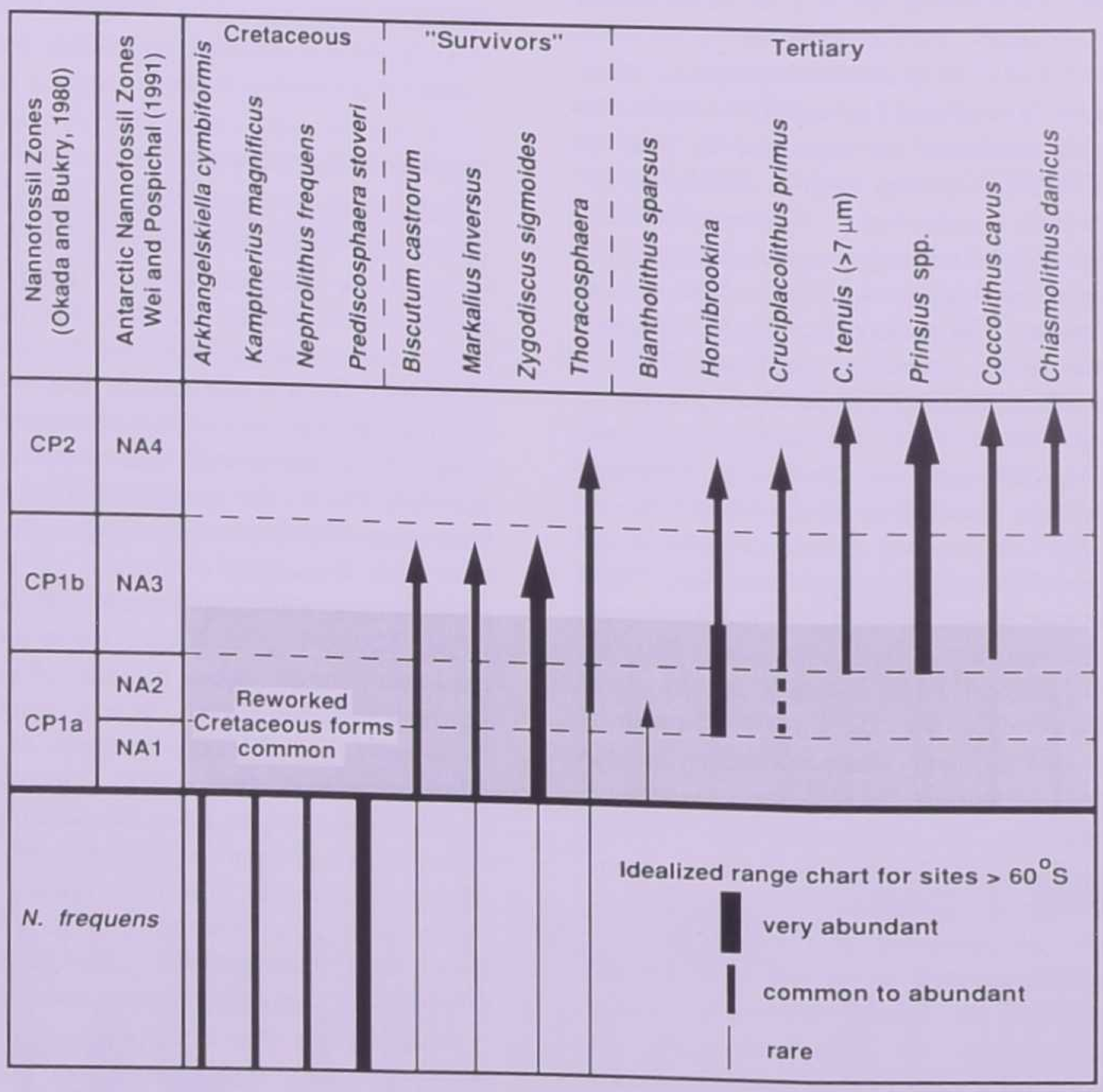


FIG. 8 - An idealized range chart of important species and their relative abundances across the Cretaceous-Tertiary boundary at sites greater than 55°-60°S latitude.

DSDP Legs 73-75 (PERCIVAL, 1984; MANIVIT, 1984; STEINMETZ and STRADNER, 1984). *Hornibrookina*, although very rare, was also observed by JIANG and GARTNER (1986) in boundary sediments of the mid latitude section of Brazos River, Texas. Hence, this would be the expected distribution of a predominantly high latitude form.

## SUMMARY

With the addition of new calcareous nannofossil data on the K/T boundary from the Indian and Atlantic sectors of the Southern Ocean, it is apparent that biogeographic provinciality exists which distinguishes these high austral latitude sections from the equatorial and boreal realms. Characteristic features of this austral biogeographic K/T province are summarized in Figure 8, which is an idealized range chart, including relative abundance of some important taxa across the K/T boundary.

For the uppermost Maastrichtian, nannofossil assemblages are similar to those northern high latitudes, but contain a much higher abundance of *Prediscosphaera stoveri*. This form is most dominant in extremely high southern latitudes such as at Site 690 (65°S). The marker species *Micula murus* and *M. prinsii* are absent.

The transitional K/T assemblage or the "survivor" group is generally dominated by *Zygodiscus sigmoides* with *Biscutum castrorum (B. constans), Markalius inversus*, and *Neocrepidolithus* in higher abundance than in lower latitude sections. *Thoracosphaera* does not bloom as intensely in the sections of the southern Indian Ocean and does not become abundant until higher in the section (CP2) at Site 690 in the Weddell Sea. *Braarudosphaera* is rare to absent in these deep-sea sections.

The Tertiary assemblage is dominated initially by *Hornibrookina* and subsequently by *Cruciplacolithus* and the small forms of *Prinsius*. Forms such as *Neobiscutum romeinii, N. parvulum*, and *Futyania petalosa* are absent or, in the case of the latter, extremely rare. The *Hornibrookina* bloom appears to be of short duration, straddling the CP1a/CP1b boundary, and limited to the extreme (>55°-60°S) southern latitudes.

## APPENDIX

Calcareous nannofossils considered in this report (In alphabetical order of Generic epithets)

### TERTIARY

*Bianthalithus sparsus* BRAMLETTE and MARTINI, 1964
*Coccolithus cavus* (HAY and MOHLER) PERCH-NIELSEN, 1969
*Cruciplacolithus primus* PERCH-NIELSEN, 1977
*C. tenuis* (STRADNER) HAY and MOHLER, 1967
*Futyania petalosa* (ELLIS and LOHMANN) VAROL, 1989
*Hornibrookina edwardsii* PERCH-NIELSEN, 1977
*H. teuriensis* EDWARDS, 1973
*Neobiscutum romeinii* (PERCH-NIELSEN) VAROL, 1989
*N. parvulum* (ROMEIN) VAROL, 1989
*Prinsius dimorphosus* (PERCH-NIELSEN) PERCH-NIELSEN, 1977
*P. tenuiculum* (OKADA and THIERSTEIN) PERCH-NIELSEN, 1984

### "SURVIVORS"

*Biscutum castrorum* BLACK, 1959
*Braarudosphaera bigelowii* (GRAN and BRAARUD) DEFLANDRE, 1947
*Cyclagelosphaera reinhardtii* (PERCH-NIELSEN) ROMEIN, 1977
*Chiastozygus ultimus* PERCH-NIELSEN, 1981a
*Lapideacassis* sp.
*Markalius inversus* (DEFLANDRE) BRAMLETTE and MARTINI, 1964
*Neocrepidolithus cruciatus* (PERCH-NIELSEN) PERCH-NIELSEN, 1981a
*Thoracosphaera* KAMPTNER, 1927
*Zygodiscus sigmoides* BRAMLETTE and SULLIVAN, 1961.

### CRETACEOUS

*Acuturris scotus* (RISATTI) WIND and WISE in WISE and WIND, 1977
*Arkhangelskiella cymbiformis* VEKSHINA, 1959
*A. specillata* VEKSHINA, 1959
*Biscutum constans* (GORKA) BLACK, 1959
*Cribrosphaerella daniae* PERCH-NIELSEN, 1973
*Kamptnerius magnificus* DEFLANDRE, 1959
*Micula decussata* VEKSHINA, 1959
*M. murus* (MARTINI) BUKRY, 1973
*M. prinsii* PERCH-NIELSEN, 1979a
*Nephrolithus frequens frequens* GORKA, 1957
*N. frequens miniporus* (REINHARDT and GORKA) POSPICHAL and WISE, 1990b
*Prediscosphaera cretacea* (ARKHANGELSKY) GARTNER, 1968
*P. quadripunctata* (GORKA) REINHARDT, 1970
*P. stoveri* (PERCH-NIELSEN) SHAFIK and STRADNER, 1971
*Watznaueria barnesae* (BLACK *in* BLACK and BARNES) PERCH-NIELSEN, 1968

*Zygolithus crux* (DEFLANDRE and FERT) BRAMLETTE and SULLIVAN, 1961

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