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GUNNAR OLAFSSON * and GIULIANA VILLA **

RELIABILITY OF SPHENOLITHS AS ZONAL MARKERS IN OLIGOCENE SEDIMENTS FROM THE ATLANTIC AND INDIAN OCEANS

CONTENTS

Key words: *Atlantic Ocean, Indian Ocean, Oligocene, sphenolith events, reliability.*

ABSTRACT

Counts of sphenolith abundances have been determined for four out of nine datum levels used for the subdivision of the Oligocene into biozones. These four events are: the first occurrence of *Sphenolithus distentus*, the first occurrence of *Sphenolithus ciperoensis*, the last occurrence of *Sphenolithus distentus* and the last occurrence of *Sphenolithus ciperoensis*. Material from the South Atlantic Ocean and from the equatorial Indian Ocean is used in an attempt to assess the reliability of these events.

The appearance of the abundance plots of the sphenoliths show that the last occurrences of *S. ciperoensis* and *S. distentus*, and the first occurrence of *S. ciperoensis* are distinct events in both regions and can be considered reliable biostratigraphic events. The first occurrence of *S. distentus* is not as distinct as the other three sphenolith events, therefore it is considered less reliable as a biostratigraphic marker event.

An attempt to quantify the reliability of the sphenolith events is made by calculating a reliability index for each of the events.

The abundance plot of *Sphenolithus predistentus* shows that its last occurrence is a distinct and reliable biostratigraphic event, both in the South Atlantic Ocean and in the equatorial Indian Ocean.

The abundance plot of *Sphenolithus pseudoradians*, an easily recognized species, shows that it is of limited biostratigraphical value.

RIASSUNTO

Nel lavoro vengono riportati i risultati di analisi quantitative sulla distribuzione degli Sfenoliti nell'Oligocene di due successioni recuperate nell'Oceano Atlantico meridionale (DSDP Site 522) e nell'Oceano Indiano equatoriale (ODP Site 711). Lo scopo del lavo-

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* Department of Geology, University of Stockholm, S-106 91 STOCKHOLM, Sweden.

** Istituto di Geologia, Mineralogia e Petrografia, Università degli Studi di Parma, Viale delle Scienze, I-43100 PARMA (Italia).

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ro è quello di valutare l'attendibilità di quattro eventi biostratigrafici basati sugli Sfenoliti utilizzati nelle zonature standard dell'Oligocene. Tali eventi sono: comparsa e scomparsa di *Sphenolithus distentus* e comparsa e scomparsa di *Sphenolithus ciperoensis*. I dati ottenuti indicano che la comparsa di *S. distentus* rappresenta un evento poco attendibile, mentre gli altri tre sono chiari e correlabili nelle due successioni esaminate così come in altre riportate in letteratura. L'attendibilità biostratigrafica degli eventi è stata valutata quantitativamente, calcolando un indice di attendibilità per ognuno di essi.

I dati raccolti indicano che anche l'estinzione di *Sphenolithus predistentus* è un buon evento biostratigrafico nell'Oligocene superiore. Al contrario *Sphenolithus pseudoradians*, specie di facile riconoscimento, mostra una distribuzione tale da renderlo poco utile come indicatore biostratigrafico nell'Oligocene.

INTRODUCTION

The number of conventionally used biostratigraphic marker events is lower in the Oligocene time interval than it is in most other Cenozoic intervals of corresponding duration (Fig. 1). Four sphenolith events have been used to define datum levels for the subdivision of the Oligocene into biozones (BUKRY, 1973, 1975; OKADA and BUKRY, 1980; MARTINI, 1971; ROTH, 1970). These events are: the first occurrence of *S. distentus*, the first occurrence of *S. ciperoensis*, the last occurrence of *S. distentus* and the last occurrence of *S. ciperonesis*.

Because of the low number of nannofossil events available in the Oligocene (Fig. 1), it is of great importance that they are used in a reproducible way. The reliability of a nannofossil event can be described in terms of how it is defined, *e.g.*, by the last occurrence, absolutely last specimen observed, end of acme, first occurrence, absolutely first specimen observed, etc. Furthermore, the method by which the event is determined is important (qualitatively, semi-quantitatively or quantitatively, sampling interval). The taxonomic concepts used by different investigators is also of importance.

Few methods are available to evaluate the reliability of nannofossil events. HAY (1972, 1974) introduced probabilistic stratigraphy as a method to determine the most likely sequence of first and last occurrences of species. This method was later adopted by HILLS and THIERSTEIN (1989) as a tool to evaluate the reliability of several Pliocene - Pleistocene biostratigraphic events.

Another method to determine the reliability is that of WESTBERG and RIEDEL (1982). This is a semi-quantitative approach to obtain a reliablity index of biostratigraphic events. The reliability index has numerous contribution factors, some of which are qualitatively determined.

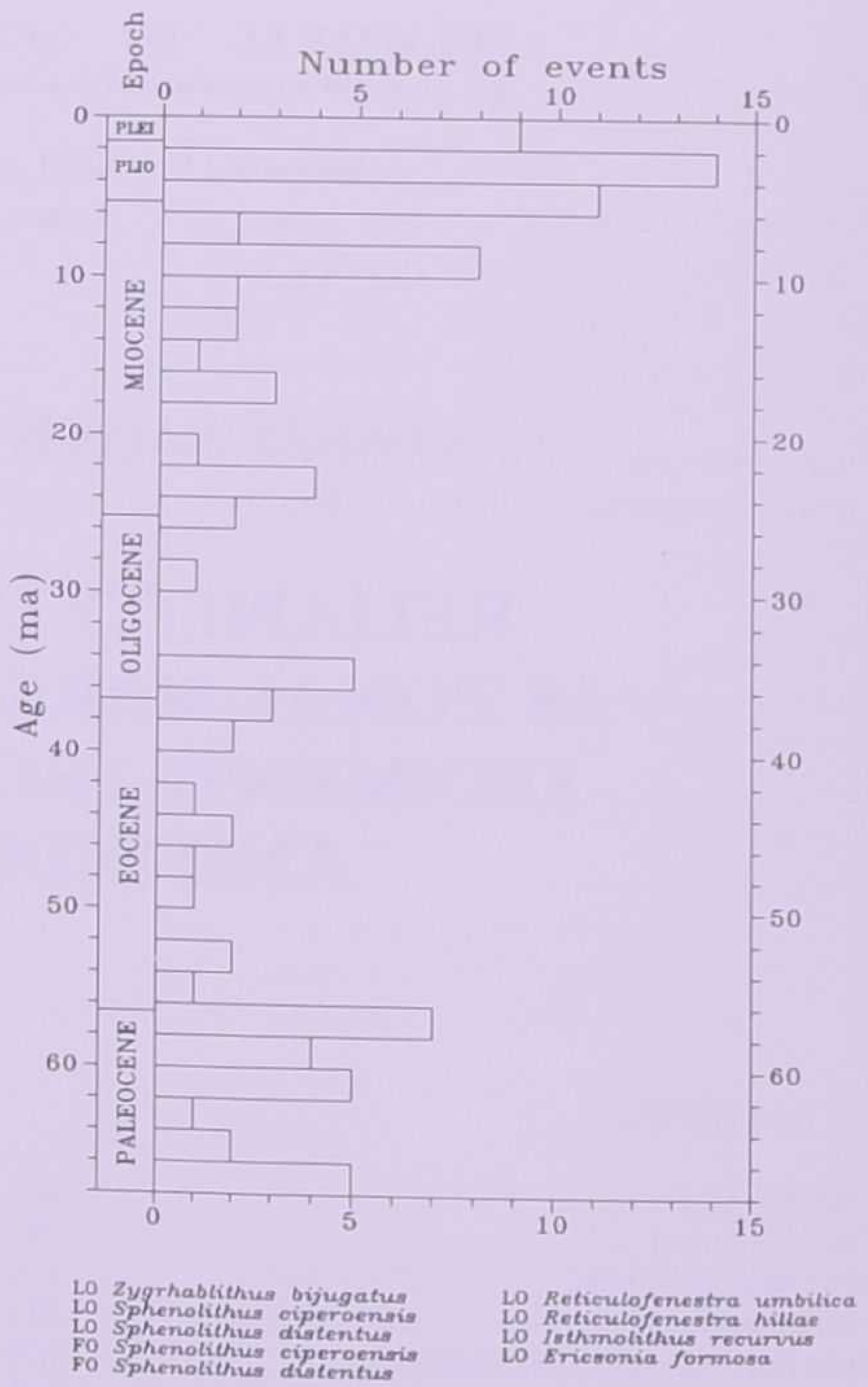

FIG. 1 - Numer of nannofossil events used in Cenozoic zonation scheme (BUKRY, 1973, 1975; OKADA and BUKRY, 1980) that are dated by BERGGREN *et al.* (1985a; 1985). Note the low number of events in the Oligocene. Nannofossil events used for subdivision of the Oligocene into biozones are listed.

A quantitative method to determine the reliability of biostratigraphical events was introduced by BRALOWER *et al.* (1989). They defined a reliability index based on the abundance and distribution of a species of interest in the first or last samples of its range.

One method that can be used to evaluate the reliability of nannofossil events is to plot the abundances of the species under consideration (BACKMAN, 1986a, 1986b; BACKMAN and SHACKLETON, 1983). The abundance plots reveal the distinctiveness of the events, which in turn is a good indication of the reliability.

Few attempts have been made to assess the reliability of Oligocene nannofossil events. WEI and WISE (1989) made a compilation of the biostratigraphical significance of several Cenozoic index species. They gave examples of different ranges and diachroniety of several index species. According to WEI and WISE (1989), the only reliable sphenolith event in the Oligocene is the LO of *S. ciperoensis*. This conclusion is mainly based on the diachroneity of the events that they observed when comparing published data from different DSDP sites.

Terms like "extinction", "last appearance" and "last occurrence" need to be clearly defined in order to minimize confusion, especially when comparing works of different authors. Inconsistencies in the use of such terms are bound to lead to problems in estimates of species ranges and hence in biostratigraphy.

The purpose of this paper is to examine four Oligocene sphenolith events in order to evaluate their relative degree of "reliability" in biostratigraphy.

TAXONOMIC NOTES

The Oligocene sphenoliths have intermediate or transitional forms that can be considered members of an evolutionary lineage going from *S. predistentus* through *S. distentus*, resulting in *S. ciperoensis* (BRAMLETTE and WILCOXON, 1967; ROTH *et al.*, 1971a, 1971b; HAQ, 1972; MORAN and WATKINS, 1988). The taxonomic status of the intermediate forms is not fully understood and several forms have been described as being transitional between *S. predistentus* and *S. distentus*, and between *S. distentus* and *S. ciperoensis* (ROTH *et al.*, 1971b; MORAN and WATKINS, 1988; FORNACIARI *et al.*, 1990; OKADA, 1990).

Sphenolithus predistentus, *S. ciperoensis* and *S. pseudoradians* were first described by BRAMLETTE and WILCOXON (1967). *Sphenolithus distentus* was first described by MARTINI (1965) and later recombined by BRAMLETTE and WILCOXON (1967). BRAMLETTE and WILCOXON (1967) recognized the biostratigraphical usefulness of the *S. predistentus* - *S. ciperoensis* lineage. Several investigators have noted the problems of distinguishing between *S. predistentus* and *S. distentus*, and *S. distentus* and *S. ciperoensis* (ROTH *et al.*, 1971a, 1971b; HAQ, 1972; MORAN and WATKINS 1988). In this study the method described by ROTH *et al.* (1971b) is used to distinguish between *S. predistentus* and *S. distentus*. If the angle between the extinction lines in the proximal part of the sphenolith and the median axis is 90 degrees or less (light microscope, crossed nicols), the forms are assigned to *S. predistentus*. If the angle is more than 90 degrees and the extinction lines still reach the median axis, the form is assigned to *S. distentus* (ROTH *et al.*, 1971b, p. 1106, Fig. 5).

The diagnostic morphologic features presented by MORAN and WATKINS (1988) are used to distinguish between *S. distentus* and *S. ciperoensis* (Tab. 1).

TABLE 1 - Diagnostic morphological characteristics of *S. distentus* and *S. ciperoensis* (from MORAN and WATKINS, 1988)

S. distentus

1. Apical spine generally large; tapering gradual or not at all for proximal half, then quickly for distal half.
2. Proximal shield rarely wider than base of apical spine.
3. Extinction lines of proximal shield are "V"-shaped and cross when apical spine is at 45 degrees to either polarizer.

S. ciperoensis

1. Apical spine small, with uniform taper throughout its length.
2. Proximal shield wider than any point on apical spine.
3. Extinction lines of proximal shield are "chevronlike" and do not cross when apical spine is at 45 degrees to either polarizer.

MATERIAL AND METHODS

The material used in this study is from Deep Sea Drilling Project (DSDP) Hole 522 (Fig. 2) in the South Atlantic Ocean at 26°6.843'S, 5°7.784'W and water depth of 4441.0 m (HSÜ, LABRECQUE *et al.*, 1984). The age control is based on linear interpolation between magnetic reversal boundaries (TAUXE *et al.*, 1984) using the marine magnetic anomaly time scale of BERGGREN *et al.* (1985a). The investigated interval spans the time interval from approximately 35 Ma to approximately 25 Ma, using a sampling interval of generally 0.05 m.y. The results from Hole 522 were compared with the results of FORNACIARI *et al.* (1990) from Ocean Drilling Program (ODP)

Hole 711A (Fig. 2) in the equatorial Indian Ocean at 2°44.56′S, 61°9.78′ and water depth of 4429.8 m (BACKMAN, DUNCAN *et al.*, 1988).

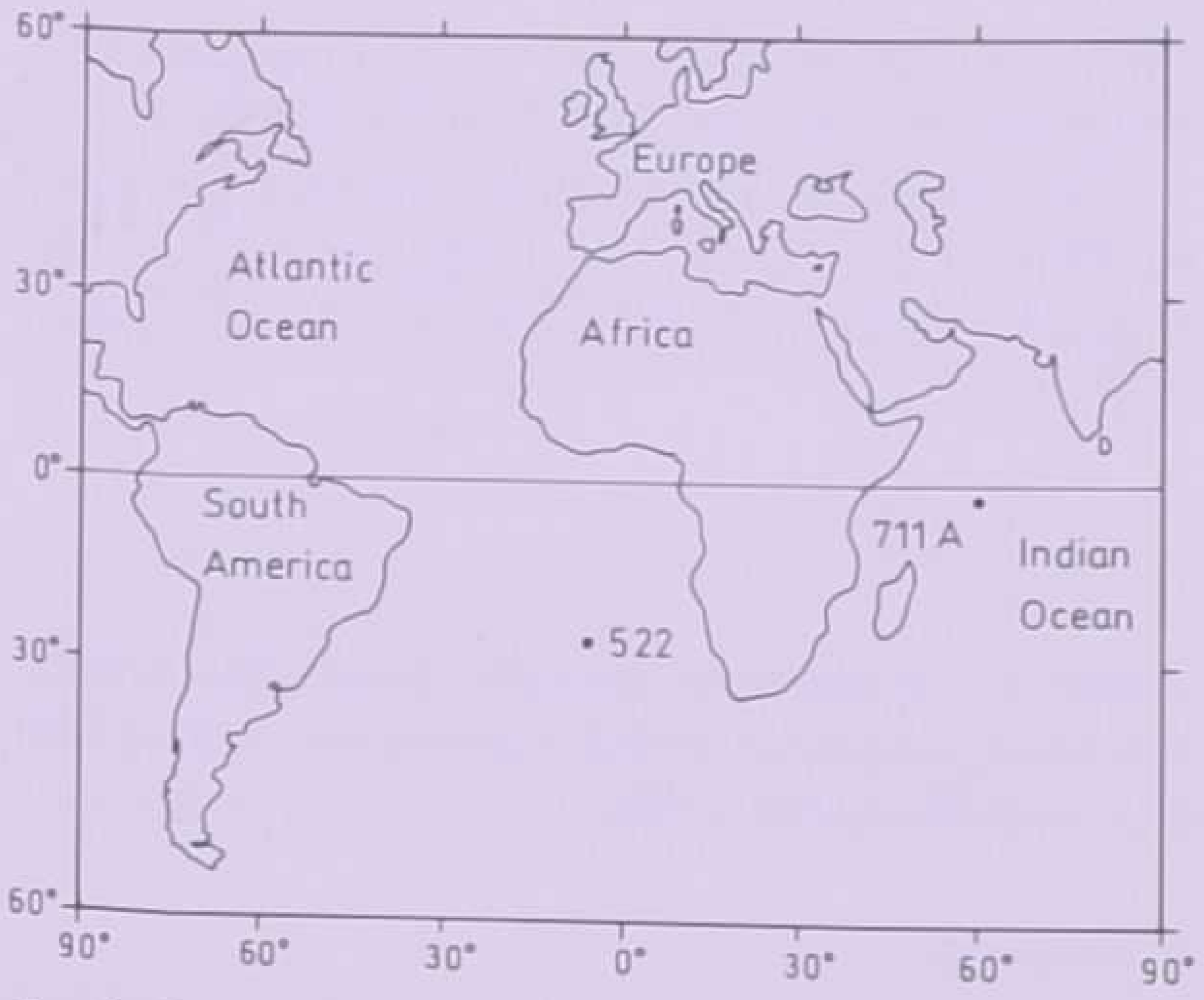

FIG. 2 - Location map showing the sites studied.

When identifying and counting the specimens, only light microscope techniques were used (plane-polarized and cross-polarized light). In each of the samples from Hole 522 the sphenoliths where counted in 25 viewfields (at x 1250 magnification) and their abundances plotted as number of individuals per squaremillimeter (N/mm^2). In the samples from Hole 711A, the sphenoliths were counted up 100 specimens, and their abundances were plotted as percent of the sphenolith assemblage. The counting methods are described and discussed by BACKMAN and SHACKLETON (1983). The taxonomic concepts used were conservative, using the original descriptions of the species involved combined with the criteria of ROTH *et al.* (1971b) and MORAN and WATKINS (1988).

The following terms are used in the discussions of the nannofossil events:

HO = Highest Occurrence, defined as the highest sample in which a species is observed.
AEL = Assumed Extinction Level = last occurrence, defined as the final sharp decline in the abundance of a species.
AAL = Assumed Appearance Level = first occurrence, defined as the sharp rise in abundance at the beginning of the range of a species.
LO = Lowermost Occurrence, defined as the lowest sample in which a species is observed.

When the abundance of a nannofossil species is plotted against age or depth, the assumed appearance level and the lowermost occurrence sometimes coincide. On the other hand, when the events are separated, a "tail" of low abundance precedes the consistent occurrence (BACKMAN 1986a, 1986b). The same is often observed when the highest occurrence and the assumed extinction level are separated, a "tail" of low abundance follows the consistent occurrence. Because of this, it is necessary to distinguish between these events, in order to minimize the confusion when determining species ranges and zonal boundaries.

The method of HAY (1972, 1974) was used to calculate the probability that the sequence first appearance *S. distentus*, first appearance *S. ciperoensis*, last occurrence *S. pseudoradians*, last occurrence *S. predistentus*, last occurrence *S. distentus* and last occurrence *S. ciperoensis* is correct, going from older to younger events. The results of this study are summarized in Table 2.

A reliability index (BRALOWER *et al.*, 1989) was calculated for the sphenolith events in both holes and are summarized in Table 3 together with the age estimates obtained in this study.

The age estimates for the Oligocene sphenolith events obtained in this study were compared to age estimates obtained by calculating mean ages from several DSDP holes and to those of BERGGREN *et al.* (1985a). These age estimates are summarized in Table 4.

RESULTS

SPHENOLITHS IN DSDP HOLE 522

The abundance of all sphenoliths in Hole 522 is plotted against age in Figure 3. In the interval from approximately 117 mbsf up to 102 mbsf a general rise in the abundance is observed. The abundance goes from approximately 400 up to 1300 N/mm^2 and a maximum peak of approx. 1100 N/mm^2 is seen at 110 mbsf. An interval with slightly lower abundances is observed up to 88 mbsf, where the abundance rises again and reaches a value of 1450 N/mm^2 at 84.5 mbsf. Above this maximum peak, the abundance gradually decreases reaching a value of approximately 500 N/mm^2 at 75 mbsf. From this level, the abundance rises again, reaching the highest value observed, 1540 N/mm^2 at 63.5 mbsf.

Sphenolithus pseudoradians was counted in order to try to assess the reliability of its last occurrence (Fig. 4). It occurs sporadically and in low abundances up to the highest occurrence at 94.1

TABLE 2 - Results of the probability test (HAY, 1972) of the Oligocene sphenolith events, based on published data from numerous DSDP and ODP Holes (see references)

A

Nannofossil event	1	2	3	4	5	6
1 AEL[1] *S. ciperoensis*	0	16	17	13	18	16
2 AEL *S. distentus*	0		13	13	17	17
3 AEL *S. predistentus*	0	1		12	13	17
4 AEL *S. pseudoradians*	0	0	0		7	11
5 AEL[2] *S. ciperoensis*	0	1	2	6		17
6 AEL *S. distentus*	0	0	0	2	0	

B

Nannofossil event	1	2	3	4	5	6
1 AEL *S. ciperoensis*		1	1	1	1	1
2 AEL *S. distentus*			1	1	1	1
3 AEL *S. predistentus*				1	1	1
*4 AEL *S. pseudoradians*					0	.98
5 AAL *S. ciperoensis*						1
6 AAL *S. distentus*						

[1] AEL = Assumed extinction level (last occurrence).

[2] AAL = Assumed appearance level (first occurrence).

A: The nannofossil events are numbered form i = 1 to 6. The number (n) in the upper right part of the table is the number of sections in which event number (i) occurs below event number (i-1). The numbers (m) in the lower left part of the table is the number of sections in which event number (i-1) occurs below event number (i). The number of sections in which the events can be separated is N = n + m. The probability (P) that the observed sequence of events is caused by random distribution is:

$$P = \sum_{r=n}^{N} (N!/(r!(N-r)!))*0.5^{n-1}$$

The probability that the observed sequence is caused by nonrandom distribution is: 1-P.

B: The probability that the observed sequence is caused by non random distribution. Based on this table and performing the same test as described by HILLS and THIERSTEIN (1989) the LO *S. pseudoradians* (marked with an asterix) is judged as being unreliable and an unuseful biostratigraphic event.

References: GARTNER and CHOW (1985): DSDP Hole 574C. LANG and WATKINS (1984): DSDP Holes 538A and 540. MORAN and WATKINS (1988): ODP Hole 628. OKADA (1990): ODP Holes 707A, 708A, 710A, 711A. PARKER *et al.* (1985): DSDP Hole 563. PERCIVAL (1984): DSDP Holes 522 and 522A. PUJOS (1985): DSDP Holes 573B and 574C. FORNACIARI *et al.* (1990): ODP Holes 707A, 708A, 709C, 710A, 711A. SHACKLETON *et al.* (1984): DSDP Hole 528. TAKAYAMA and SATO (1987): DSDP Hole 608. WEI and WISE (1989): DSDP Hole 516F.

± 0.2 mbsf. Since no distinct last occurrence of *S. pseudoradians* was observed, it is assumed that it coincides with the highest occurrence. The age estimate for this event is 30.95 ± 0.03 Ma and the reliability index (R) is 0.17. *Sphenolithus pseudoradians* was the only species that was rejected in the probability test (Tab. 2) of HAY (1972).

The abundances of *S. predistentus*, *S. distentus* and *S. ciperoensis* in Hole 522 are plotted together in Figure 5. Where present, *Sphenolithus predistentus* comprises about 50% of the total sphenolith assemblage and its last occurrence is very distinct at 80.6 ± 0.7 mbsf (28.56 ± 0.14 Ma; R = 31.34). The reliability index for this event is the highest obtained for the sphenolith events in Hole 522. The age estimates and relaibility indexes for the sphenolith events are summarized in Table 3.

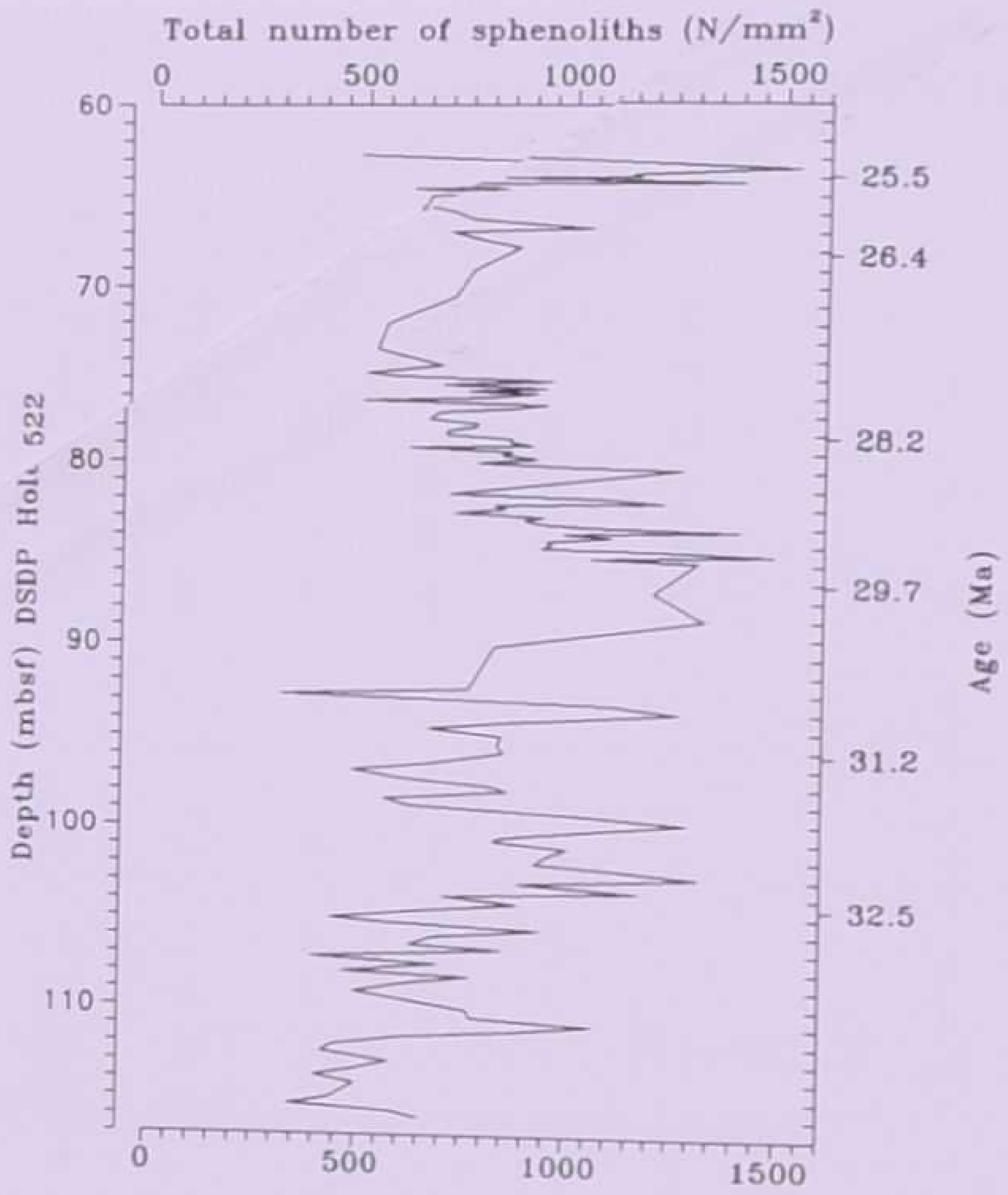

FIG. 3 - Total abundance of Oligocene sphenoliths in DSDP Hole 522 in the South Atlantic Ocean. The abundance is found by counting the total number of sphenoliths in 25 viewfields and plotted as number of sphenoliths per squaremillimeter (N/mm²). The time frame is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

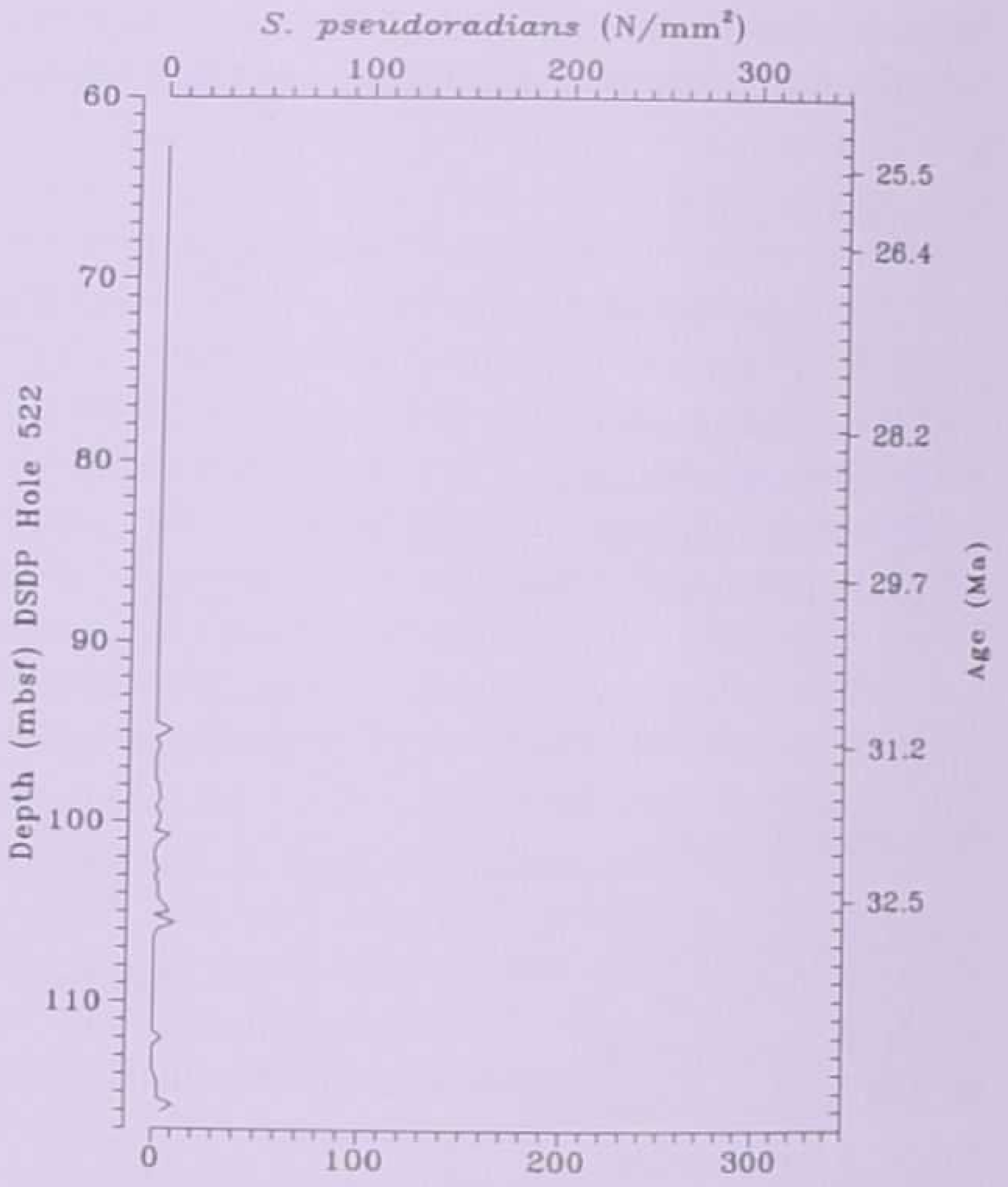

FIG. 4 - Abundance plot for *Sphenolithus pseudoradians* in DSDP Hole 522 showing sporadic occurrences with low abundances. The abundance is found by counting the total number of sphenoliths in 25 viewfields and plotted as number of sphenoliths per squaremillimeter. The time frame is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

The highest occurrence of *S. predistentus* was observed at 67.3 ± 0.2 mbsf (26.17 ± 0.04 Ma; R = 0.54). This event has a reliability index which is much lower than the reliability index of the last occurrence.

The lowermost appearance of *S. distentus* is not a distinct event in Hole 522. It occurs at 116.0 ± 0.8 mbsf (33.83 Ma; R = 0.47). Above the lowermost appearance the abundance of *S. distentus* is somewhat constant up to 104.0 ± 0.2 mbsf, where the first appearance was observed. The age estimate for this event is 32.42 ± 0.02 Ma and the reliability index is 2.00. The first appearance of *S. distentus* has the lowest reliability index of the four sphenolith events used for the subdivision of the Oligocene into biozones.

The last occurrence of *S. distentus* is a very distinc event and occurs at 76.0 ± 0.1 mbsf (27.74 ± 0.02 Ma; R = 7.75). The reliability index of the last occurrence of *S. distentus* is relatively high, but still much lower than of the last occurrence of *S. predistentus*.

Sphenolithus distentus occurs sporadically and in low abundances throughout the rest of the interval investigated. The highest occurrence was observed at 64.05 ± 0.05 mbsf (25.52 ± 0.01 Ma).

The lowermost appearance of *S. ciperoensis* is at 99.9 + 0.1 mbsf (31.83 ± 0.02 Ma; R = 0.13). The reliability index for the lowermost occurrence of *S. ciperoensis* is the lowest obtained from Hole 522.

A distinct rise in the abundance of *S. ciperoensis* is observed at 84.8 ± 0.1 mbsf followed by a one meter interval of rising abundance (Fig. 5). At approximately 83 mbsf, the abundance drops and is low up to approximately 81.5 mbsf where another, more distinct rise in the abundance is observed. Similar, although not as distinct intervals of low abundances can be observed in the total abundance of the sphenoliths (Fig. 3) and in the abundances of the other sphenoliths (Figs. 5 and 6). This lowering of the abundance is considered to be a result of dissolution, and therefore the first appearance of *S. ciperoensis* was defined

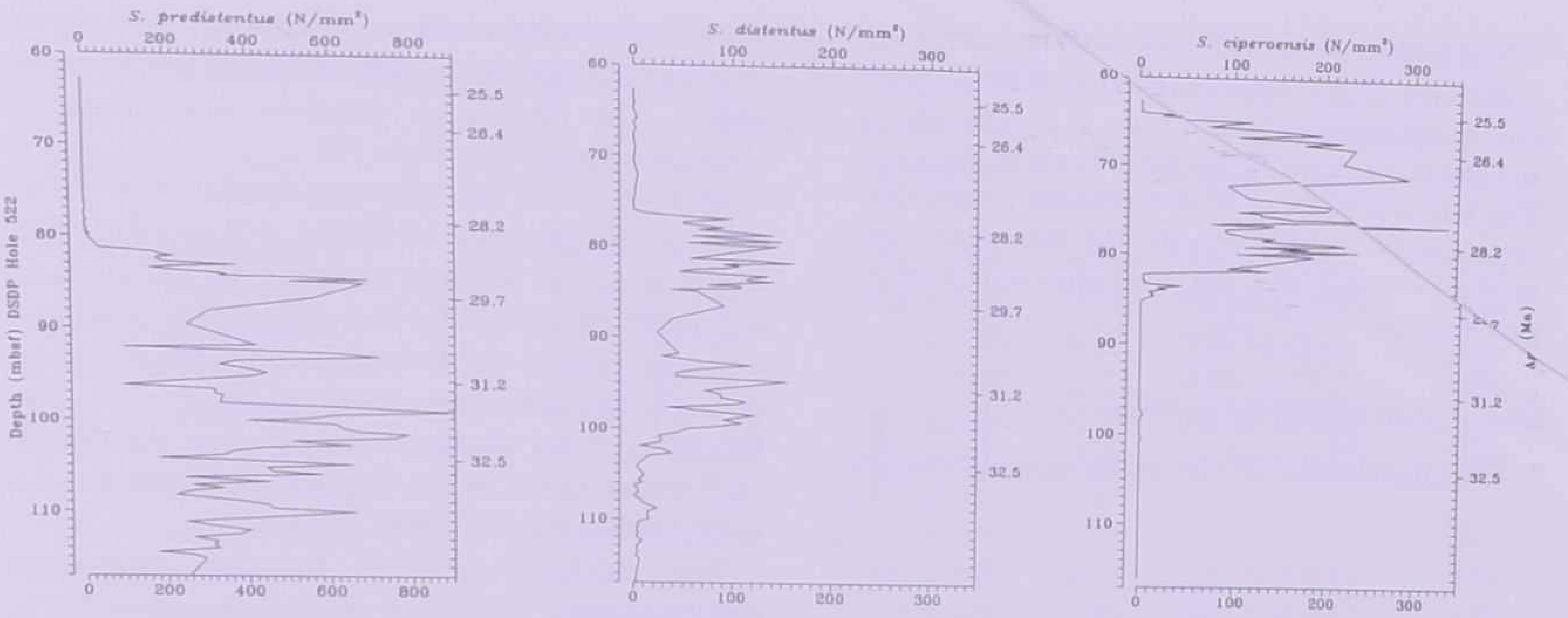

FIG. 5 - Abundance plots for *Sphenolithus predistentus*, *Sphenolithus distentus* and *Sphenolithus ciperoensis* in DSDP Hole 522 in the south Atlantic Ocean. The abundance is found by counting the total number of sphenoliths in 25 viewfields and plotted as number of sphenoliths per squaremillimeter (N/mm²). The time frame is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a). Note the different scale for the abundance of *S. predistentus*.

as the rise in abundance observed at 84.8 ± 0.1 mbsf (29.38 ± 0.02 Ma; R = 6.16).

In Hole 522 the last occurrence of *S. ciperoensis* is a distinct event and concides with the highest occurrence at 64.05 ± 0.05 mbsf (25.52 ± 0.01 Ma; R = 8.71). The last occurrence of *S. ciperoensis* is the only Oligocene sphenolith event that WEI and WISE (1989) considered as consistent.

When counting *S. ciperoensis* and *S. distentus* in Hole 522, a sphenolith considered to be a transitional form between the two species (MORAN and WATKINS, 1988) was counted separately (Fig. 6). It is present throughout the whole interval investigated and has an interval of high abundance that overlaps with the last part of the range of *S. distentus* and the first part of the range of *S. ciperoensis*.

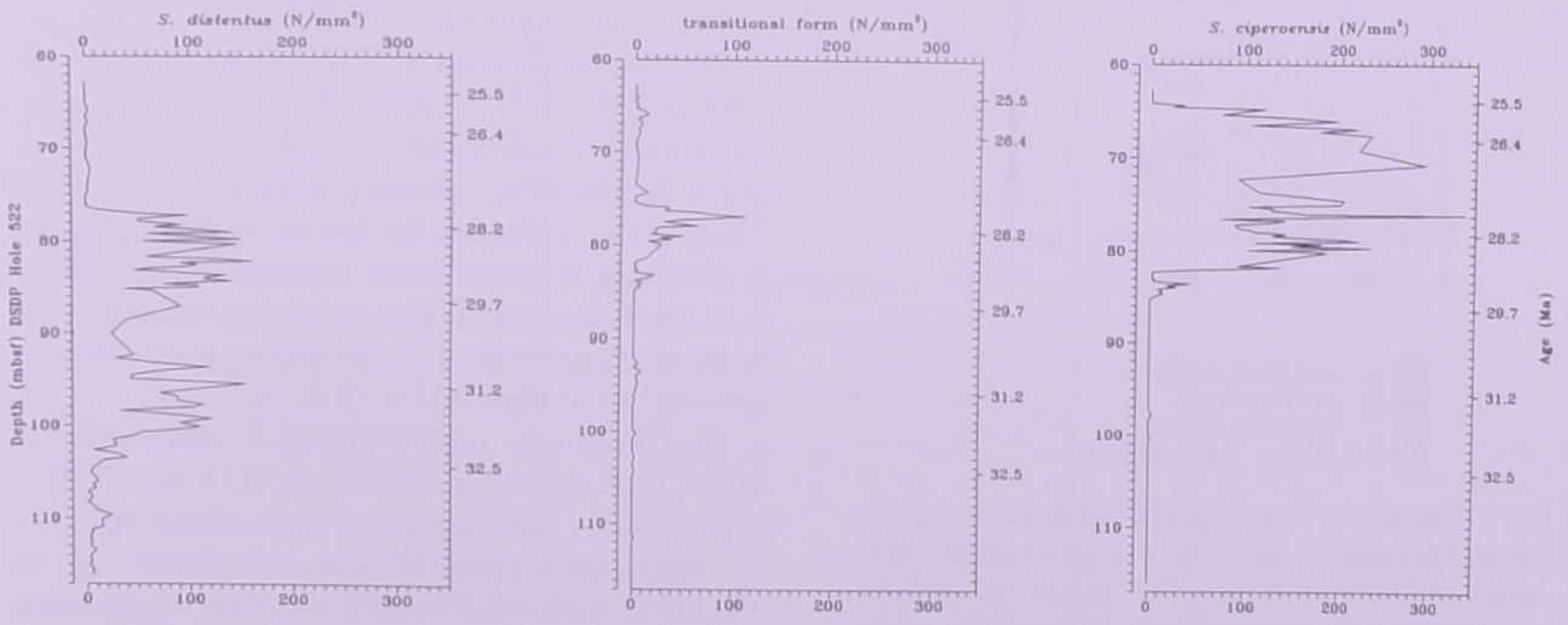

FIG. 6 - Abundance plots of *Sphenolithus distentus* and *Sphenolithus ciperoensis* together with the abundance of what is considered as a transitional form between these two species in DSDP Hole 522. The abundance is found by counting the total number of sphenoliths in 25 fields of view and plotted as number of sphenoliths per squaremillimeter. The time frame is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

The cumulative frequencies of *S. predistentus*, *S. distentus* and *S. ciperoensis* and all other sphenoliths, including *S. moriformis*, *S. pseudoradians* and the transitional form, are plotted in Figure 7. The last occurrence of *S. predistentus* is very distinct and the same is true for the last occurrence of *S. ciperoensis* and the first appearance of *S. distentus*.

SPHENOLITHS IN ODP HOLE 711A

The abundances of the three sphenoliths in Hole 711A are plotted as percent of the sphenolith assemblage in Figure 8 (FORNACIARI *et al.*, 1990). The abundance patterns are similar to those obtained from Hole 522.

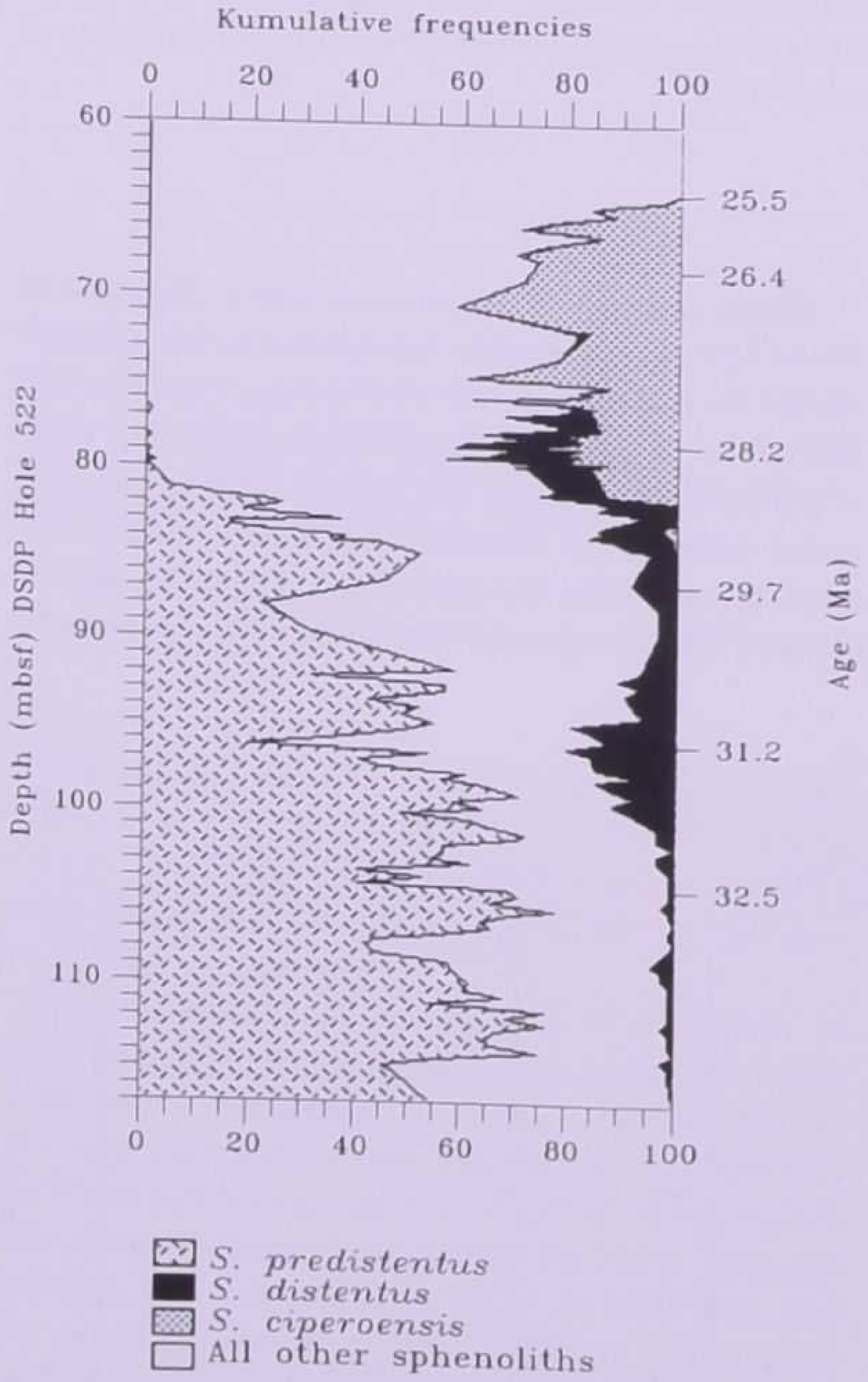

FIG. 7 - Cumulative frequencies of *Sphenolithus predistentus*, *Sphenolithus distentus* and *Sphenolithus ciperoensis* in DSDP Hole 522. The "other" sphenoliths are: *Sphenolithus pseudoradians*, *Sphenolithus moriformis* and the transitional form between *Sphenolithus distentus* and *Sphenolithus ciperoensis*. The time frame is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

In Hole 711A the last occurrence of *S. predistentus* was observed at 106.46 ± 0.46 mbsf. This event is not as distinct as in Hole 522 and the reliability index for the last occurrence of *S. predistentus* is 1.73 (to be compared with the value of 31.34 for the same event in Hole 522). The reliability index obtained for the last occurrence of *S. predistentus* is the highest obtained for the sphenolith events in Hole 711A.

The reliability indexes for the sphenolith events in Hole 711A are much lower than those obtained from Hole 522 (Tab. 3). This is due to the larger sampling interval used, since the sampling interval is one of the major constituents of the reliability index (BRALOWER *et al.*, 1989). Despite the low values of the indexes in Hole 711A, their internal relation of the values is similar as in Hole 522.

The highest occurrence of *S. predistentus* was observed at 85.85 ± 0.65 mbsf (R = 0.05). The highest occurrence and the small peak observed at approximately 95 mbsf (Fig. 8) are probably due to reworking of the sediments (RIO, personal comm.).

The lowermost appearance of *S. distentus* was observed at approximately 149 mbsf (Fig. 8). This event is not very distinct and the reliability index of 0.09, is the second lowest obtained from Hole 711A. The first appearance of *S. distentus* is a distinct event in Hole 711A. It was observed at 124.55 ± 0.65 mbsf (R = 1.17).

The last occurrence of *S. distentus* is quite distinct at 99.85 ± 0.75 mqbsf (R = 0.56). The reliability index for this event is relatively high compared to the other indexes obtained from Hole 711A (Tab. 3). Above the last occurrence (Fig. 8), *S. distentus* is sporadically present up to 78.75 + 0.35 mbsf (R = 0.03). The reliability index for the highest occurrence of *S. distentus* is the lowest obtained from Hole 711A (Tab. 3).

The lowermost occurrence of *S. ciperoensis* in Hole 711A occurs at 117.75 ± 0.75 mbsf (R = 0.17). Above the lowermost appearance (Fig. 8), *S. ciperoensis* occurs in low abundances up to 107.96 ± 0.85 mbsf where the first appearance was observed (R = 1.31).

The last occurrence of *S. ciperoensis* is distinct at 78.18 ± 0.23 mbsf and coincides with the highest occurrence. The reliability index for this event is 0.66 (Tab. 3).

TABLE 3 - Age estimates obtained for the Oligocene sphenolith events in DSDP Hole 522, together with their respective reliability indexes in DSDP Hole 522 and ODP Hole 711A

Nannofossil event	DSDP Hole 522			ODP Hole 711A	
	Depth (mbsf)	Age (Ma)	R*	Depth (mbsf)	R
HO[1] *S. ciperoensis*	64.05 ± 0.05	25.52 ± 0.01	8.71	78.18 ± 0.23	0.66
AEL[2] *S. ciperoensis*	64.05 ± 0.05	25.52 ± 0.01	8.71	78.18 ± 0.23	0.66
HO *S. predistentus*	67.30 ± 0.20	26.17 ± 0.04	0.54	85.85 ± 0.65	0.05
AEL *S. distentus*	76.00 ± 0.10	27.72 ± 0.02	7.75	99.85 ± 0.75	0.56
AEL *S. predistentus*	80.60 ± 0.70	28.56 ± 0.14	31.34	106.46 ± 0.46	1.73
AAL[3] *S. ciperoensis*	84.80 ± 0.10	29.38 ± 0.02	6.76	107.96 ± 0.85	1.31
HO *S. pseudoradians*	94.10 ± 0.20	30.95 ± 0.03	0.17	—	—
AEL *S. pseudoradians*	94.10 ± 0.20	30.95 ± 0.03	0.17	—	—
LO[4] *S. ciperoensis*	99.90 ± 0.10	31.83 ± 0.01	0.13	117.75 ± 0.17	0.17
AAL *S. distentus*	104.00 ± 0.20	32.42 ± 0.02	2.00	124.55 ± 0.65	1.19
LO *S. distentus*	116.00 ± 0.80	33.83 ± 0.10	0.47	approx. 149	0.09

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[1] HO = Highest occurrence. [2] AEL= Assumed extinction level (last occurrence). [3] AAL = Assumed appearance level (first occurrence). [4] LO = Lowermost occurrence. *R = Reliability index according to BRALOWER *et al.* (1989): $R = Z * X_i ((n + 1) - i) * 1/1000$

Z = number of samples per unit thickness. i= number of sample. x_i = specimens in sample number i. n = number of samples below last occurrence/above first occurrence.

Ages are found by interpolating between reversal boundaries (TAUXE *et al.*, 1984) using the timescale of BERGGREN *et al.* (1985a).

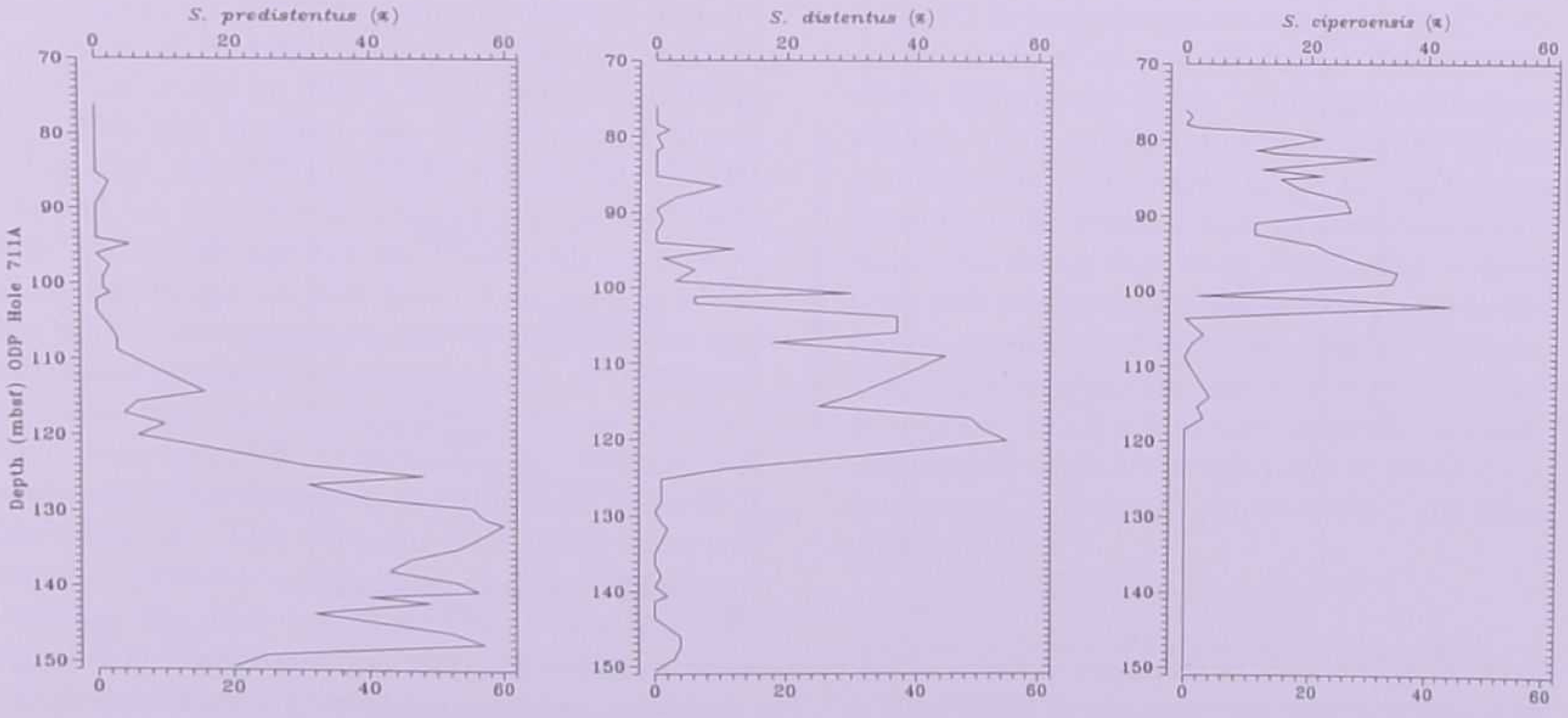

FIG. 8 - Abundance plots for *Sphenolithus predistentus*, *Sphenolithus distentus* and *Sphenolithus ciperoensis* in ODP HOle 711A in the equatorial Indian Ocean. The abundance is found by counting the total number of sphenoliths in 25 viewfields and plotted as number of sphenoliths per squaremillimeter.

RELIABILITY OF OLIGOCENE SPHENOLITH EVENTS

LAST OCCURRENCE OF *Sphenolithus pseudoradians*

The age estimate for the last occurrence of *S. pseudoradians* in Hole 522 is 30.95 ± 0.03 Ma and the mean age, based on only 3 sections, is 31.14 Ma. The abundance of *S. pseudoradians* is low and the occurrence is sporadic. This results in an indistinct last occurrence (Fig. 4), reflected in the lowest reliability index observed. The last occurrence of *S. pseudoradians* can thus be considered an unreliable biostratigraphic event and it was the only biostratigraphic event rejected in the probabilistic test.

The probabilistic stratigraphy method of HAY (1972) does not measure directly the reliability of an individual biostratigraphic event. On the other hand, it gives the probability of a postulated sequence of biostratigraphic events being correct (Tab. 2) and it can be used to reject unreliable events as shown by HILLS and THIERSTEIN (1989).

Care must be taken when using this method. It is based on the works of different authors, and the more events that are used, the higher becomes the probability of rejecting events that otherwise can be considered reliable.

FIRST OCCURRENCE OF *Sphenolithus distentus*

The lowermost occurrence of *S. distentus* is not a distinct biostratigraphic event (Fig. 10). The reliability index is low, the second lowest in Holes 522 and 711A (Tab. 3). If the reliability indexes for this event in the two holes are compared, it is seen that the index in Hole 711A is much lower than in Hole 522. The reason for this is mainly the greater sampling interval used in Hole 711A, since the number of samples per unit thickness of the sediment is a major constituent of the reliability index (BRALOWER *et al.*, 1989). This makes it difficult to compare the work of different authors by the use of reliability indexes, unless they use the same sampling interval and the species abundances are determined in a quantitative way. Furthermore, the same number of samples should be used when calculating the index since its value increases linearly with increased number of samples. Despite this, the internal relation of the indexes in the two sections is nearly the same. In other words, the relative reliability of the events within each section is nearly the same.

In both Hole 522 and 711A, the first occurrence of *S. distentus*, defined as the sharp rise in abundance observed in the lower part of the range, is a more distinct biostratigraphic event than the lowermost occurrence. If the plots of the

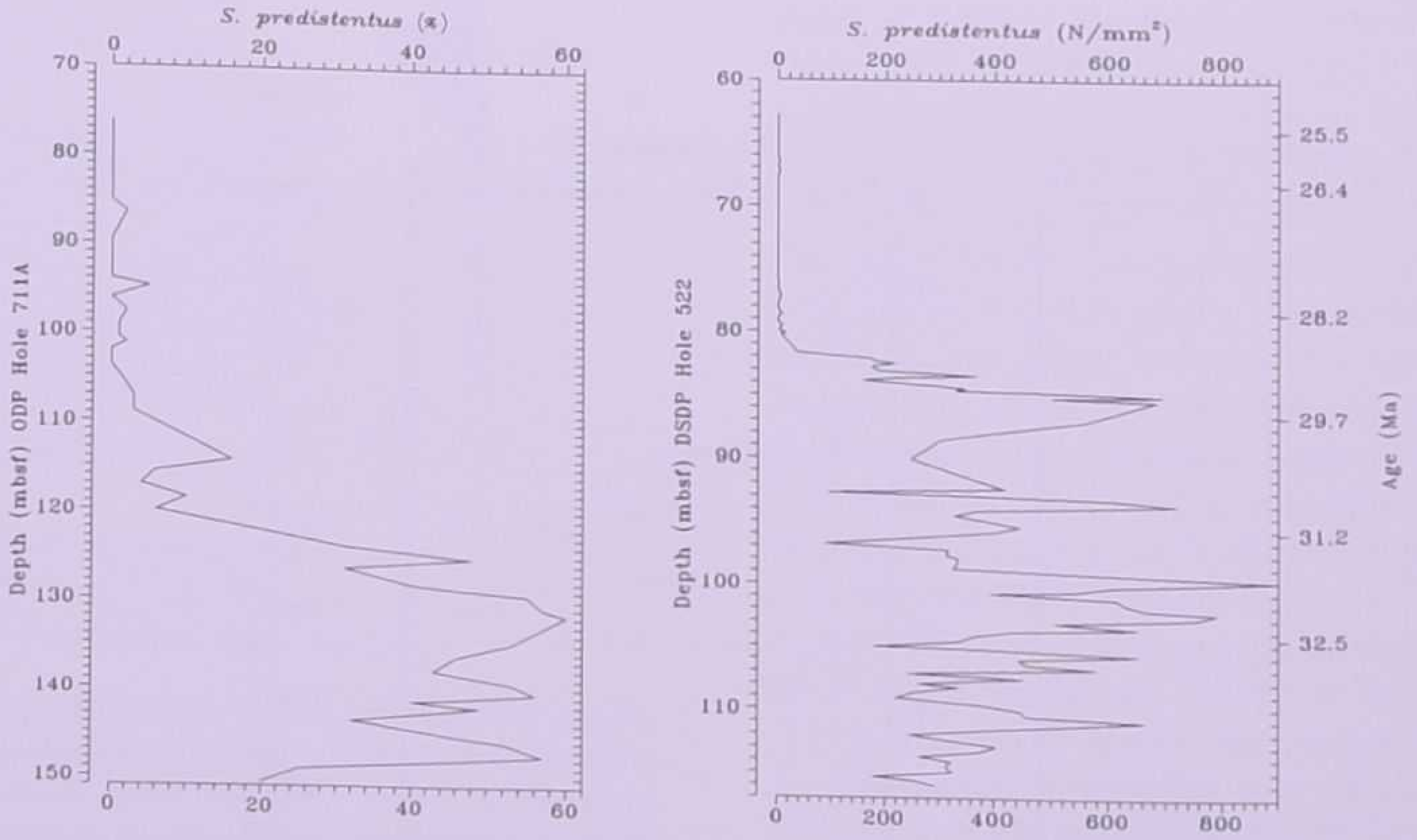

FIG. 9 - Comparison of the abundance of *Sphenolithus predistentus* in DSDP Hole 522 and ODP Hole 711A. Note the somewhat sharper last occurrence in DSDP Hole 522. The abundance peaks that can be seen in ODP Hole 711A at approximately 95 and 85 meters respectively, are probably caused by reworking (RIO, personal comm.). The time frame used in DSDP Hole 522 is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

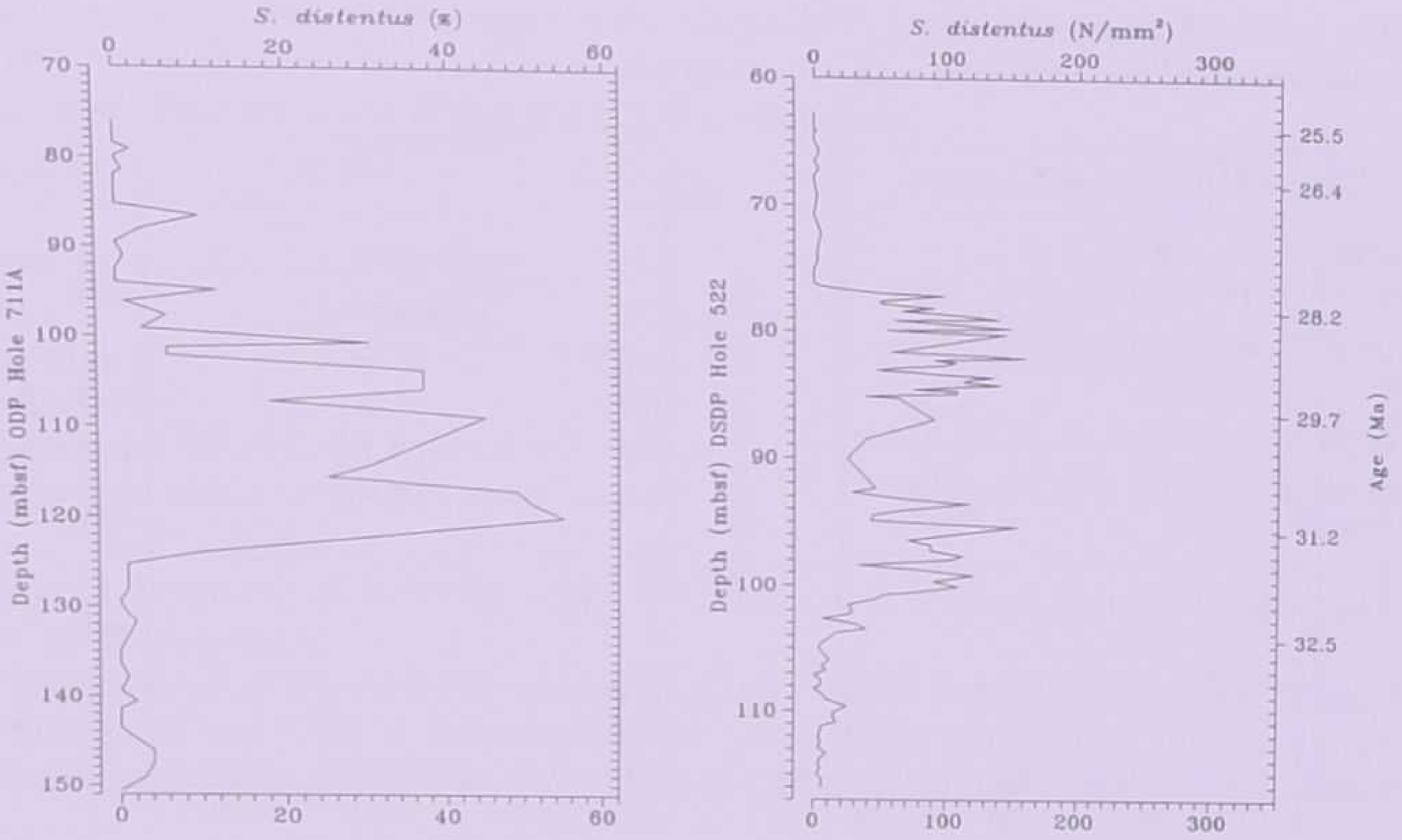

FIG. 10 - Comparison of the abundance of *Sphenolithus distentus* in DSDP Hole 522 and ODP Hole 711A. Note the more distinct first occurrence in ODP Hole 711A. The abundance peaks that can be seen in ODP Hole 711A at approximately 95 and 85 meters respectively, are probably caused by reworking (RIO, personal comm.). The time frame used in DSDP Hole 522 is obtained by correlating the magnetic reversal boundaries (TAUXE *et al.*, 1984) to the magnetic anomaly timescale of BERGGREN *et al.* (1985a).

abundance of *S. distentus* in the two holes are compared, it is observed that the first occurrence is more distinct in Hole 711A than in Hole 522 (Fig. 10). This is reflected in a relatively high reliability index in Hole 711A, whereas the reliability index in Hole 522 is low compared, for example, to the index for the last occurrence of *S. predistentus* (Tab. 3). This indicates that the first occurrence of *S. distentus* is a reliable biostratigraphic event in Hole 711A but not in Hole 522. The age estimate for the lowermost occurrence of *S. distentus* in Hole 522 is 33.83 ± 0.10 Ma and for the first occurrence it is 32.42 ± 0.02 Ma. The mean age for the first occurrence of *S. distentus*, based on data from 4 sections, is 33.91 Ma with a standard deviation of 0.21 and the age estimates published by BERGGREN *et al.* (1985a) is 34.2 Ma. WEI and WISE (1989), concluded that the first occurrence of *S. distentus* is an unreliable event and gave the age as ranging from 34.0 -35.2 Ma (Tab. 4). The difference in these age estimates is probably a reflection of different ways of defining the first occurrence of *S. distentus*. In this study, the first occurrence of *S. distentus* is not defined as the lowermost or absolute first occurrence, but as the sharp rise in the abundance of the species observed in the lower part of the range (Fig. 10). The results in this study indicate that this is a more reliable biostratigraphic event than the lowermost occurrence. In Hole 522 the age estimate obtained for the lowermost occurrence of *S. distentus* is closer to both the mean age shown in Table 4, and the age published by BERGGREN *et al.* (1985a). In Hole 711A, a "tail" of low abundance is observed, ranging from the lowermost occurrence up to the first occurrence. Other studies (BACKMAN 1986a, 1986b, 1987) indicate that these "tails" of low abundances can be of variable duration, and the rise in abundance is more likely to be an isochronous event than the absolute first or lowermost occurrence. Assuming that these "tails" vary in duration, then the lowermost occurrence occurs at different stratigraphic levels in different sections. This leads to different age estimates when the events are correlated to the magnetic timescale which could explain the age range of the first occurrence of *S. distentus* shown by WEI and WISE (1989).

FIRST OCCURRENCE OF *Sphenolithus ciperoensis*

The first occurrence of *S. ciperoensis* (Fig. 11) is a distinct biostratigraphic event in both sections. This is reflected by the reliability index being the second highest. In Hole 711A, the first

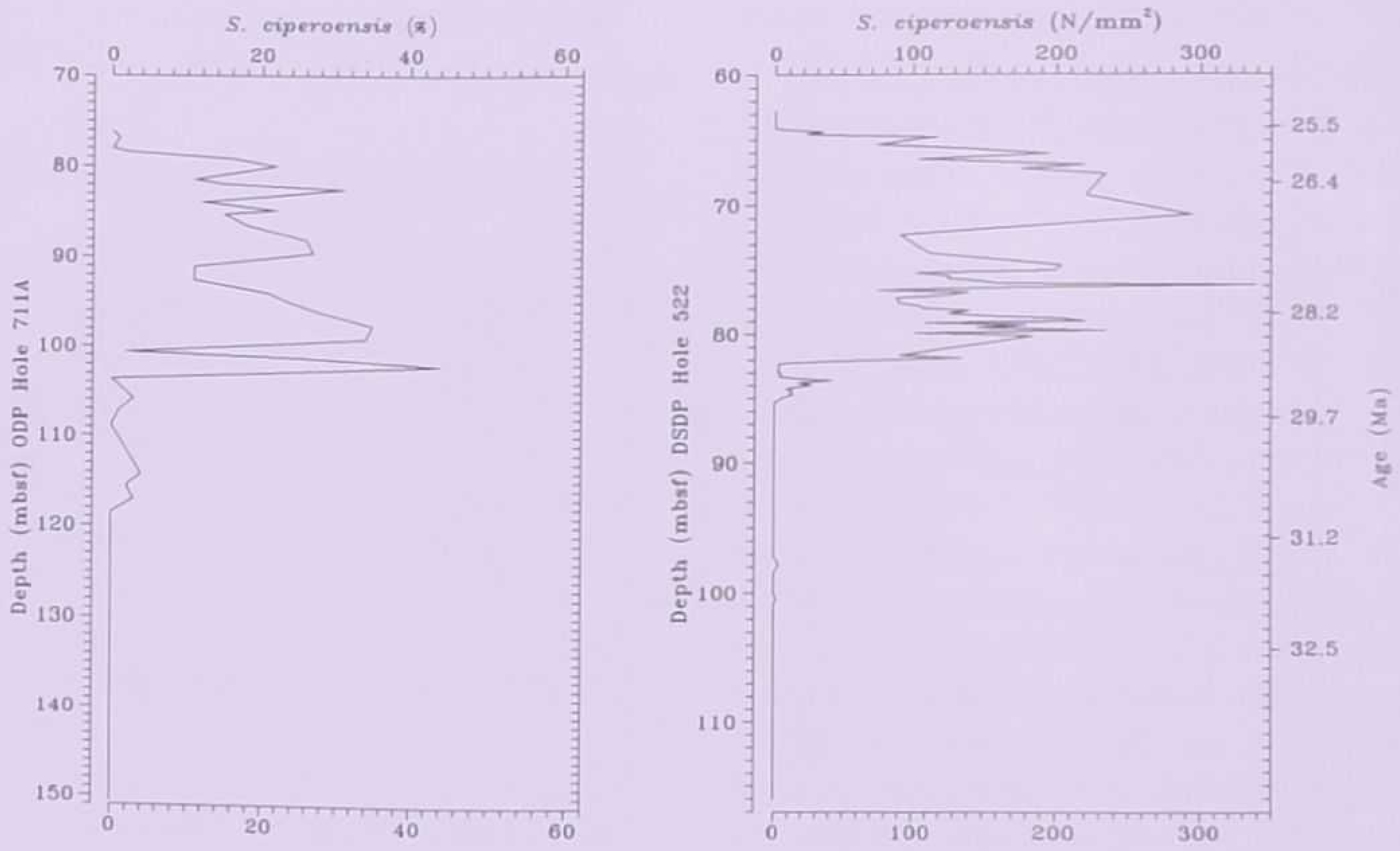

Fig. 11 - Comparison of the abundance of *Sphenolithus ciperoensis* in DSDP Hole 522 and ODP Hole 711A. Note the "tail" of low abundance preceding the first occurrence in ODP Hole 711A. The time frame used in DSDP Hole 522 is obtained by correlating the magnetic reversal boundaries (Tauxe *et al.*, 1984) to the magnetic anomaly timescale of Berggren *et al.* (1985a).

occurrence is preceded by a "tail" of low abundances, and the lowermost occurrence is not a distinct event. No such tail is observed in Hole 522, instead two sporadic occurrences are observed below the first occurrence. In both sections, the reliability index for the lowermost occurrence of *S. ciperoensis* is much lower than that for the first occurrence (Tab. 3), indicating the latter to be a more reliable event. The age estimate for the lowermost occurrence of *S. ciperoensis* in Hole 522 is 31.83 ± 0.01 and the age estimate for the first occurrence is 29.34 ± 0.02. The mean age obtained for this event using 5 sections is 30.24 Ma with an standard deviation of 1.01 and the age published by Berggren *et al.* (1985a) is 30.2 Ma. Wei and Wise (1989) gave an age ranging from 28.5 to 31.9 Ma and they concluded that the first occurrence of *S. ciperoensis* is an unreliable event. The different age estimates obtained for the first occurrence of *S. ciperoensis* can be explained in the same way as for the first occurrence of *S. distentus*.

Last occurrence of *Sphenolithus predistentus*

The last occurrence of *S. predistentus* is an event that has never been used in Cenozoic zonation schemes. The reason for this can be the taxonomical problems that arise when studying forms that are transitional between *S. predistentus* and *S. distentus*. By applying the criteria of Roth *et al.* (1971b) and plotting the abundances of *S. predistentus*, the last occurrence of *S. predistentus* becomes a distinct biostratigraphic event, both in the South Atlantic Ocean and in the equatorial Indian Ocean (Fig. 9). The distinctiveness of the last occurrence of *S. predistentus*, reflected in the high reliability index, indicates that it is a reliable biostratigraphic event which could be used to increase the biostratigraphic resolution of the Oligocene. The age estimate for this event in Hole 522 is 28.56 ± 0.14 Ma which is close to the mean age of 28.74 Ma obtained from 4 sections.

Last occurrence of *Sphenolithus distentus*

The last occurrence (final decline in abundance) of *S. distentus* (Fig. 10) is a distinct biostratigraphical event in both sections. The reliability indexes are relatively high (Tab. 3), indicating that the last occurrence of *S. distentus* is a reliable biostratigraphical event.

The age estimate for this event obtained from Hole 522 is 27.7 ± 0.02 Ma, whereas the mean age obtained from 5 sections is 27.17 Ma and the

TABLE 4 - Mean age and standard deviation of the Oligocene sphenolith events based on published data from several DSDP Holes. For comparison are shown the age estimates published by BERGGREN *et al.* (1985a) and the ages obtained from DSDP Hole 522 in this study

Nannofossil event	Mean age	Std. dev.	n	References	1*	522
AEL[1] *S. ciperoensis*	25.04	0.82	8	1, 2, 3, 4, 5, 6, 7	25.2	25.52
AEL *S. distentus*	27.17	2.03	5	1, 2, 3, 4, 7	28.2	27.72
AEL *S. predistentus*	28.74	0.62	4	2, 3, 7		28.56
AEL[2] *S. ciperoensis*	30.24	1.01	5	1, 3, 4, 7	30.2	29.32
AEL *S. pseudoradians*	31.14	0.26	3	3, 7		30.95
AAL *S. distentus*	33.91	0.21	4	1, 3, 7	34.2	32.42

*Reference number 1, BERGGREN *et al.* (1985a). [1]AEL = Assumed extinction level (last occurrence). [1]AAL = Assumed appearance level (first occurrence).

References: 1. BERGGREN *et al.* (1985a). 2. PARKER *et al.* (1985): DSDP Hole 558. 3. PERCIVAL (1984), TAUXE *et al.* (1984): DSDP Holes 522 and 522A. 4. SHACKLETON *et al.* (1984): DSDP Hole 528. 5. TAKAYAMA and SATO (1987), CLEMENT and ROBINSSON (1987); DSDP Hole 608. 6. WEI and WISE (1989); DSDP Hole 516F. 7. This study; DSDP Hole 522.

age estimates published by BERGGREN *et al.* (1985a) is 28.2 Ma. Again, this difference in the age estimates could be explained by "tails" of varying duration. WEI and WISE (1989) show an age ranging from 25.9 to 30.0 Ma for the last occurrence of *S. distentus* and concluded that the event is unreliable.

LAST OCCURRENCE OF *Sphenolithus ciperoensis*

The last occurrence of *S. ciperoensis* is distinct in both Hole 522 and in Hole 711A and the reliability indexes are relatively high (Tab. 3). The last occurrence of *S. ciperoensis* is the only Oligocene sphenolith event that WEI and WISE (1989) considered reliable, with an age of 25.9 Ma. The age estimate for this event in Hole 522 is 25.52 ± 0.01 Ma and the age estimate published by BERGGREN *et al.* (1985a) is 25.2 Ma. Once again the different age estimates can be explained by different definitions of the last occurrence.

CONCLUSIONS

Whenever possible detailed quantitative methods, combined with short sampling intervals, should be applied when estimating the abundances of nannofossil species and determining first or last occurrences of the species. The abundances should be plotted, either against depth or, when possible, against age. If this is done, then the abundance patterns alone can reveal if a biostratigraphic event is reliable or not.

The abundance plots reveal that the Oligocene sphenolith events can all be considered reliable except the first occurrence of *S. distentus*.

The methods of probabilistic stratigraphy (HAY, 1972) confirm that the sequence first occurrence of *S. distentus,* first occurrence of *S. ciperoensis*, last occurrence of *S. predistentus*, last occurrence of *S. distentus* and last occurrence *S. ciperoensis* is correct, when going from older to younger biostratigraphic events in the Oligocene.

The reliability index introduced by BRALOWER *et al.* (1989) is a good measurement of the distinctiveness or the accuracy of the determination of biostratigraphic events. The index clearly shows that the accuracy can be improved considerably by using shorter sampling intervals, which is reflected in the abundance plots.

A comparison of age estimates of nannofossil events does not give good estimates of their reliability. In Table 4 are shown three age estimates for each of the four sphenolith events used for the subdivision of the Oligocene. They all differ and the obvious conclusion would be, that all the events are unreliable. This need not be the case. The age estimates are based on the works of numerous investigators and once again we are confronted with the problem of the accuracy of the determination and the definitions of the events.

The age estimates for the Oligocene sphenolith events obtained from Hole 522 in the South Atlantic Ocean are:

First occurrence of *S. distentus*: 32.42 ± 0.02 Ma.
First occurrence of *S. ciperoensis*: 29.38 ± 0.02 Ma.
Last occurrence of *S. predistentus*: 28.56 ± 0.14 Ma.

Last occurrence of *S. distentus*: 27.71 ± 0.02 Ma.
Last occurrence of *S. ciperoensis*: 25.52 ± 0.01 Ma.

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