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Proposed calcareous nannofossil zonation scheme for the Miocene to Holocene of Southeast Asia

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Abstract: This paper proposes a calcareous nannofossil zonation scheme for the Miocene to Holocene of Southeast Asia. It is modified from the schemes of Martini (1971) and Okada and Bukry (1980). Each zone is defined and compared with those of the above mentioned workers. The ranges of selected marker species useful in Southeast Asia are presented.

INTRODUCTION

The calcareous nannofossil zonation schemes currently used in marine biostratigraphy are based on the same studies and therefore have many similar features. With increasing study, modifications to detail have resulted in substantial differences between schemes over a similar interval, but it is still evident that their basic premises are the same. For example, over the interval Miocene to Holocene, the zones of Martini (1971) and Okada and Bukry (1980) rely heavily on the proposals of Hay *et al.* (1967), Bramlette and Wilcoxon (1967) and Gartner (1969). Okada and Bukry (1980) is basically a redistillation of the schemes of Bukry (1973; 1975) with code numbers introduced, and, for the purpose of the present study they are regarded essentially as one.

Detailed analysis of a number of sections in Southeast Asia has indicated that the zonation schemes of Martini (1971) and Okada and Bukry (1980) are, in several respects, difficult to apply directly within the area. The current investigation proposes, therefore, a series of further modifications based on a combination of these two schemes with the aim of defining zonal boundaries of greater local reliability. Cosmopolitan and solution resistant nannofossil species similar to those used in previous investigations were chosen for study, in order that necessary correlations would be meaningful.

Correlations between the proposed zonation and those of Martini (1971), Okada and Bukry (1980) and Blow's (1969; 1979) scheme for planktonic foraminifera, are included in figure 1. The ranges of selected marker species referred to are outlined in figure 2.

DEFINITION OF CALCAREOUS NANNOFOSSIL ZONES

Emiliania huxleyi Zone

Definition: Interval above the first evolutionary appearance of *Emiliania huxleyi* (Lohmann).

Remarks: This zone was first introduced by Bordreaux and Hay in Hay *et al.* (1967) and has been adopted by Martini (1971) and Okada and Bukry (1980) in their zonation schemes.

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BLOW (1969, 1979)	AGE	CALCAREOUS NANNOFOSSIL ZONATION VAROL (This study)	CALCAREOUS NANNOFOSSIL DATUM	MARTINI (1971)	OKADA & BUKRY (1980)
N 23 – N 22	HOLOCENE	*Emiliania huxleyi*	*E huxleyi*	NN 21	CN 15
	LATE PLEISTOCENE	*Gephyrocapsa oceanica*	*P lacunosa*	NN 20	CN 14b
	EARLY PLEISTOCENE	*Pseudoemiliania lacunosa*	*D brouweri*	NN 19	CN 14a – CN 13a
N 21	LATE PLIOCENE	*Discoaster brouweri*	*D pentaradiatus*	NN 18	CN 12d
		Discoaster pentaradiatus	*D surculus*	NN 17	CN 12c
		Discoaster surculus	*D tamalis*	NN 16	CN 12b
		Discoaster tamalis	*S abies*		CN 12a
N 20 – N 18	EARLY PLIOCENE	*Reticulofenestra pseudoumbilica*	*A tricorniculatus*	NN 15	CN 11
		Amaurolithus tricorniculatus	*C acutus*	NN 14 – NN 13	CN 10c
		Ceratolithus acutus	*T rugosus*	NN 12	CN 10b
		Triquetrorhabdulus rugosus	*D quinqueramus*		CN 10a
N 18 – N 15	LATE MIOCENE	*Discoaster quinqueramus*	*D neohamatus* / *D loeblichii*	NN 11	CN 9b / CN 9a
		Discoaster neohamatus	*C coalitus* / *C calyculus*	NN 10	CN 8b
		Catinaster calyculus	*D hamatus*		CN 8a
N 15 – N 11	MIDDLE MIOCENE	*Discoaster hamatus*	*D hamatus*	NN 9	CN 7
		Catinaster coalitus	*C coalitus*	NN 8	CN 6
		Discoaster kugleri	*C gammation*	NN 7 – NN 6	CN 5
		Cyclicargolithus gammation	*S heteromorphus*		
N 11 – N 9		*Sphenolithus heteromorphus*	*H ampliaperta*	NN 5	CN 4
N 8 – N 7	EARLY MIOCENE	*Helicosphaera ampliaperta*	*S heteromorphus*	NN 4 – NN 2	CN 3
N 7 – N 5		*Helicosphaera carteri*	*H carteri*		CN 2 / CN 1c
N 5 – N 4		*Triquetrorhabdulus carinatus*	*H recta* / *S ciperoensis*	NN 1	CN 1b – CN 1a
N 3	OLIGOCENE	*Sphenolithus ciperoensis*		NP 25	CP 19

Fig. 1. Proposed calcareous nannofossil zonation scheme for the Miocene to Holocene of Southeast Asia

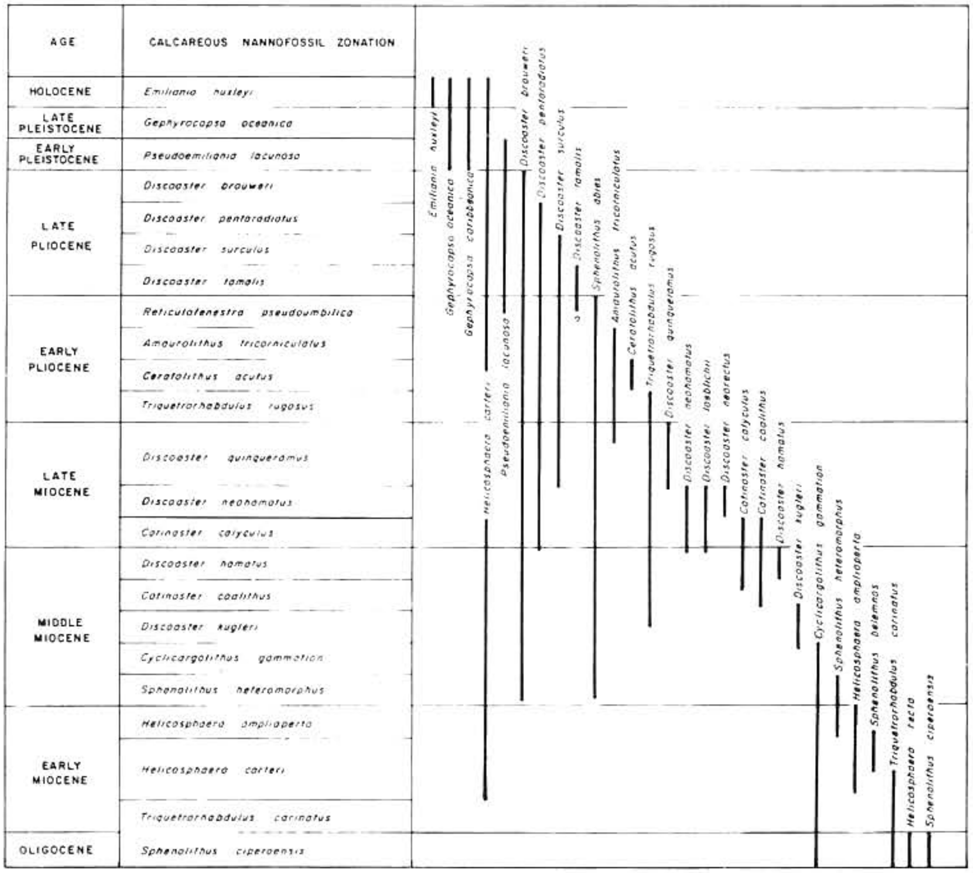

Fig. 2. Calcareous nannofossil zonation scheme and ranges of stratigraphically important species

Gephyrocapsa oceanica Zone

Definition: Interval from the first evolutionary appearance of *Emiliania huxleyi* (Lohmann) to the extinction of *Pseudoemiliania lacunosa* (Kamptner).

Remarks: *Emiliania annula* (Cohen) and *Emiliania ovata* (Bukry) are accepted as junior synonyms of *Pseudoemiliania lacunosa* (Kamptner) following Gartner (1977). The first appearance of *Gephyrocapsa oceanica* Kamptner ranges older than indicated by Bukry (1973). *Gephyrocapsa oceanica* Kamptner and *Gephyrocapsa caribbeanica* Bordreaux and Hay are very similar and differ only in the size of the coccolith and in the size of the central opening.

Pseudoemiliania lacunosa Zone

Definition: Interval from the extinction of *Pseudomiliania lacunosa* Kamptner to the extinction of *Discoaster brouweri* Tan.

Remarks: Both *Gephyrocapsa oceanica* Kamptner and *Gephyrocapsa caribbeanica* Boudreaux and Hay are present in this zone.

Discoaster brouweri Zone

Definition: Interval from the extinction of *Discoaster brouweri* Tan to the extinction of *Discoaster pentaradiatus* Tan.

Remarks: *Ceratolithus rugosus* Bukry and Bramlette appears to have its extinction at the top of this zone.

Discoaster pentaradiatus Zone

Definition: Interval from the extinction of *Discoaster pentaradiatus* Tan to the extinction of *Discoaster surculus* Bramlette and Martini.

Remarks: *Discoaster asymmetricus* Gartner has its extinction at the top of this zone.

Discoaster surculus Zone

Definition: Interval from the extinction of *Discoaster surculus* Martini and Bramlette to the extinction of *Discoaster tamalis* Kamptner.

Remarks: Rare occurrence of *Discoaster decorus* (Bukry) is present in this zone.

Discoaster tamalis Zone

Definition: Interval from the extinction of *Discoaster tamalis* Kamptner to the extinction of *Sphenolithus abies* Deflandre.

Remarks: Large specimens of *Reticulofenestra pseudoumbilica* (Gartner) are present in the lower part of this zone.

Reticulofenestra pseudoumbilica Zone

Definition: Interval from the extinction of *Sphenolithus abies* Deflandre to the extinction of *Amaurolithus tricorniculatus* (Gartner).

Remarks: Large specimens of *Reticulofenestra pseudoumbilica* (Gartner) are common. Okada and Bukry (1980) subdivided this zone into two subzones based on the first accumulation depth of *Discoaster asymmetricus* Gartner, however this species has been reported in Late Miocene sediments by Raffi and Rio (1979) and Varol (1981). There are no distinct differences between *Sphenolithus abies* Deflandre and *Sphenolithus neoabies* Bukry and Bramlette and they are considered to be the same species in this paper. *Pseudoemiliania lacunosa* (Kamptner) has its first evolutionary appearance in this zone (Varol, 1982). The extinction of *Sphenolithus abies* Deflandre corresponds to the extinction of *Globorotalia margaritae* Bolli and Bermudes whereas *Globoquadrina altispira* Cushman and Jarvis has a younger range than both of these species (Cita, 1975; Raffi and Rio, 1979).

Amaurolithus tricorniculatus Zone

Definition: Interval from the extinction of *Amaurolithus tricorniculatus* Gartner to the extinction of *Ceratolithus acutus* Gartner and Bukry.

Remarks: *Amaurolithus delicatus* Gartner and Bukry, *Amaurolithus primus* Bukry and Percival and *Ceratolithus armatus* Müller have their extinction at the top of this zone almost together with *Amaurolithus tricorniculatus* Gartner. In the absence of *Amaurolithus tricorniculatus*, the extinction of any of the above mentioned species can therefore be taken to approximate the upper boundary of this zone. *Ceratolithus rugosus* Bukry and Bramlette is very rare or absent.

Ceratolithus acutus Zone

Definition: Interval from the extinction of *Ceratolithus acutus* Gartner and Bukry to the extinction of *Triquetrorhabdulus* rugosus Bramlette and Wilcoxon.

Remarks: The first evolutionary appearance of *Ceratolithus acutus* Gartner and Bukry can be also taken to mark the lower boundary of this zone. *Ceratolithus armatus* Müller has its first evolutionary appearance in this zone.

Triquetrorhabdulus rugosus Zone

Definition: Interval from the extinction of *Triquetrorhabdulus rugosus* Bramlette and Wilcoxon to the extinction of *Discoaster quinqueramus* Gartner.

Discoaster quinqueramus Zone

Definition: Interval from the extinction of *Discoaster quinqueramus* Gartner to the extinction of *Discoaster neohamatus* Bukry and Bramlette and/or *Discoaster loeblichii* Bukry.

Remarks: The extinction of *Discoaster quinqueramus* Gartner is taken to mark the Pliocene-Miocene boundary following Rio *et al.* (1976) and Ellis and Lohmann (1979). Using the first evolutionary appearance of *Amaurolithus primus* Bukry and Percival this zone is subdivided into two subzones by Okada and Bukry (1980) but this was not followed in this study due to the scarcity or absence of nominate species. Martini (1971) and Okada and Bukry (1980) used the first evolutionary appearance of *Discoaster quinqueramus* Gartner to mark the lower boundary of this zone whereas in the present study the extinction of *Discoaster neohamatus* Bukry and Bramlette and/or *Discoaster loeblichii* Bukry is used following Ellis (1982). *Discoaster berggrenii* Bukry is accepted as a synonym of *Discoaster quinqueramus* Gartner.

Discoaster neohamatus Zone

Definition: Interval from the extinction of *Discoaster neohamatus* Bukry and Bramlette and/or *Discoaster boeblichii* Bukry to the extinction of *Catinaster coalitus* Martini and Bramlette and/or *Catinaster calyculus* Martini and Bramlette.

Remarks: The range of *Discoaster neorectus* Bukry falls within this zone but it is very rare or absent. *Discoaster quinqueramus* Gartner and *Discoaster surculus* Bramlette and Martini have their first evolutionary appearance whereas *Catinaster mexicanus* has its extinction in the upper part of this zone.

Catinaster calyculus Zone

Definition: Interval from the extinction of *Catinaster coalitus* Martini and Bramlette and/or *Catinaster calyculus* Martini and Bramlette to the extinction of *Discoaster hamatus* Martini and Bramlette.

Remarks: *Discoaster bollii* Martini and Bramlette has its extinction in the upper part of this zone together with *Discoaster pseudovariabilis* Martini and Worsley.

Discoaster hamatus Zone

Definition: Interval from the extinction to the first evolutionary appearance of *Discoaster hamatus* Martini and Bramlette.

Remarks: *Discoaster pentaradiatus* Tan, *Discoaster neohamatus* Bukry and Bramlette and *Discoaster loeblichii* Bukry have their first evolutionary appearance in this zone.

Castinaster coalitus Zone

Definition: Interval from the first evolutionary appearance of *Discoaster hamatus* Martini and Bramlette to the first evolutionary appearance of *Catinaster coalitus* Martini and Bramlette.

Remarks: *Catinaster calyculus* Martini and Bramelette has its first evolutionary appearance in the upper part of this zone.

Discoaster kugleri Zone

Definition: Interval from the first evolutionary appearance of *Catinaster coalitus* Martini and Bramlette to the extinction of *Cyclicargolithus gammation* (Bramlette and and Sullivan).

Remarks: *Discoaster pseudovariabilis* Martini and Worsley, *Discoaster bollii* Martini and Bramlette. *Discoaster calcaris* Gartner and *Triquetrorhabdulus rugosus* Bramlette and Wilcoxon have their first evolutionary appearance in this zone.

Cyclicargolithus gammation Zone

Definition: Interval from the extinction of *Cyclicargolithus gammation* (= C. floridanus) to the extinction of *Sphenolithus heteromorphus* Deflandre.

Remarks: This zone is equivalent to the *Cyclicargolithus floridanus* zone of Chi (1979). *Discoaster kugleri* Martini and Bramlette first appears in the upper part of this zone but this species is very rare and shows affinity to *Discoaster bollii* Martini and Bramlette.

Sphenolithus heteromorphus Zone

Definition: Interval from the extinction of *Sphenolithus heteromorphus* Deflandre to the extinction of *Helicosphaera ampliaperta* Bramlette and Wilcoxon.

Remarks: *Discoaster brouweri* Tan and *Discoaster exilis* Martini and Bramlette have their first evolutionary appearance in this zone and the first evolutionary appearance of the latter approximately corresponds to the Early-Middle Miocene boundary. However, this species is often difficult to set apart from *Discoaster variabilis* Martini and Bramlette and *Discoaster challengeri* Bramlette and Riedel. Therefore, the extinction of *Heliocosphaera ampliaperta* Bramlette and Wilcoxon is tentatively taken to mark this boundary. The extinction of *Discoaster druggi* Bramlette and Wilcoxon falls in the lower part of this zone.

Helicosphaera ampliaperta zone

Definition: Interval from the extinction of *Helicosphaera ampliaperta* Bramlette and Wilcoxon to the first evolutionary appearance of *Sphenolithus heteromorphus* Deflandre.

Remarks: *Heliocosphaera euphratis* Haq, *Sphenolithus dissimilis* Bukry and Percival and *Sphenolithus belemnos* Bramlette and Wilcoxon have their extinction in this zone.

Helicosphaera carteri Zone

Definition: Interval from the first evolutionary appearance of *Sphenolithus heteromorphus* Deflandre to the first evolutionary appearance of *Helicosphaera carteri* (Wallich).

Remarks: *Sphenolithus belemnos* Bramlette and Wilcoxon and *Triquetrorhabdulus carinatus* Martini are often very rare or absent and therefore it is found necessary to combine the zones NN.3 and NN.2 of Martini (1971) and the zones CN.2 and CN.1c of Okada and Bukry (1980). *Discoaster druggi* Bramlette and Wilcoxon first appears at the base of this zone but the first evolutionary appearance of *Helicosphaera carteri* (Wallich) is taken to mark the lower boundary of this zone because it is easy to identify and commonly present whereas *Discoaster druggi* Bramlette and Wilcoxon shows enormous variation and affinity to *Discoaster deflandrei* Bramlette and Riedel.

Triquetrorhabdulus carinatus Zone

Definition: Interval from the first evolutionary appearance of *Helicosphaera carteri* (Wallich) to the extinction of *Helicosphaera recta* Haq and/or *Sphenolithus ciperoensis* Bramlette and Wilcoxon.

Remarks: The extinction of *Helicosphaera recta* Haq and *Sphenolithus ciperoensis* Bramlette and Wilcoxon are tentatively taken to mark the Miocene-Oligocene boundary following Bizon and Muller (1979), while the extinction of *Reticulofenestra bisecta* (Hay, Mohler and Wade) and *Zygrhablithus bijugatus* (Deflandre) also lies very close to this boundary.

DISCUSSION

Within the study area, difficulties have been encountered in the application to the Pleistocene of the zonation scheme of Okada and Bukry (1980). The basis for their zonation are the separate evolutionary appearances of *Gephyrocapsa oceanica* and *Gephyrocapsa caribbeanica*. However, recent work suggests that both of these species have very similar ranges and may even occur together from the Pliocene-Pleistocene boundary. Furthermore, with light microscope techniques, the two species are extremely difficult to distinguish as a result of their particularly small size. Therefore it is proposed that the scheme of Martini (1971) which has been successfully applied for the Pleistocene of Southeast Asia, is more reliable and can be used with considerable confidence.

Working back through time, the Late Pliocene zones of Martini (1971) and Okada and Bukry (1980) are both found to relate well in the study area. This is a reflection of their great similarity. The main difference between the two systems is that whereas Martini (1971) subdivides the Late Pliocene into 3 zones—*D. surculus*, *D. pentaradiatus* and *D. brouweri*—Okada and Bukry (1980) regards the interval as within only one zone (*D. brouweri*), with four subzones. Okada and Bukry (1980) include two subzones within the zone occupied by Martini's (1971) *D. surculus*, on the basis of the extinction of *D. tamalis*.

The current author has successfully applied Okada and Bukry's (1980) subzones in Southeast Asia where they are easily identified. However, it is suggested that they should be emended to separate zonal status. The result, therefore is similar to the scheme of Martini (1971) with four zones instead of three identified—*D. brouweri*, *D. pentaradiatus*, *D. surculus* and *D. tamalis*.

The upper part of the Early Pliocene has in both of the previous studies cited, been included within the *R. pseudoumbilica* zone of Gartner (1969). This is subdivided by Okada and Bukry (1980) into two subzones using the first appearance of *D. asymmetricus*. In the present study, three zones are easily identified underlying *R. pseudoumbilica* zone in the Early Pliocene of Southeast Asia. The *A. tricorniculatus*, *C. acutus* and *T. rugosus* zones are equivalent to the *C. rugosus*, *C. acutus* and *T. rugosus* subzones of Okada and Bukry's (1980) *A. tricorniculatulatus* zone. The lower boundary of the currently proposed *A. tricorniculatus* zone is, however based on the extinction of *C. acutus* as *C. rugosus* is either very rare or absent in the study area. *C. acutus* is the second marker used by Okada and Bukry (1980) for that datum. The three proposed zones are also equivalent to the *D. asymmetricus*, *C. rugosus* and *C. tricorniculatus* zones of Martini (1971).

The Miocene-Pliocene boundary is based on the extinction of *D. quinqueramus* following Rio *et al.* (1976) and Ellis and Lohmann (1979), whereas in Okada and Bukry (1980) it is located at the base of the *C. acutus* subzone and in Martini (1971) it is placed in the *C. rugosus* zone. Cita (1975) similarly reported the Miocene-Pliocene boundary very close to the extinction of *D. quinqueramus*.

The base of the *D. quinqueramus* zone in the Late Miocene is defined in the present study by the extinction of *D. neohamatus* and/or *D. loeblichii*, following Ellis (1982). This is at variance with both Martini (1971) and Okada and Bukry (1980) who used, rather, the evolutionary appearance of *D. quinqueramus*. Furthermore Okada and Bukry (1980) subdivided the *D. quinqueramus* zone into the *A. primus* and *D. berggrenii* subzones and these are not found useful in Southeast Asia.

Underlying the *D. quinqueramus* zone, the *D. calcaris* zone of Martini (1971) is equivalent to the *D. neohamatus* zone of Okada and Bukry (1980) which they subdivided using the evolutionary appearance of *D. neorectus* and/or *D. loeblichii*. However, in the current study *D. neorectus* was found to occur only very rarely or was absent and *D. loebichii* has been identified within the underlying *D. hamatus* zone of Middle Miocene age. In the present study two zones are proposed, the *C. calyculus* zone being separated from the *D. neohamatus* zone at the extinction level of *C. calyculus* and/or *C. coalitus*, following the suggestion of Ellis (1982).

The Middle-Late Miocene boundary is defined at the base of the *C. calyculus* zone by the extinction of *D. hamatus*. Within the Middle Miocene, the *D. hamatus* and *C. coalitus* zones have been adopted by both Martini (1971) and Okada and Bukry (1980). The latter however, subdivided the *D. hamatus* zone using the evolutionary appearance of *C. calyculus*, although more recent work suggest that this form may be longer ranging. The current investigation uses both the *D. hamatus* and *C. coalitus* zones. The *D. kugleri* and *D. exilis* zones in the zonation scheme of Martini (1971) are combined within the *D. exilis* zone of Okada and Bukry (1980) who similarly subdivide the zone on the basis of the evolutionary appearance of *D. kugleri*.

In the present study *D. kugleri* and *D. exilis* were identified rarely or were absent and a different criterion for zonation was found necessary. Therefore a *C. gammation* (= *C. floridanus*) zone was identified underlying the *D. kugleri* zone and the boundary between the two is based on the extinction of *C. gammation*. This zone is almost equivalent to the *D. exilis* zone of Martini (1971) and the *C. miopelagicus* subzone of the *D. exilis* zone of Okada and Bukry (1980).

The top of the *S. heteromorphus* zone is marked by the extinction of that taxon and the base Middle Miocene, corresponding with the base of the *S. heteromorphus* zone is tentatively identified by the extinction of *H. ampliaperta*.

Within the Early Miocene the base of the *H. ampliaperta* zone is based on the evolutionary appearance of *S. heteromorphus*, in accordance with the suggestion of Okada and Bukry (1980). However, the *S. belemnos* and *D. druggi* zones of Martini (1971), equivalent to zone CN.2 and subzone CN.1c of Okada and Bukry (1980) were combined in the current investigation into the *H. carteri* zone. This is because of the rare occurrence or absence of *S. belemnos* and *T. carinatus* in Southeast Asia. The evolutionary occurrence of *H. carteri* marks the base of this zone as *D. druggi* is also rare and shows affinity to the *D. deflandrei* group.

Underlying the *H. carteri* zone a *T. carinatus* zone has been identified, the base of which tentatively marks the Miocene-Oligocene boundary with the extinction of *H. recta* and *S. ciperoensis* (Bizon and Müller, 1979). This differs from the criteria adopted by Okada and Bukry (1980) who use the last accumulation depth of *C. abisectus*, which is found to be unreliable in this study, due to the changes in palaeoecological conditions and preservational factors.

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