



Paleobathymetry in the backstripping procedure: Correction for oxygenation effects on depth estimates

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Abstract

This paper aims to provide a straightforward and easily applicable method for estimating the depositional depth evolution of marine basins. Vertical movements of the basin floor can be reconstructed from the sedimentary record, and more accurately constrained when information from the sedimentary history is combined with palaeodepth estimates derived from fauna. To this end we propose to extend an existing method based on the percentage of planktonic foraminifera with respect to the total (planktonic and benthic) foraminiferal association, which is expressed as the percentage planktonics (%*P*).

The ratio between planktonic and benthic foraminifera is related to water depth, and the %*P* generally increases with increasing distance to shore. However, next to water depth the oxygen level of bottom waters has a profound effect on the abundance of benthic foraminifera, and as such influences the %*P*. Depending on basin configuration, the oxygen level at the sea floor can vary on Milankovitch time scales and is reflected by the fraction of benthic foraminiferal species that indicate an effect of oxygen stress on the biotic system. These species can be used as stress-markers and their percentage with respect to the total benthic population is here expressed as %*S*.

To assess whether the effect of sea-floor oxygenation impairs depth reconstructions, we studied the percentage of planktonic foraminifera (%*P*) in five well-dated sedimentary successions from the Lower Pliocene of Crete, Corfu and Milos in Greece. Additionally, we assessed whether different foraminiferal size fractions and counting methods affect the determination of the percentage of planktonic foraminifera. The palaeobathymetric evolution calculated for each basin was confirmed for all successions by an independent check on depth-related occurrences of benthic foraminifera. After correction for bathymetry changes of the basin due to sedimentation, compaction and eustatic sea level variations, the

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vertical movement history of the basin floor was inferred. We propose a standard methodology for reconstructions of palaeobathymetry of marine sedimentary successions from foraminiferal associations.

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1. Introduction

One way to determine the timing and rates of vertical movements of the basin floor during sedimentation is to reconstruct variations in palaeodepth from the basin's sediments, together with the sediment accumulation history (geohistory analysis: Van Hinte, 1978). Palaeobathymetry estimates can be further derived from faunal distribution patterns. To this end, foraminifera are useful tools. Bandy (1953) and Bandy and Arnal (1960) already outlined the extra information that can be derived from depth distributions of benthic foraminifera when reconstructions of basin configurations and vertical movements are attempted, although no detailed quantitative estimates were made about subsidence and uplift. However, as Van Hinte (1978) stated referring to microfossils in general: "Palaeo-water-depth determination is a highly complex art". Information on depth distributions of fossil benthic foraminifera is usually obtained from indirect evidence, or by comparison with living representatives of the taxa present, or by comparing functional morphology of living and fossil taxa. A complicating factor is that depth distributions of Recent benthic foraminifera may differ between basins, as was demonstrated by Parker (1958) and Bandy and Chierici (1966), although the latter authors found a number of species to be isobathyal. Moreover, some taxa appear to be able shift to different depth zones in different environmental conditions (e.g. Pflum and Frerichs, 1976; Speijer et al., 1997; De Rijk et al., 2000). Although no consensus exists as yet about depth distributions of fossil benthic foraminifera, certain taxa are often used to constrain palaeodepths within limits of several hundreds of meters, and by using combinations of taxa occurring in a sample the palaeodepth can be more precisely constrained, provided that resedimentation and reworking can be excluded. However, this method asks for more than superficial knowledge of benthic foraminifera.

Another option mentioned by Van Hinte (1978) was to use the ratio between planktonic and benthic foraminifera (*P/B* ratio) as a tool to reconstruct palaeodepths. The abundance of benthic foraminifera generally reaches a maximum on the outer shelf and the upper slope. Planktonic foraminifera are virtually absent in neritic environments and their abundance generally increases with increasing water depth. The ratio, expressed as the percentage of planktonic foraminifera (%*P*), increases with water depth and distance to shore to reach nearly 100% in lower bathyal and abyssal environments (Douglas and Woodruff, 1981; Berger and Diester-Haas, 1988).

Theoretically, the %*P* would thus seem directly related to water depth, but this is not always the case. Studies on Recent material and in laboratory experiments have shown that a strong relationship exists between the oxygen level of bottom waters and the abundance and diversity of benthic foraminiferal populations (e.g. Harman, 1964; Sen-Gupta and Machain-Castillo, 1993; Kaiho, 1994, 1999; Loubère, 1994, 1996, 1997; Alve and Bernhard, 1995; Jorissen et al., 1995; McCorkle et al., 1997; Moodley et al., 1998; Jorissen and Wittling, 1999). These findings, when applied to the fossil record, are confirmed by sedimentological and geochemical evidence (e.g. Nolet and Corliss, 1990; Rohling et al., 1993; Nijenhuis et al., 1996; Den Dulk et al., 1998; Jorissen, 1999a,b; Seidenkrantz et al., 2000). As the oxygen level of bottom waters decreases—for instance through increased primary productivity in surface waters and the consequent increased input of organic matter—the abundance of benthic foraminifera will initially increase and then rapidly decrease until benthic life is no longer possible (e.g. Verhallen, 1991; Jorissen, 1999b). Hence, the %*P* is not only determined by depth, but also by changes in oxygenation state of the bottom waters. The concentration of oxygen in bottom waters in turn may fluctuate under the influence of astronomically induced climate variations, influencing

bottom water ventilation (e.g. De Visser et al., 1989; Hilgen et al., 1995; Lourens et al., 1996; Kouwenhoven et al., 2003). To us, longer-term variations (eccentricity: 100 and 400 ky) are of special interest, since on this time scale tectonically induced vertical movements of the basin floor can also play a significant role.

Van der Zwaan et al. (1990) determined a regression for the relationship between bathymetry and the percentage of planktonic foraminifera with respect to the total fossil foraminiferal population (%*P*), based on present-day bathymetric transects:

$$\text{Depth}(m) = e^{3.58718 + (0.03534 * \%P)} \quad (1)$$

where %*P*=percentage planktonics in the total foraminiferal association, calculated as $100 * P / (P + B)$, *P*=number of planktonic specimens and *B*=number of benthic specimens.

In their calculations, Van der Zwaan et al. (1990) discarded a number of species from the benthic population, because these were considered to be deep

infaunal (i.e. dwelling well below the sediment–water interface) and therefore not directly dependent on the flux of organic matter to the sea floor, which forms the basis for the depth relation of regression (1) (Suess, 1980; Berger and Diester-Haas, 1988; Van der Zwaan et al., 1990). These infaunal species discarded from the regression calculations were the benthic genera *Bulimina*, *Bolivina*, *Globobulimina*, *Uvigerina* and *Fursenkoina*. Several of these taxa are seen to dominate benthic assemblages under unfavourable circumstances and are then commonly indicated as stress-markers. These should be omitted from the determination of %*P*. The plankton fraction %*P* is then calculated as

$$\%P = 100 * (P / (P + B - S))$$

where *S*=number of stress markers (deep infauna).

Regression (1) was constructed from modern transects in the Gulf of Mexico, the Gulf of California, the west coast of the USA and the Adriatic Sea, yielding near-identical results. Values of %*P* of 0 and

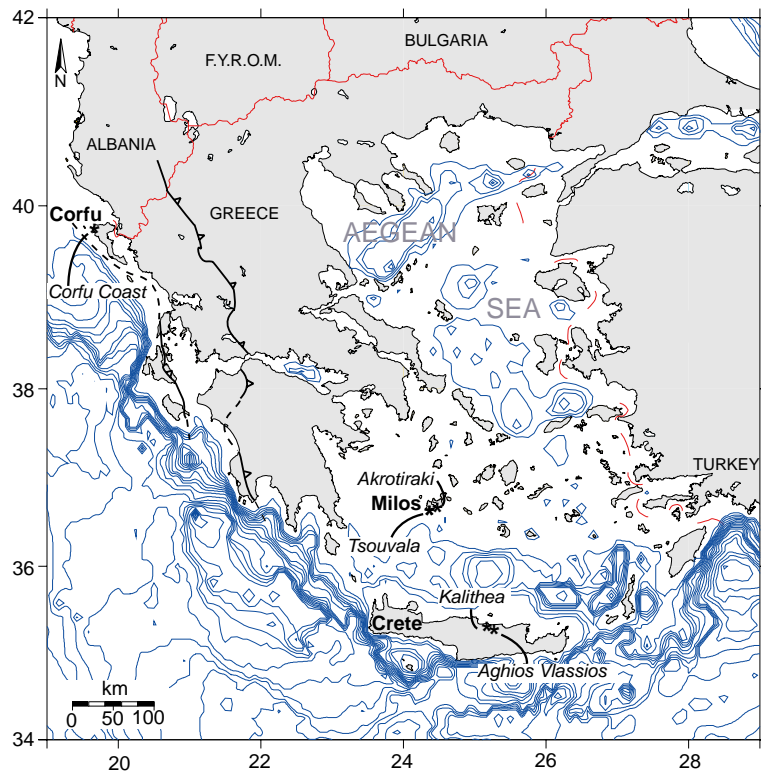


Fig. 1. Map of the Aegean area with sample locations.

100 lead to calculated depths of 36 and 1238 m, respectively. The standard error increases with increasing %*P*, and in the original regression of Van der Zwaan et al. (1990), the 90% confidence limit at a single %*P* value of 50% (430 m) was approximately 100–150 m, and at a %*P* value of 99% (1200 m) 400 m. The first and most important way to improve the resolution of the depth estimate is to use large numbers of samples covering a small time interval. Additionally, Van der Zwaan et al. (1990) noted that thorough screening of the samples for resedimentation also significantly adds to a higher resolution of the bathymetry estimate.

To determine the influence of the amount of oxygen in bottom waters on %*P* (and to distinguish between this effect—if present—and bathymetry variation), we studied the foraminiferal content of five well-dated sedimentary successions in the Lower Pliocene of Crete, Milos and Corfu (Greece) (Fig. 1). Various authors have used regression (1) of Van der Zwaan et al. (1990) to reconstruct tectonic vertical movements in sedimentary basins (e.g. Barbieri, 1992; Meulenkamp et al., 1994; Gräfe, 1999; Van der Meulen et al., 1999, 2000; Ten Veen and Kleinspehn, 2000; Baldi et al., 2001; Van Hinsbergen et al., 2004) and every paper makes different choices regarding omission of samples and species and the assumptions on the resolution of the method. Therefore, we propose a standard methodology for the reconstruction of palaeodepths based on foraminiferal associations and apply this to reconstruction of vertical movements of the basin floor.

2. Geologic setting and successions

The selected sedimentary successions on Corfu, Crete and Milos each occupy a distinct structural position within the Hellenides (Fig. 1). During the Early Pliocene, Corfu was situated in a foreland basin, and characterised by a high sedimentation rate and deposition of clays and sandy turbidites (Linssen, 1991; Weltje and De Boer, 1993). The succession at Corfu Coast is located along the northwestern coast of Corfu, where approximately 500 m of clays and sandy turbidites were sampled at 100 levels at 5 m intervals. Linssen (1991) magneto- and biostratigraphically dated the succession (Fig. 2). Milos was situated in a

restricted back-arc basin that developed in the central part of the Aegean (Fig. 1). The successions near Tsouvala and Akrotiraki were sampled in the south of Milos (for exact locations, see Van Hinsbergen et al., 2004) and contain 20–30 m of marl-sapropel alternations. The Akrotiraki succession was sampled at 99 levels and the Tsouvala succession at 95 levels. On central Crete, Early Pliocene sedimentation occurred in a narrow graben cross-cutting the Aegean arc (Meulenkamp, 1985; Meulenkamp et al., 1994). The successions near Aghios Vlassios and Kalithea were sampled in the central northern part of Crete (Figs. 1 and 2; for detailed locations and descriptions see Spaak, 1983; Jonkers, 1984; Driever, 1988). These successions consist of alternating marls and sapropels and were sampled at 141 and 162 levels, respectively. Previously, micropalaeontological analyses were carried out by Spaak (1983), Jonkers (1984) and Driever (1988), and Bianchi et al. (1985) dated some volcanic ash layers. This age information was used to correlate the cyclic alternations of sapropels and marls to the astronomical polarity time scale (APTS: Hilgen, 1991; Fig. 2). The Cretan successions were used for a vertical movement study by Meulenkamp et al. (1994).

3. Screening of the successions and samples

3.1. Age control

In order to assess the effect of orbitally induced trends, the successions should preferably represent at least 400 ky—a full eccentricity cycle—and should be well dated, preferentially by tuning to the astronomical polarity time scale (e.g. Hilgen, 1991; Krijgsman et al., 1995; Sierro et al., 2001; Abdul Aziz et al., 2003). Moreover, to increase the accuracy of palaeobathymetry and to reconstruct long-term eccentricity induced trends, one sample per 10–20 ky is preferentially analysed. The successions on Crete are well dated by biostratigraphy, can be astronomically tuned, and have a sample spacing of 1 sample per 10–15 ky (Spaak, 1983; Jonkers, 1984; Driever, 1988). The Corfu Coast succession is accurately dated by magnetostratigraphy (Linssen, 1991), with a sample spacing of 1 per 5 ky. The successions on Milos have a sample spacing of 10–15 ky and are dated by bio-, cyclo- and magnetostratigraphy (Van Hinsbergen et al., 2004).

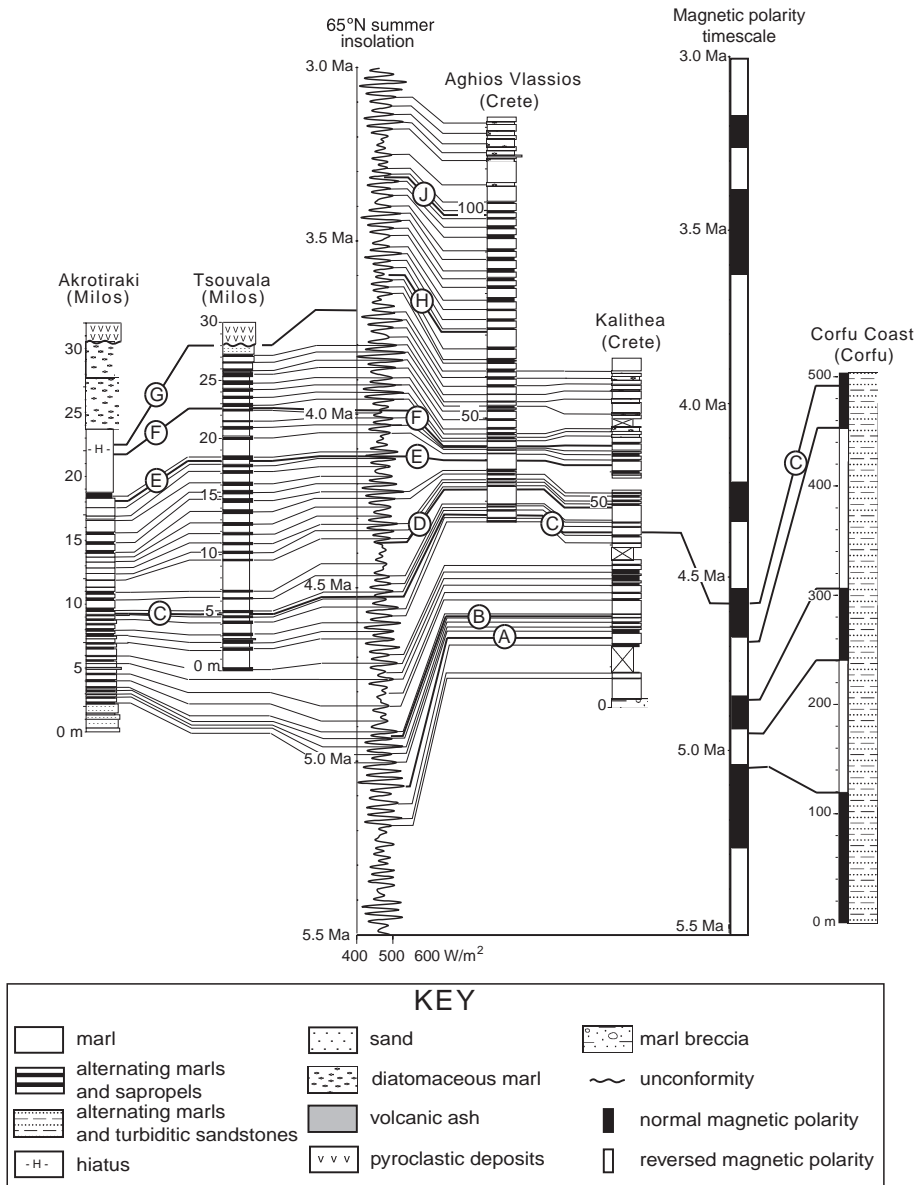


Fig. 2. Bio-, magneto-, and cyclostratigraphic correlations between the successions of Milos, Crete and Corfu. The cyclic successions are tuned using the target curve of Laskar et al. (1993). For biostratigraphy of the Cretan successions, see Spaak (1983), Jonkers (1984) and Driever (1988), cyclostratigraphic correlation of these successions is further explained in Van Hinsbergen and Meulenkamp (submitted for publication). Bio- and cyclostratigraphy of the Milos successions is carried out by and explained in Van Hinsbergen et al. (2004). Magnetostratigraphic dating of succession Corfu Coast was carried out by Linsse (1991). Ages of the bioevents are taken from Lourens et al. (2004): A=First Occurrence (FO) *Globorotalia margaritae*; B=Last Occurrence (LO) *Reticulophenestra antarctica* (4.91 Ma); C=FO *G. puncticulata* (4.52 Ma); D=First Common Occurrence (FCO) *Gephyrocapsa* spp. (4.33 Ma); E=FCO *Discoaster asymmetricus* (4.12 Ma); F=Last Common Occurrence (LCO) *G. margaritae* (3.98 Ma); G=LCO *Sphenolithus* spp. (3.70 Ma); H=LO *G. puncticulata* (3.57 Ma); J=FO *G. bononiensis* (3.31 Ma).

Plate I. Depth markers. (see page 251)

1. *Ammonia beccarii*;
 2. *Discorbis* sp.;
 3. *Elphidium macellum*;
 4. *Elphidium gerthi*;
 5. *Cibicides lobatulus*;
 6. *Cibicides ungerianus*;
 7. *Cibicides pseudoungerianus*;
 8. *Gyroidina soldanii*;
 8. *Cibicides pachydermus*;
 9. *Uvigerina peregrina*;
 - 10 and 11. *Uvigerina peregrina*;
 12. *Uvigerina proboscidea*;
 13. *Uvigerina hispida*;
 14. *Uvigerina semiornata rutila*;
 15. *Planulina ariminensis*;
 16. *Siphonina reticulata*. SEM pictures from: 1: Jorissen (1988); 2, 5, 6, 7, 8, 10, 11, 12, 13: Den Dulk (2000); 3: <http://www.ucl.ac.uk/GeolSci/micropal>; 4: http://palaeo.electronica.org/2002_2/guide/rota.htm; 9, 14, 15, 16: Kouwenhoven (2000); scale bar 1 μm .
-

Plate II. Depth markers. (see page 252)

1. *Oridorsalis stellatus*;
 2. *Cibicides kullenbergi*;
 3. *Cibicides bradyi*;
 4. *Cibicides robertsonianus*;
 5. *Karrieriella bradyi*;
 6. *Eggerella bradyi*;
 7. *Cibicides wuellerstorfi*;
 8. *Cibicides italicus*. SEM pictures from: 1, 3, 4, 8: Kouwenhoven (2000); 2, 5, 6, 7: Den Dulk (2000); Scale bar 1 μm .
-

Plate III. Stress markers. (see page 253)

1. *Cancris auricula*;
2. *Valvulineria bradyana*;
3. *Bolivina striatula*;
4. *Bolivina spathulata*;
5. *Bolivina alata*;
6. *Bolivina tortuosa*;
7. *Bolivina dilatata*;
8. *Chilostomella oolina*;
9. *Bulimina marginata*;
10. *Bulimina aculeata*, *marginata* type;
11. *Bulimina aculeate*;
12. *Bulimina aculeate*;
13. *Bulimina exilis*;
14. *Fursenkoina pauciloculata*;
15. *Stainforthia fusiformis*;
16. *Globobulimina* spp.;
17. *Hopkinsina (Uvigerina) pacifica*;
18. *Uvigerina (Rectuvigerina) cylindrica cylindrica*;
19. *Uvigerina (Rectuvigerina) cylindrica gaudryinoides*;
20. *Bolivina plicatella*;
21. *Bulimina alazanensis*. SEM pictures from 1, 3, 7, 9, 14, 15, 17: Barmawidjaja (1991); 2, 10, 12: Jorissen (1988); 4, 5, 8, 11, 13, 16, 21: Den Dulk (2000); 6, 18, 19, 20: Kouwenhoven (2000); Scale bar 1 μm .

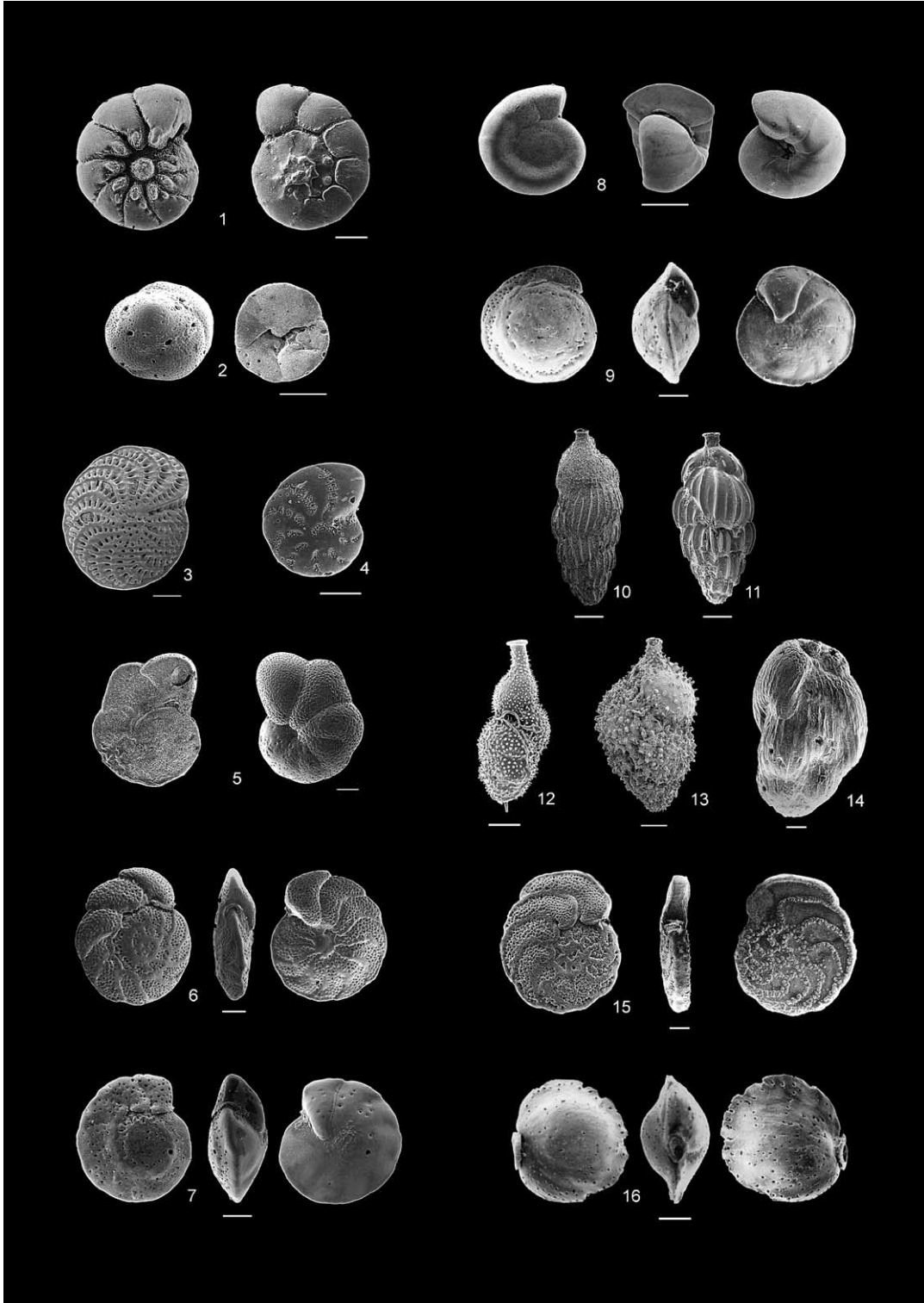


Plate I (caption on page 250).

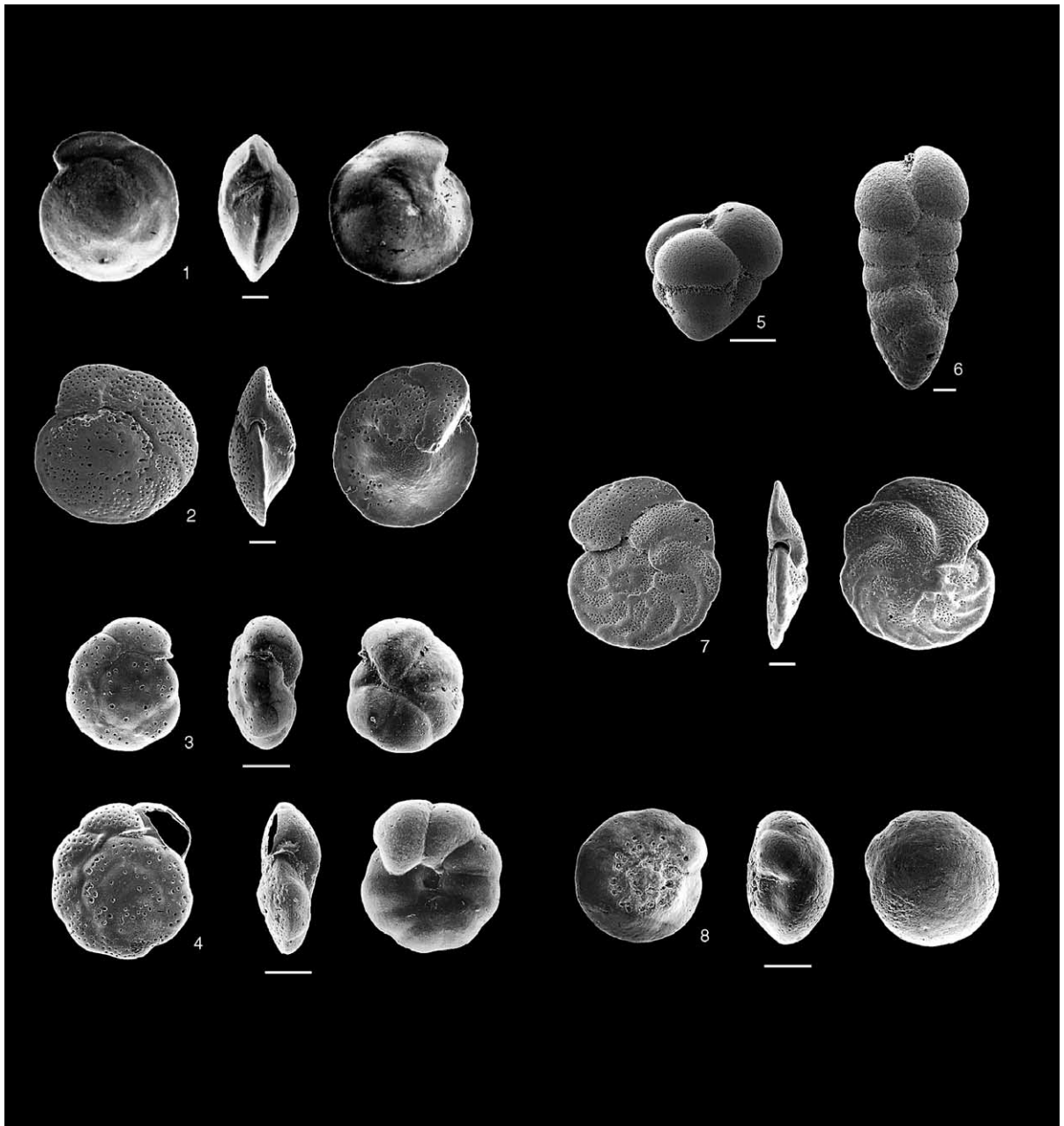


Plate II (caption on page 250).

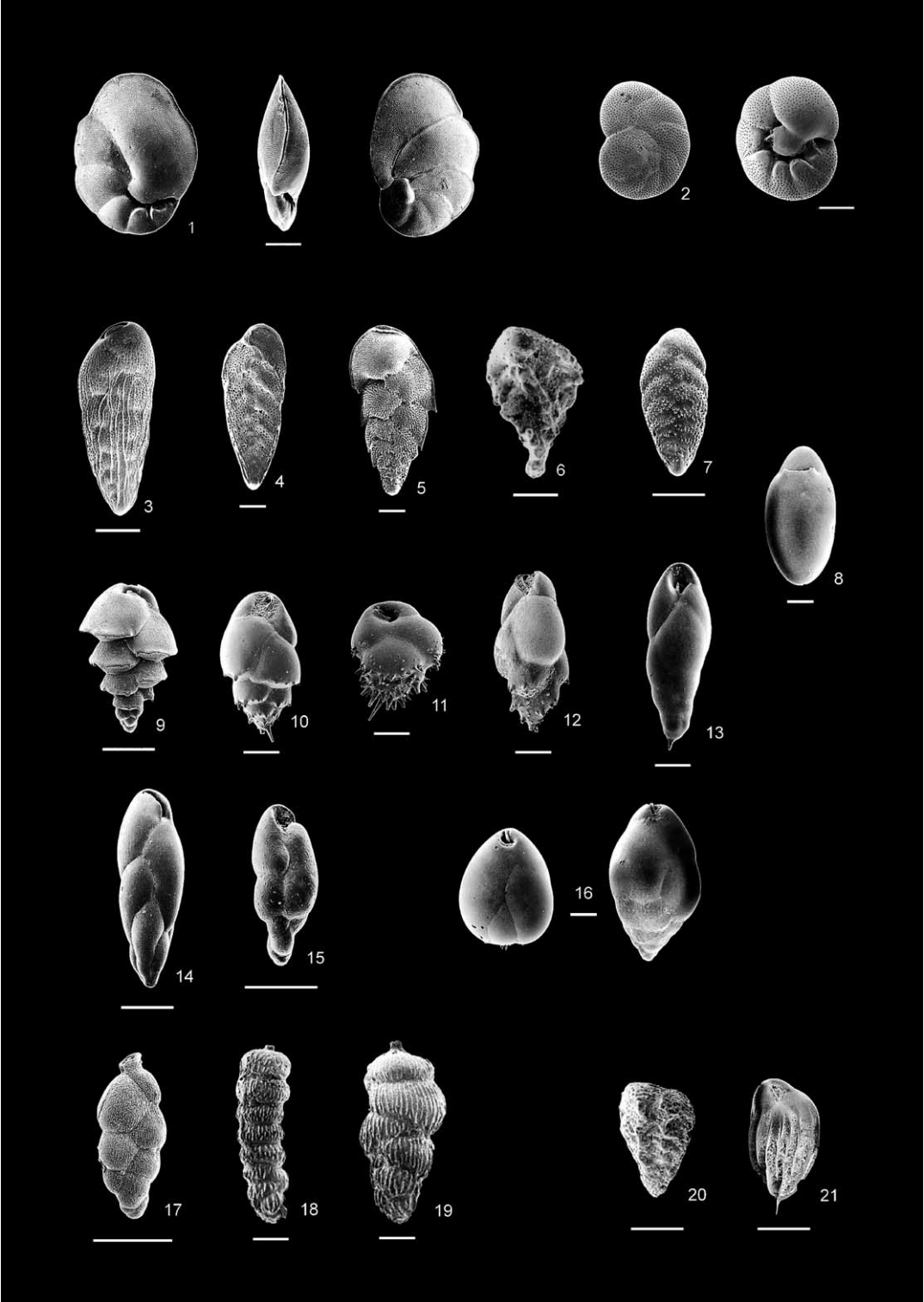


Plate III (caption on page 250).

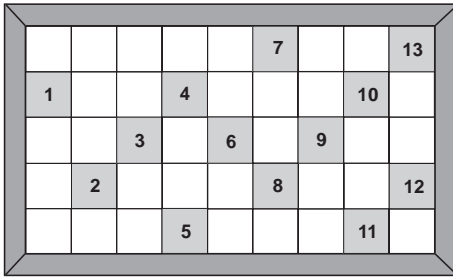


Fig. 3. Schematic drawing of a picking tray. In grey the fields of the counting scheme we applied are indicated, with numbers indicating the counting order.

3.2. Suitability of samples

Most suitable for palaeobathymetry reconstructions are fine-grained pelagic marine sediments that were deposited in low-energy environments. These sediments generally contain faunal populations that are least affected by downslope transport. Bandy (1953), referring to Natland and Kuenen (1951) already stated: “one might expect coarser laminae representing turbidity flows, etc., to carry the

shallow-water species; whereas the thin shales, representing gradual deposition, would carry the deep-water populations”.

Individual samples are suitable for analysis of the %P if:

- No dissolution of carbonate has occurred. Dissolution of carbonate will preferentially affect planktonic, rather than benthic foraminifera (Van der Zwaan et al., 1990; Boltovskoy and Totah, 1992), thus influencing the %P. Samples with evidence for carbonate dissolution, also evidenced by abundant fragmented shells, should be discarded. Our criterion was, that preservation should allow determination of benthic foraminifera at species level.
- The sample is not contaminated by down-slope transport. To determine whether the sample was likely to contain transported foraminifera, we checked for presence of quartz grains or rock fragments in the washed and sieved fraction of the sample, and for benthic taxa expected to live at very different water depths (Bandy, 1953). In

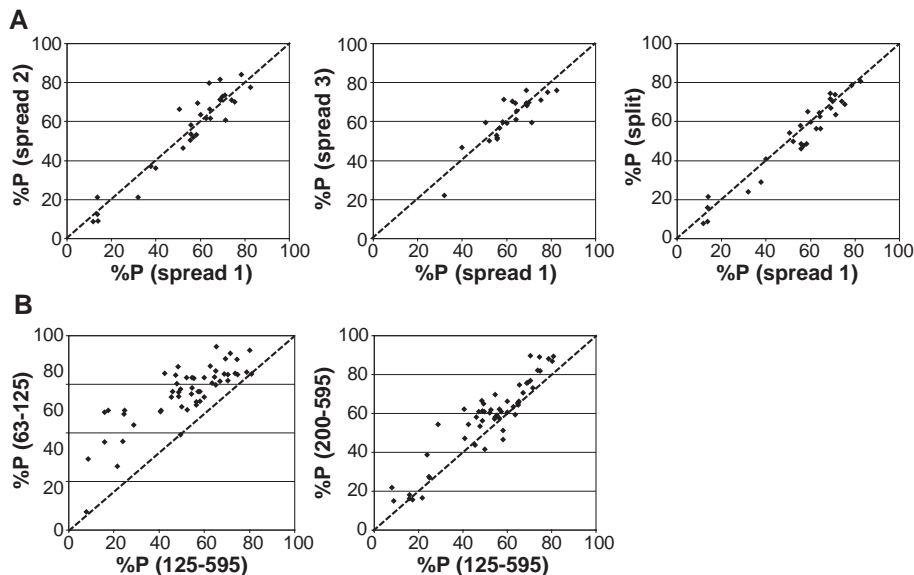


Fig. 4. A) Cross-plots showing reproducibility of %P counts. Differences between the preading and splitting procedures are minimal. The counts used to construct this figure are given in online Appendix I. B) Cross-plots, showing that a smaller or larger size fraction of foraminifera than the 125–595 μm fraction used by Van der Zwaan et al. (1990) gives significantly different results. The counts used to construct this figure are given in online Appendix II.

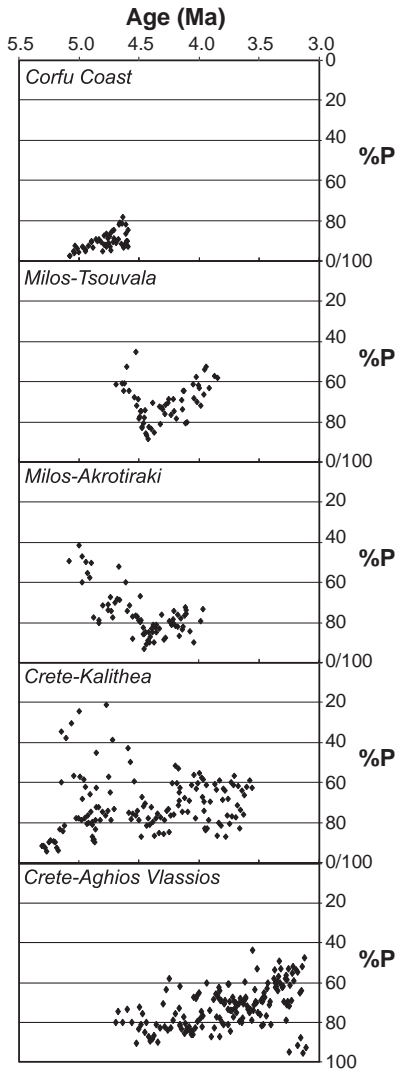


Fig. 5. Plots of the percentage of planktonic foraminifera (%*P*) versus age of the successions. The counts used to construct this figure are given in online Appendix III.

combination with broken specimens and/or a size sorting of planktonic and benthic foraminifera, this might indicate transportation and/or winnowing.

- Finally, we omitted all samples from sapropels, since these were deposited during more or less severe anoxic conditions, which significantly modifies %*P* values (see above).

Samples that passed these criteria were considered suitable for analysis of %*P*. All samples of the

Aghios Vlassios and Kalitheia successions, together with 53 samples of the Corfu Coast succession, 57 samples of the Tsouvala succession and 77 samples of the Akrotiraki succession were used for further analysis.

4. Analysis of the percentage of planktonic foraminifera (%*P*) and the percentage of stress markers (%*S*)

4.1. Basic taxonomic concept

Some basic taxonomic knowledge about foraminifera is needed for the analysis of the %*P*. For images of planktonic and benthic foraminifera, and in order to discriminate between taxonomic groups at a generic level, the reader is referred to e.g. Loeblich and Tappan (1964, 1988). Accessible taxonomy on the species level can be found in, for instance, AGIP (1982) and Jones (1994). For convenience, some common Neogene taxa are shown in Plates I–III.

As above mentioned, %*P* depends not only on depth, but also on the oxygen level of bottom waters. When oxygen levels are low, benthic associations will change and genera and species with high tolerance to stressed conditions tend to flourish. Under normal, oxic conditions, these genera will generally have an infaunal habitat. In many cases the infaunal genera that were discarded from the %*P* determination by

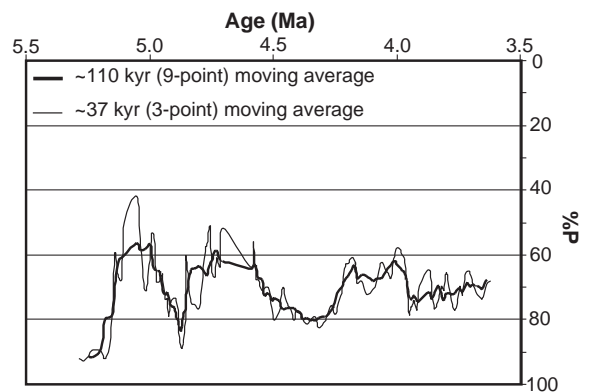


Fig. 6. Graph of the results of the Upper Pliocene Kalitheia succession on Crete (Greece), illustrating the visual effect of a moving average filter.

Van der Zwaan et al. (1990) can be considered as stress markers, especially when they occur in relatively high numbers. We propose to calculate the percentage of stress markers with respect to the total benthic foraminiferal population (%S) separately. We have included recent progress on knowledge about benthic foraminifera in stressed environments in our list of stress markers, modifying the original list of Van der Zwaan et al. (1990) to include: *Bolivina* spp., except for *B. plicatella* and *B. pseudoplicata*, non-costate *Bulimina*, *Uvigerina* spp., except for *U.*

semiornata, *Rectuvigerina* spp., *Valvulineria* spp., *Cancris* spp., *Fursenkoina* spp., *Stainforthia* spp., *Globobulimina* spp. and *Chilostomella* spp. (Seiglie, 1968; Van der Zwaan, 1982; Jonkers, 1984; Van der Zwaan et al., 1985, 1999; Van der Zwaan and Jorissen, 1991; Verhallen, 1991; Rathburn and Corliss, 1994; Fariduddin and Loubère, 1997; Jorissen, 1999b; Kouwenhoven, 2000) (Plate I).

In summary, we counted planktonic and benthic foraminifera, the latter subdivided in ‘normal’ open marine taxa and stress markers.

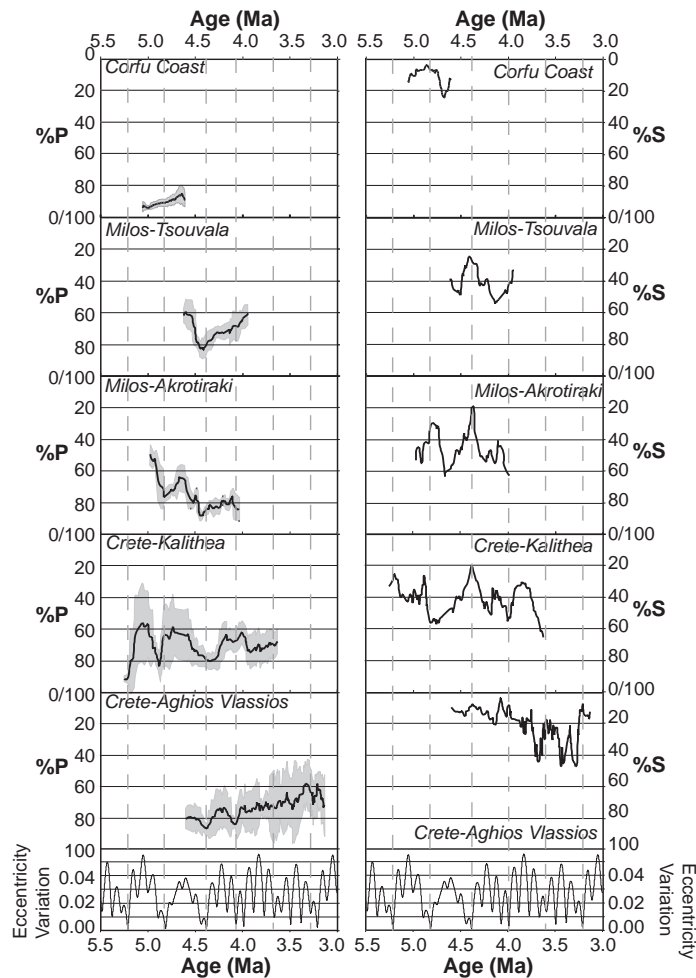


Fig. 7. Approximately 100 ky moving average curves of the percentage of planktonic foraminifera (%P) and the percentage of stress markers among the total benthic population (%S) versus time. Grey interval around the %P curve represents the standard deviation on the depth of the averaged interval. The curves are correlated to the Eccentricity La93 curve (Laskar et al., 1993). The well-defined eccentricity minima around 4.8 and 4.4 Ma are easily recognised in both the %S and %P diagrams. The less pronounced minima around 4.0 and 3.6 Ma have less influence on the curves.

4.2. Counting procedures

4.2.1. Split versus spread

To obtain a representative collection of foraminifera, samples can repeatedly be split in half, until the desired number of specimens is reached. This method was used by e.g. Jonkers (1984), who counted splits of samples of the Kalithea and Aghios Vlassios successions until 200 benthic specimens were obtained. This method, however, is rather time-consuming.

We applied a second, much quicker method, which starts with putting approximately half of the sample in one corner of the picking tray and then randomly spreading the required amount on the rest of the tray. This method corrects for size fractionation when the sample is stewed. Our counting was carried out following the predetermined scheme shown in Fig. 3. As a rule, a minimum of 100 specimens of the larger group, benthic or planktonic foraminifera, was counted.

To evaluate whether the results obtained by both methods are statistically different, 30 samples of the Kalithea succession, splits of which were previously counted by Jonkers (1984), were spread and counted three times by two different people using the spreading procedure. The cross-plots of Fig. 4A show that the results are reproducible, using either way of counting.

4.2.2. Influence of the size of the sieved fraction on %P

Jonkers (1984) provided counts of three different size fractions, based on 54 samples from the Kalithea succession. A clear difference in %P exists between the 125–595 μm fraction and the smaller (63–125 μm) and larger (200–595 μm) fraction (Fig. 4B). For the construction of the regression (1), the fraction of 125–595 μm was used (Van der Zwaan et al., 1990), which for reasons of comparison should thus be considered as the standard for our palaeobathymetric analysis.

4.3. Results

We determined the %P and %S of the successions at Crete, Milos and Corfu following the procedures described in the previous sections. The counts were obtained by spreading the 125–595 μm fraction on a

picking tray and counting according to the scheme of (Fig. 3), with a minimum of 100 specimens of either planktonic or benthic foraminifera. The results are shown in Fig. 5. The age is constrained by bio-, magneto- and cyclostratigraphy. Fig. 5 will be used as the basis for further interpretation and discussion.

5. Interpretation of the results and discussion

The diagrams of Fig. 5 reflect the interplay between the effect on %P of oxygen level of the bottom waters and depth variation. We aim to discern between palaeobathymetry-induced and oxygenation-induced variations of %P. High-amplitude short-term oscillations of the %P (<100 ky, e.g. across sapropels: Jorissen, 1999b; Kouwenhoven, 2000) are unlikely to result from true palaeobathymetry variations. To filter the long-term %P trend, which is more likely to result from both palaeobathymetry and oxygenation variations, one can use a moving average, which for the Kalithea succession is illustrated in Fig. 6. In Fig. 7 the %P curves of the five successions are plotted, applying a moving

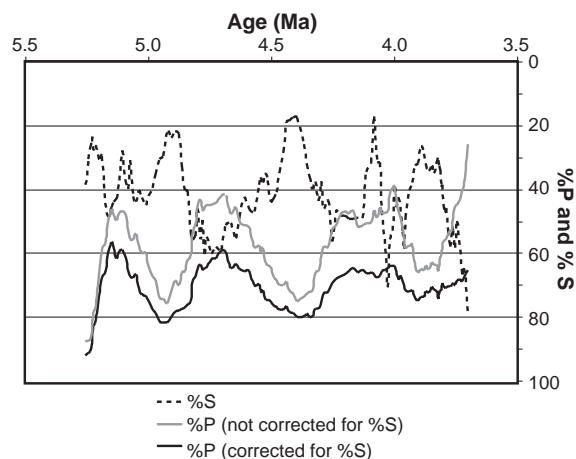


Fig. 8. Graph showing the effect of the correction for stress markers on %P. Correction for stress markers will diminish the amplitude of %P oscillations resulting from oxygenation variations, but %P variation still remains. The intervals of least oxygen induced stress—corresponding to the intervals of minimal %S—are the most reliable to estimate the true palaeobathymetry form. For the astronomically tuned eustatic sea level curve since 15 Ma of Lourens and Hilgen (1997), see online Appendix IV.

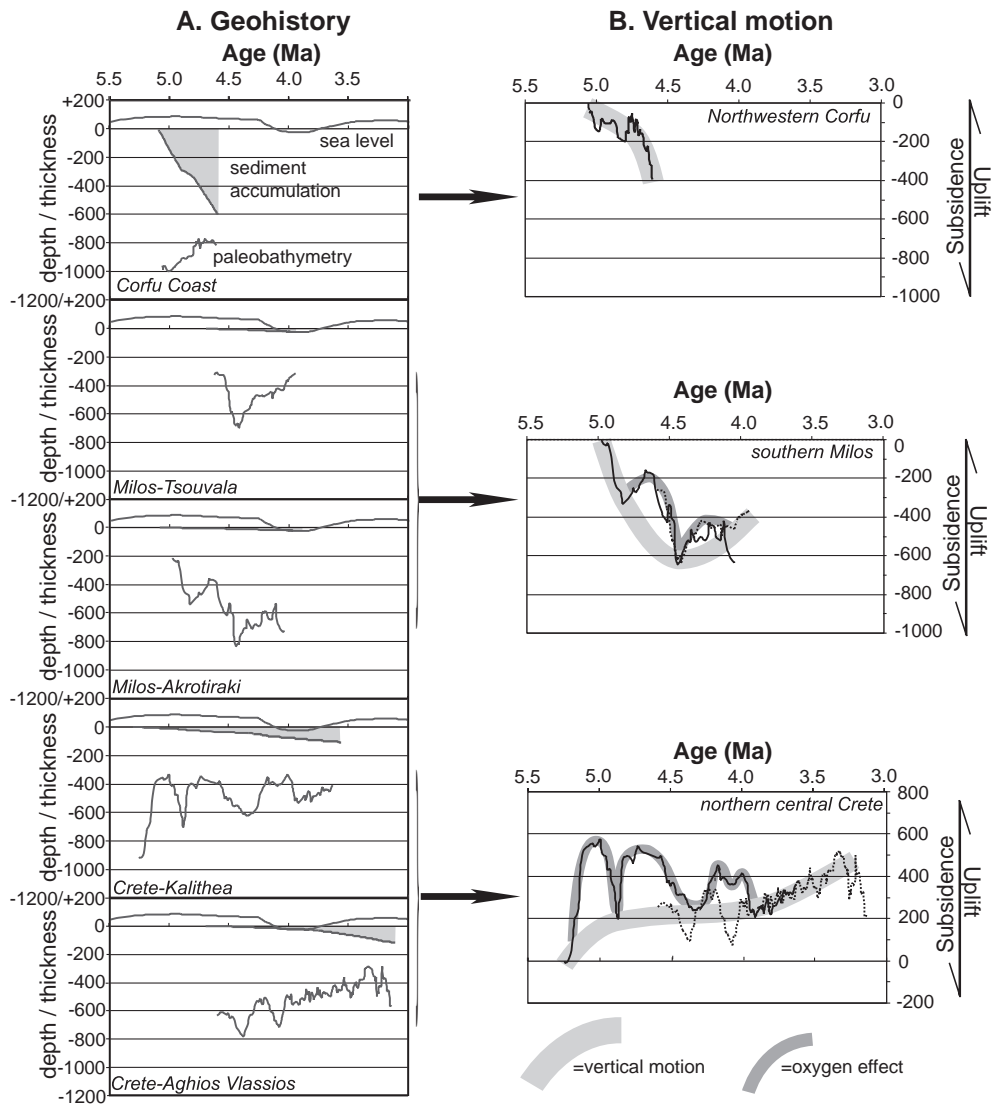
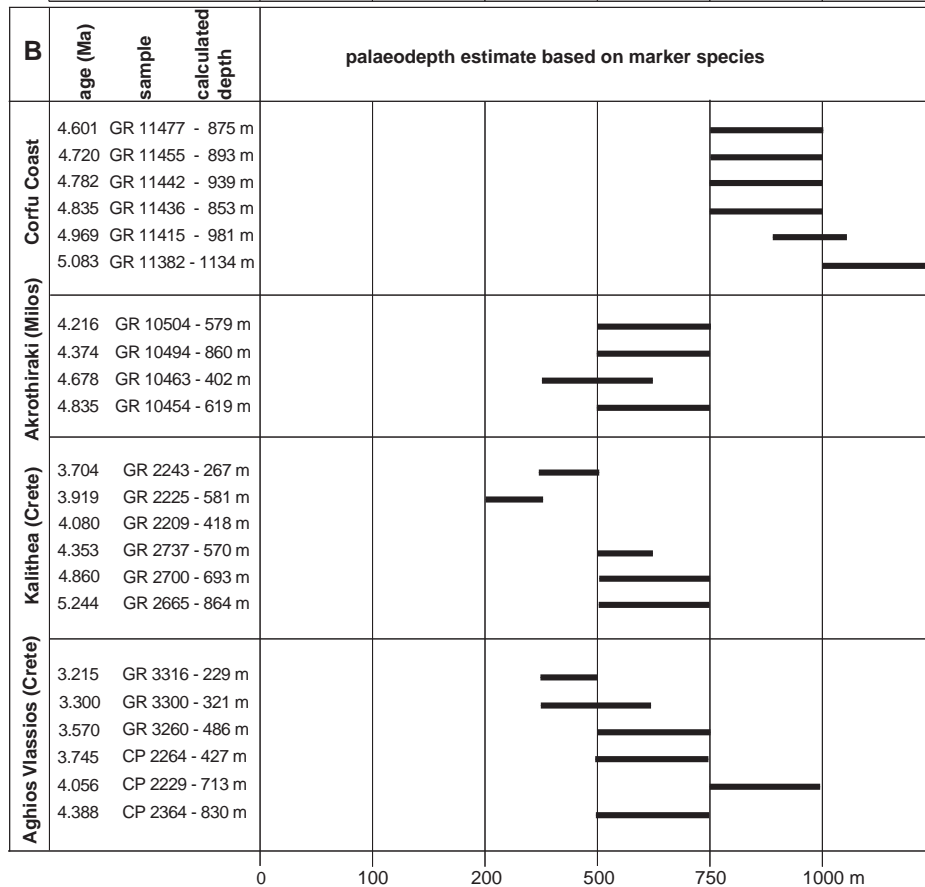
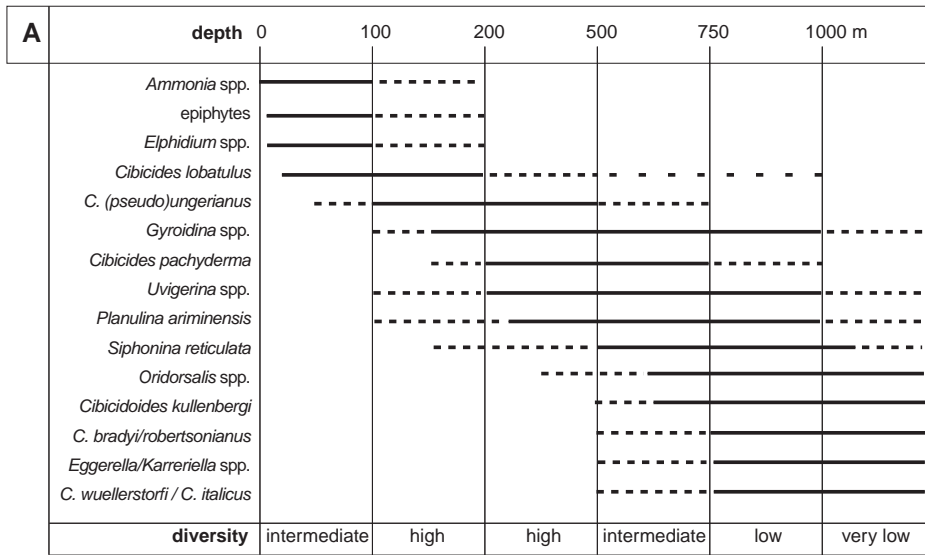


Fig. 9. Construction of vertical movement curves obtained by correction of the palaeobathymetry for sedimentary infill, compaction and eustatic sea level fluctuations. The sea level curve is taken from Lourens and Hilgen (1997) (see Appendix II). The base of the oldest succession is taken as reference level and thus set at 0 m. As a result, Corfu and Milos reveal subsidence, and a negative vertical axis, whereas Crete shows uplift and a positive vertical axis.

Fig. 10. A. Depth distribution of a selection of benthic marker species, based on Parker (1958), Blanc-Vernet (1969), Wright (1978), Parisi (1981), Jorissen (1987), Sprovieri and Hasegawa (1990), Sgarella and Moncharmont Zei (1993), De Stigter et al. (1998), De Rijk et al. (2000), Seidenkrantz et al. (2000), Jannink (2001), Kouwenhoven et al. (2003). Note that these studies are all based on the Mediterranean. See Plates II and III for images of these species. B. Results of the taxonomic check for a selection of samples of the various successions. The depth values calculated from the %P are shown in the left-hand column and the depth range estimated from the depth marker species of (A) are represented as horizontal bars. The results confirm the observed depth trends, although the depth estimated for the Kalitheia succession based on the taxa is somewhat shallower than the calculated depth, whereas the calculated depth of the Aghios Vlassios succession is shallower than estimated by benthic taxa.



average that approximates 100 ky (50 ky before and after each data point).

The %*P* curves, constructed from the successions from Milos and Crete reveal a cyclic fluctuation of %*P*, superimposed on a decreasing and increasing trend on Crete and Milos, respectively. This cyclicity corresponds to the 400 ky eccentricity-driven insolation fluctuation, shown in the curves of Laskar (1990) and Laskar et al. (1993) (Fig. 7). Fig. 7 also includes the curves of the percentage stress markers among the total benthic population (%*S*) in these successions, showing, that the cyclic decrease and increase in %*P* corresponds to an increase and decrease in %*S*, respectively. This suggests that the 400 ky fluctuations are caused by changes in bottom-water oxygenation. If one aims to reconstruct the bathymetry variations, data points representing comparable oxygen levels should be connected, preferably the best-ventilated intervals, as regression (1) was constructed on the basis of samples taken from well-ventilated intervals and disregarding infauna, largely corresponding to our stress markers (Van der Zwaan et al., 1990). These intervals can be recognised, because they coincide with the intervals of lowest %*S* (Figs. 7 and 8).

It should be noted that the oxygenation variations not only influence the %*S*, but also the %*P*: abundance of the total benthic population appears to fluctuate with oxygenation variations, assuming that primary production of planktonic foraminifera is constant (Fig. 8). Correction for stress markers will therefore diminish the amplitude of the oxygenation-induced %*P* variation, but still oxygenation-induced variations remain in the %*P*-curves. This explains the strong 400 ky %*P* variations in the curves of Figs. 7–9, despite the fact that stress markers are corrected for. The omission of stress markers from the benthic population therefore will not fully correct for oxygenation effects on benthic populations, but measuring %*S* provides a strong tool to distinguish between oxygenation and depth-effects on the %*P*, as the %*S* is not directly related to water depth. Therefore, %*P* variations resulting from oxygenation variation will be accompanied by %*S* variations, whereas %*P* variations as a response to true depth changes will not be.

Cyclic fluctuations on Milankovitch time-scales are absent in both the %*P* and %*S* curves constructed from the Corfu Coast succession, which is in line with

its position in a wide and deep, and therefore probably well-ventilated foreland basin. Restricted basins, for instance silled basins are generally less well ventilated, as was already noted by Bandy (1953) (See also Krijgsman, 2002). The high-resolution %*P* and %*S* curves obtained from the successions of Milos and Crete allow us to discern unambiguously between oxygen-induced and bathymetry-induced effects on the %*P* curve. If palaeobathymetry-analysis is attempted on successions with a poorer time resolution, this distinction can be more difficult or even impossible to make. In such cases, samples with very low %*S* levels probably best represent the true bathymetry, whereas samples with increasing %*S* give a decreasing confidence in the depth estimate. A case study on the Kalithea succession shows, that if all samples with %*S*>60 are discarded the closest match is made between the constructed and the best-ventilated depth trend. Discarding more samples (e.g. %*S*>40 or 50) will not yield a better match, but it will decrease the amount of data drastically. It should be noted that in cases of lower-resolution successions the bathymetry estimation has a much larger uncertainty and should be interpreted accordingly.

In summary, the %*P* trend is strongly influenced by oxygen depletion in poorly ventilated basins and the most reliable bathymetry trend can be constructed from the 'best-ventilated' intervals. It is now possible to calculate the bathymetry from the %*P* curves by using regression (1).

The resulting moving average curves reveal a shallowing trend on Corfu and Crete, and a deepening trend on Milos (Fig. 9).

6. Taxonomic check

Any significant trends in palaeobathymetry can be independently checked on selected samples along the succession, by identifying marker species for selected depth intervals. Fig. 10A and Plates II and III show a selection of benthic species from Middle Miocene to Recent that can well be used as depth markers. One should keep in mind, however, that many of these taxa are in themselves sensitive to low-oxygen conditions on the sea floor. Unexpected absence of these depth markers may be related to environmental conditions as well as to depositional

depth. The depth markers confirm the depth trends calculated from the %*P* (Fig. 10B).

7. From palaeobathymetry to vertical movement

To reconstruct vertical movements from these palaeobathymetry trends, corrections should be carried out, which have been described in backstripping procedures of e.g. Steckler and Watts (1978), Watts et al. (1982) and Steckler et al. (1999). Sediment deposition in a basin will have a shallowing effect. To construct the true movement of a chosen reference level (normally, the first sample level of the succession), the thickness of the accumulated sediment should be added to the estimated palaeobathymetry at each datum. Additional corrections can be carried out for compaction of the sediment. Van Hinte (1978) and Van der Meulen et al. (1999) used the present thickness–initial thickness relationships for sedimentary rocks of Perrier and Quiblier (1974) to correct for compaction. This relationship shows a general reduction of the sedimentary column of 15–25%, but this is strongly determined by lithology and amount of overburden. Not correcting will therefore yield an overestimation of subsidence or an underestimation of uplift. The present thickness of succession Corfu Coast is 500 m, which, following Perrier and Quiblier (1974) must originally have been approximately 600 m assuming that no large overburden was once present on top of Corfu Coast. On Milos and Crete, the amount of compaction must have been of the order of 10–20 m and hence is neglected.

Finally, to determine the true movement of the reference level, bathymetry variation due to eustatic sea level changes should be corrected for. An astronomically tuned eustatic sea level curve since the Middle Miocene with respect to the present-day sea level was constructed by Lourens and Hilgen (1997). Fig. 9b shows the resulting vertical movement curves for southern Milos, the north of Central Crete and northeastern Corfu. In case of the Milos and Cretan successions, the last corrections have only minor influence and the deepening and shallowing trends are caused by subsidence and uplift, respectively (Fig. 9). The curve obtained from the Corfu Coast succession indicates approximately 200 m of shallowing, but reveals several hundreds of meters of

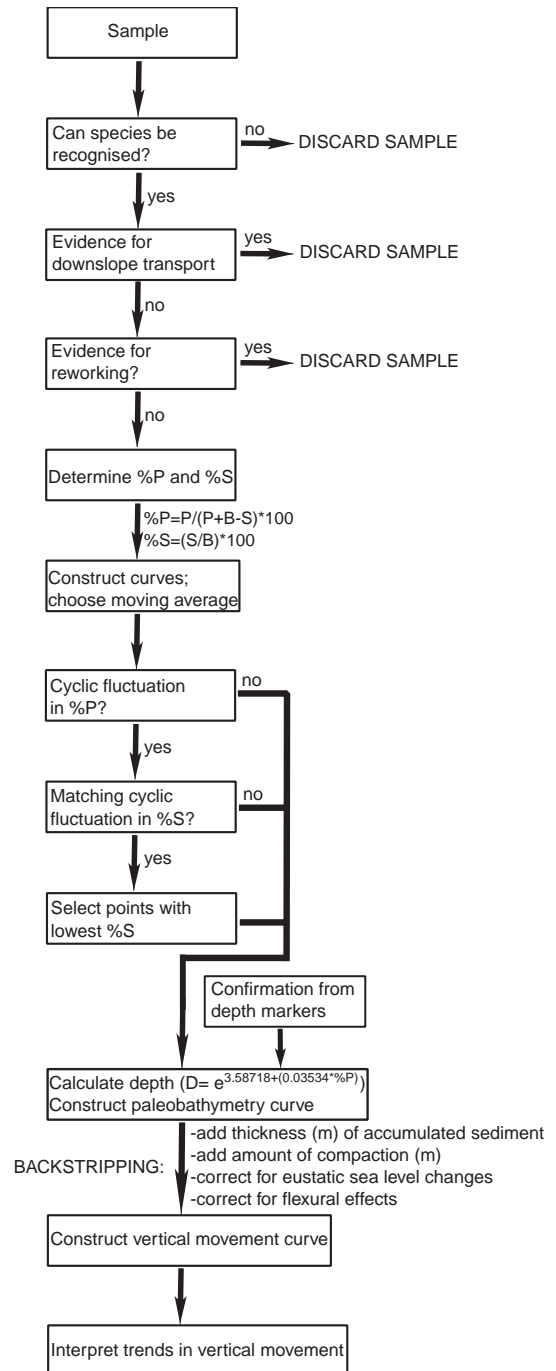


Fig. 11. Flow chart, showing the subsequent steps from sampling of the succession toward an interpretable vertical movement curve. *P*=number of specimens of planktonic foraminifera, *B*=number of specimens of benthic foraminifera, *S*=number of specimens of stress markers (see text for further explanation).

subsidence after correction for sedimentation and eustatic sea level changes (Fig. 9). The older succession Akrotiraki shows evidence for subsidence between 4.8 and 4.4 Ma, whereas the younger succession Tsouvala reveals slight uplift between 4.4 and 4.0 Ma (Figs. 9 and 10). The resulting movement curves are the combined effect of tectonic motions and isostasy (e.g. due to sediment loading or crustal thickening/thinning).

8. From the percentage of plankton to vertical movements: a flow chart

The procedures followed in the determination of the vertical movements in the five successions discussed in this paper are summarised in a flow chart (Fig. 11). In general, the steps in the flowchart will lead to an accurate reconstruction of vertical movements. In practice, however, successions might not contain only fine clay, may not be accurately dated or may comprise only little time spans. Generally, the accuracy of the palaeobathymetry reconstruction should be discussed carefully.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.palaeo.2005.02.013](https://doi.org/10.1016/j.palaeo.2005.02.013).

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