Barium, SiO₂ (excess), and P₂O₅ as proxies of biological productivity in the Middle East during the Palaeocene and the latest Palaeocene benthic extinction event

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ABSTRACT

The distribution of barium and other elements related to biological productivity has been studied in two Palaeocene sections from the Middle East. In the bathyal Ben Gurion section, Israel, Ba* (= Ba/Al₂O₃ × 15%) concentrations are low, in the range 0.04% to 0.3% in the lower Palaeocene, and very high, 1% to 2%, throughout most of the upper Palaeocene. In the neritic Gebel Aweina section in Egypt Ba* values are low, < 0.1%, throughout the entire Palaeocene. The Ba* enrichments at Ben Gurion and their correlations with increases in P₂O₅ and opaline silica, and local and global δ¹³C maxima, indicate that upwelling and high productivity were important in this region during the

late Palaeocene. The absence of Ba* enrichments in the shallower Gebel Aweina section probably reflects the strong depth dependence of biobarium deposition.

In the uppermost Palaeocene, at the level where the global benthic extinction event is registered, Ba* concentrations in the Ben Gurion section increase to anomalous 6%, which suggests that upwelling and possibly wind strengths intensified during this event. The results speak against deep-water formation in this region since downwelling and not upwelling is required.

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Introduction

The Palaeocene Epoch is characterized by several prominent global environmental changes (Corfield, 1994; Schmitz, 1994). In the earliest Palaeocene, in the aftermath of the Cretaceous–Tertiary boundary crisis, an impoverished fauna and flora inhabited the planktic oceanic realm (Corfield and Shackleton, 1988). Gradually, over several million years, various new planktic groups diversified and reinhabited the ocean surface waters. The oceanic carbon isotopic record reflects this biological expansion, with gradually more positive δ¹³C values, indicative of higher productivity, through the early late Palaeocene and reaching the highest values of the entire Cenozoic in the middle late Palaeocene (Corfield, 1994; Thompson and Schmitz, 1997). Following this, in the latest Palaeocene to earliest Eocene, there was a long-term δ¹³C and productivity decrease. Superimposed was a short-term (< 100 kyr) oceanic event, marked by a large negative δ¹³C excursion and warming of high-latitudes, coinciding with a dramatic extinction of 35–50% of deep-sea benthic foraminifera species (the benthic extinction event = BEE) (Thomas, 1990; Kennett and Stott, 1991).

The Tethyan region played an important role in the evolution of global oceanic and climatic change during

the Palaeocene. Global deep-water is thought to have formed in restricted basins in this region in connection with the BEE (Kennett and Stott, 1991; Barron and Peterson, 1991). In the present Middle East, which was situated at the southern margin of the Tethyan Seaway, there were basins where deep water potentially could have been sinking. However, because of the trade winds, upwelling rather than downwelling conditions may have been dominant (Schmitz *et al.*, 1996). In the present study we use chemical parameters to establish the record of biological productivity in this region during the Palaeocene. We also focus on productivity during the BEE. The Middle East sections contain some of the best-developed records across this event (Schmitz *et al.*, 1996).

Barium, bound in the mineral barite, is known to accumulate under recent and ancient pelagic high-productivity zones (see Schmitz, 1987a), but the reason for the association with biological productivity is not clear. It has been suggested that barium precipitates from sea-water in decaying, sulfate-saturated organic matter settling through the water column, or that it is formed by some planktic organisms (see, Schmitz, 1987a; Dymond and Collier, 1996). Barite is perhaps the most reliable palaeoproductivity indicator because of a generally high resistance to dissolution (at least in oxic and suboxic sediments; Schmitz, 1987a; Shimmield, 1992; Von Breymann *et al.*, 1992; Dymond *et al.*,

1992). Thompson and Schmitz (1997) show that in Palaeocene deep-sea cores (DSDP Holes 577, 527 and 384) from the Pacific and the Atlantic, barium shows a strong correlation with δ¹³C, confirming that there was a global increase in biological productivity in the late Palaeocene. Here we investigate whether a similar relation between Ba and δ¹³C can be found in bathyal and neritic sections from Israel and Egypt.

The Israeli and Egyptian sections

In Israel we have studied the Ben Gurion section (near Sdeh Boqer) in the north-central Negev Desert (Benjamini, 1992; Figs 1–2). The part of the section studied is about 65 m thick and comprises a relatively complete record through planktic foraminiferal Zones P2 to P6c (Benjamini, 1992; this study). The section formed in the NE–SW trending trans-Sinai basin at bathyal depths (500–700 m) (Speijer, 1995). Abundance of cosmopolitan deep-water benthic foraminifera indicates open connections with the Tethys and the world ocean (Speijer, 1995). The Palaeocene part of the section belongs to the Taqiya Formation (Fm), which is overlain by the early Eocene Mor Fm. The dominant lithology of the Taqiya Fm is grey marls, but intervals with clay or calcareous clay occur, and a prominent 5 m-thick chalk-limestone cliff with flint (Hafr Member; Mbr) occurs in the upper part of the formation (Benjamini, 1992; this study). The studied lower

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Fig. 1 Location of studied sites in the Middle East. Dashed lines indicate inferred general palaeobathymetry. HS indicates hypothetical shore line.

part of the Mor Fm consists of chalk and limestone with flint concretions.

A similar early Palaeogene sedimentary succession as at Ben Gurion is widespread in Israel and adjacent countries, including Egypt. In Egypt we have studied the Gebel Aweina outcrop on the eastern border of the Nile valley near Esna (Figs 1 and 3). The studied interval is 100 m thick and comprises a relatively complete and expanded record through Zones P1c to P5 (Charisi and Schmitz, 1995). The section formed on a broad North-African shelf, a few 100 km north of the shoreline in present northern Sudan (Said, 1990). Benthic foraminifera studies indicate outer neritic (150–200 m) depths through most of the Palaeocene (Speijer *et al.*, 1996b). The lower 35 m of the section, corresponding to the Dakhla Shale Fm, is dominated by grey calcareous clay, with some marl and limestone intercalations. In the middle part there is a ≈ 20 m-thick chalk-limestone cliff, constituting the Tarawan Fm (corresponding to the Hafir Mbr in Israel). The Esna Shale Fm, in the upper 45 m of the section, is characterized by grey marls in the lower 15 m, which grade into clays with little or no calcite (Charisi and Schmitz, 1995).

In the two sections studied, the latest Palaeocene benthic extinction event is registered at the base of a conspicuous 20–40 cm thick calcarenitic layer, the BEE bed, (at 51.9 m at Ben Gurion and 71.0 m at Gebel Aweina), in which a 2–3 ‰ negative $\delta^{13}\text{C}$ excursion occurs (Schmitz *et al.*, 1996; Fig. 4).

Fig. 2 Chemical profiles for the Ben Gurion section in Israel. All analyses on whole-rock samples. Biozonal notation, this study, after Berggren *et al.* (1995). SiO_2^* -excess concentrations > 100% reflect absence of closure effect after data normalization. see main text. BEE at 51.9 m.

Fig. 3 Chemical profiles for the Gebel Aweina section in Egypt. BEE at 71.0 m. See caption for Fig. 2.

Materials and methods

For the chemical analyses 125 mg of rock powder was fused with LiBO_2 and dissolved in HNO_3 . Element concentrations were determined with an ARL 3560 Inductively Coupled Plasma-Atomic Emission Spectrometer at SGAB in Luleå, Sweden. For details on the chemical analyses, see Thompson and

Schmitz (1997). Calcite concentrations were calculated from CaO data.

Measured element concentrations were normalized according to: $Y^* = (Y/\text{Al}_2\text{O}_3 \text{ (whole rock)}) \times \text{Al}_2\text{O}_3 \text{ (av. continental crust)}$, where Y^* is the recalculated concentration of the element considered (Schmitz, 1987a). The Al_2O_3 content of average continental crust is 15% (Wedepohl, 1995). The

Fig. 4 Chemical profiles across the BEE at Ben Gurion and Gebel Aweina. Last appearance of typical Palaeocene benthic foraminifera occurs at the base of the calcarenitic bed. All analyses on whole-rock samples. Isotopic profiles based on benthic foraminifera tests show a sharp 3 ‰ negative $\delta^{13}\text{C}$ shift in the lower part of the BEE bed at Gebel Aweina (Schmitz *et al.*, 1996). At both sites a minor hiatus may occur at the base of the BEE bed.

SiO_2^* -excess concentration represents the total SiO_2^* content from which an assumed average SiO_2^* content of the aluminosilicate fraction, 45%, has been subtracted (Boström *et al.*, 1973). The SiO_2^* -excess concentration represents a rough estimate of opaline silica content.

Results

At the Ben Gurion site all three productivity indicators, Ba^* , SiO_2^* -excess and P_2O_5^* , show low concentrations throughout the lower Palaeocene (Fig. 2). In the lower to middle P4 zone, the three indicators show increasing concentrations, and thereafter follow, with some lag, the trend of $\delta^{13}\text{C}$ towards maximum values in the upper P4 to lower P5 interval. The Ba^* concentrations lie in the range 0.04% to 0.3% in the lower 30 m of the section, whereas throughout most of the upper part of the section concentrations vary between 1% and 2%. SiO_2^* -excess increases from near 0% to about 10% in the middle of the P4 zone. In the Hafir Mbr, SiO_2^* -excess is high, probably related to flint occurrences. From the base of the marls immediately above the Hafir Mbr, where SiO_2^* -excess lies

at 40%, concentrations decline gradually upwards, paralleling the decline in $\delta^{13}\text{C}$. P_2O_5^* generally seems to follow CaCO_3 . At the BEE bed, where a conspicuous 2.5 ‰ negative $\delta^{13}\text{C}$ anomaly occurs, all three element productivity indicators show dramatic abundance peaks. The Ba^* content increases from 2% to 6%. The P_2O_5^* increases from 2% to 7.4%, and SiO_2^* -excess increases from 15% to 30% (Figs 1 and 4).

Throughout the Gebel Aweina section the productivity indicators show low concentrations (Fig. 3). In the marly and clayey parts the Ba^* content is 0.01–0.02%, all of which can be accounted for by the clastic aluminosilicates. In the Tarawan chalk Ba^* increases to $\approx 0.1\%$, which may reflect a small biobarite component, or alternatively, Ba incorporated in calcite or in metal-hydroxide coatings on calcite surfaces. The SiO_2^* -excess content is 0% throughout the major part of the section, only in the Tarawan Fm are concentrations high, which probably reflects flint occurrence. As at Ben Gurion, P_2O_5^* follows calcite. At the BEE, CaCO_3 , Ba^* and P_2O_5^* show abundance increases, whereas SiO_2^* -excess remains low. Ba^* increases from 0.02%

to 0.05%, and P_2O_5^* increases from 0.5% to 2.0% (Fig. 4).

High-productivity and intersite Ba^* difference

The strongly enhanced Ba^* values in the middle–upper Palaeocene part of the Ben Gurion section most likely reflect increased deposition of biobarite under a high-productivity zone. The Israeli section shows a similar Ba^* increase in connection with the upper Palaeocene $\delta^{13}\text{C}$ maximum, as observed at DSDP Holes 577, 384 and 527 (Thompson and Schmitz, 1997). Radiolarian occurrences also indicate that upwelling and high-productivity occurred at Ben Gurion during the P4–P5 interval (Benjamini, 1992). SiO_2^* -excess and P_2O_5^* also show increases in the upper Palaeocene at Ben Gurion, which further supports that the Ba^* reflects high-productivity. Excess barium may sometimes have a volcanic origin (Boström *et al.*, 1973), however, our unpublished trace element results (Fe, Ti, Mn) rule out such a source at Ben Gurion.

The strikingly lower Ba^* concentrations in the Gebel Aweina section compared with Ben Gurion probably primarily reflect a depth effect. Sediments below recent high-productivity areas off the Peruvian coast show Ba enrichments at slope and basin sites, but not on the shelves (Von Breymann *et al.*, 1992). Similarly in the upwelling systems of Baja California and the North Arabian Sea, excess Ba is only found at deeper sites (Shimmield, 1992; Von Breymann *et al.*, 1992). The reason for the depth dependence of biobarite deposition is not known.

The distance between the Ben Gurion and Gebel Aweina sites is about 600 km and differences in productivity and upwelling may have occurred. Whereas shallow depth prevents the use of Ba^* as a palaeoproductivity indicator at Gebel Aweina, biogenic opaline silica and calcite concentrations may be more informative. The opaline silica of recent high-productivity sediments does not show the same depth relation as biobarite (Von Breymann *et al.*, 1992). However, a drawback is that both opaline silica and calcite are sensitive to dissolution. Moulds of radiolarians are common in the Esna Shales at Gebel Aweina, indicating that silica dissolution, rather than low productivity, ac-

counts for the absence of opaline silica. Benthic foraminiferal $\delta^{13}\text{C}$ values are unusually low in the Esna Shales, which indicates that abundant decomposing organic matter in connection with high productivity reached the sea floor and that bottom waters were corrosive due to CO_2 release (Schmitz *et al.*, 1996). Although calcite is generally lower at Gebel Aweina than at Ben Gurion, the calcite net productivity-dissolution variations were similar at the two sites, as manifested by the occurrence of mid-Palaeocene thick limestone cliffs in both sections and profound calcarenitic BEE beds. Most likely these calcareous deposits reflect episodes of increased regional productivity.

Barium flux rates and southern Tethyan high productivity

The Ba^* concentrations of 1–2% in the upper Palaeocene sediments at Ben Gurion are high compared with other high-productivity region sediments. At DSDP Site 577, which lay under the northern margin or just north of the Pacific equatorial high-productivity zone during the Palaeocene, Ba^* concentrations increase from $\approx 1.5\%$ during the early Palaeocene to $\approx 3\%$ in connection with the $\delta^{13}\text{C}$ maximum (Thompson and Schmitz, 1997). At Atlantic oligotrophic DSDP Sites 384 and 527, Ba^* increases from 0.02–0.04% (predominantly aluminosilicate Ba) in the lower Palaeocene to 0.1–0.4% in connection with the $\delta^{13}\text{C}$ maximum. The much higher Ba^* concentrations at DSDP Site 577 reflect a situation similar to that in the present ocean, with belts of barite-rich sediments underlying the equatorial high-productivity zones (Boström *et al.*, 1973). The sediment of the P4–P6a interval is a factor of two thicker at Ben Gurion than at DSDP 577 (using zonations in Benjamini, 1992; and Lu and Keller, 1995). The average whole-rock Ba concentrations in this interval at Ben Gurion lies at 0.6%, compared to 0.06% at DSDP 577. This means that the Ba accumulation rates were about 20 times higher at Ben Gurion than at DSDP Site 577.

Recurrently, during the Late Cretaceous and early Palaeogene, prominent upwelling loci developed on the northern shelves and slopes of the African and Arabic cratons (Parrish and Curtis, 1982; Almogi-Labin *et al.*, 1993). The

widespread phosphate deposits in these regions are a result of this upwelling. Late Cretaceous deposits from the Negev Desert in Israel formed under strong upwelling conditions (Almogi-Labin *et al.*, 1993). Upwelling was particularly intense during the Campanian and decreased in intensity towards the late Maastrichtian. Our results for the Ben Gurion section give a continuation of this record, showing that the upwelling ceased during the early Palaeocene and was reinvigorated during the late Palaeocene. Phosphate, silica and barite-rich rocks from early Eocene deposits in Israel (Bogoch *et al.*, 1987) show that the upwelling situation continued throughout this period. The upwelling variations with time are the same as observed in Tunisia and Morocco, where phosphate deposition is renewed in the late Palaeocene after a low in the early Palaeocene and the late Maastrichtian (see Speijer *et al.*, 1996a). In Egypt, phosphates of late Cretaceous age are common, in accord with upwelling conditions also in this region. Speijer *et al.* (1996a) observed that at the inner neritic Duwi site in Egypt (Fig. 1) the upper Palaeocene sediments are bitumen-rich and laminated, and contain an impoverished benthic faunal assemblage, in accord with a coastal upwelling situation. If the coast line trended NE the northerly trade winds could have removed surface waters from the coasts off the north African–Arabian continent leading to the upwelling of nutrient-rich water.

Upwelling, downwelling and BEE

Anomalously high Ba^* concentrations, up to 5.9% occur in the BEE bed at Ben Gurion. Acetic-acid (2 M) leached residues of the BEE bed show Ba^* concentrations close to 6%. This indicates that nearly all of the Ba occurs as barite, and not in easily dissolvable hydroxide or carbonate phases. The barite/Ba weight ratio is 1.7, which means that the BEE bed on a calcite-free basis may contain up to 10% barite.

There are several arguments in favour of the conspicuous Ba enrichment in the BEE bed at Ben Gurion reflecting high-productivity. (i) The other productivity related indicators SiO_2^* -excess, P_2O_5^* , and calcite also show profound increases in the BEE bed. It is unlikely that any diagenetic enrichment process would have had similar

effects on all four parameters. (ii) The generally suboxic-oxic sediments and mineralogical features, such as absence of redox-sensitive authigenic minerals and other diagenetic sulphates, speak against the possibility that the BEE bed represents a redoxcline where remobilized diagenetic Ba preferentially has precipitated (although some reprecipitation has occurred). (iii) At three localities studied (Ben Gurion, G. Duwi, G. Aweina), the calcarenitic BEE bed is extremely rich in planktic foraminifera tests (typically $> 10,000$ specimens, $> 125 \mu\text{g g}^{-1}$ dry sediment) and shows very high planktic/benthic foraminifera ratios ($> 96\%$ planktics) (R. Speijer: this study). Nowhere else in the sections have similar planktic-foraminifera dominated sediments been found. In recent oceans increased planktic foraminiferal production occurs in connection with certain upwelling situations (Sautter and Thunell, 1991).

We rule out that the high Ba^* concentrations and the high planktic numbers primarily reflect a lag or a condensation effect. Only the biogenic fraction (planktic foraminifera tests) is coarse-grained (arenitic), whereas the siliciclastic fraction is as fine-grained as in the surrounding parts of the section (based on quartz grains analyses and the $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio; see Schmitz, 1987b). The BEE bed neither contains any intraclasts nor any manganese coatings.

In the stratigraphic record negative $\delta^{13}\text{C}$ excursions typically coincide with global mass extinction events and have been interpreted in terms of oceanic productivity declines (Magaritz, 1991). The $\delta^{13}\text{C}$ anomaly at the BEE, however, developed rapidly through the entire water column, and not primarily in the surface waters, and has been considered to be too large and too instantaneous to be accounted for by a productivity decline (Dickens *et al.*, 1995). Our results for the Middle East show that at least in this region the negative $\delta^{13}\text{C}$ excursion is associated with high productivity, and most likely even an increase in productivity. Further data are required in order to determine whether this increase in productivity/upwelling is related to a local change in geography, wind or current system or if it reflects a global atmospheric-oceanic change. Steineck and Thomas (1996) recently reported ostracode data indicating a possible increase in upwelling and high-productivity in

connection with the BEE also at ODP Site 689 at Maud Rise. Reduced meridional heat gradients in connection with the BEE in general would rather have led to diminished wind strengths and upwelling. However, based on climate simulations O'Connell *et al.* (1996) suggest increased wind strength over the tropical and subtropical continents during the late Palaeocene. The evidence for upwelling (and not downwelling) during the BEE in the Middle East rules out that this region was a source of global deep-water (see also Schmitz *et al.*, 1996).

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References

- Almogi-Labin, A., Bein, A. and Sass, E., 1993. Late Cretaceous upwelling system along the southern Tethys margin (Israel). Interrelationship between productivity, bottom water environments and organic matter preservation. *Paleoceanography*, **8**, 671–690.
- Barron, E.J. and Peterson, W.H., 1991. The Cenozoic oceanic circulation based on General Circulation Model results. *Paleogeogr. Palaeoclim. Palaeoecol.*, **83**, 1–28.
- Benjamini, C., 1992. The Paleocene-Eocene boundary in Israel: A candidate for the boundary stratotype. *N. Jb. Geol. Paläont. Abh.*, **186**, 49–61.
- Berggren, W.A., Kent, D.V., Swisher, I.I.I., C.C. and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: *Geochronology, Time Scales and Stratigraphic Correlation* (W. A. Berggren *et al.*, eds). *Spec. Publ. Soc. Econ. Paleont. Miner., Tulsa*, **54**, 129–212.
- Bogoch, R., Buchbinder, B. and Nielsen, H., 1987. Petrography, geochemistry, and evolution of barite concretions in Eocene pelagic chalks from Israel. *J. Sedim. Petrol.*, **57**, 522–529.
- Boström, K., Joensuu, O., Moore, C., Boström, B., Dalziel, B. and Horowitz, A., 1973. Geochemistry of barium in pelagic sediments. *Lithos*, **6**, 159–174.
- Charisi, S.D. and Schmitz, B., 1995. Stable ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotopes through the Paleocene at Gebel Aweina, eastern Tethyan region. *Paleogeogr. Palaeoclim. Palaeoecol.*, **116**, 103–129.
- Corfield, R.M., 1994. Paleocene oceans and climate: An isotopic perspective. *Earth-Sci. Rev.*, **37**, 225–252.
- Corfield, R.M. and Shackleton, N.J., 1988. Productivity change as a control on planktonic foraminiferal evolution after the Cretaceous/Tertiary boundary. *Historical Biol.*, **1**, 323–343.
- Dickens, G.R., O'Neil, J.R., Rea, D.K. and Owen, R.M., 1995. Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. *Paleoceanography*, **10**, 965–971.
- Dymond, J. and Collier, R., 1996. Particulate barium fluxes and their relationships to biological productivity. *Deep-Sea Res.*, **43**, 1283–1308.
- Dymond, J., Suess, E. and Lyle, M., 1992. Barium in deep-sea sediment. A geochemical proxy for paleoproductivity. *Paleoceanography*, **7**, 163–181.
- Kennett, J.P. and Stott, L.D., 1991. Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, **353**, 225–229.
- Lu, G. and Keller, G., 1995. Ecological stasis and saltation: species richness change in planktic foraminifera during the late Paleocene to early Eocene, DSDP Site 577. *Paleogeogr. Palaeoclim. Palaeoecol.*, **117**, 211–227.
- Magaritz, M., 1991. Carbon isotopes, time boundaries and evolution. *Terra Nova*, **3**, 251–256.
- O'Connell, S., Chandler, M.A. and Ruedy, R., 1996. Implications for the creation of warm saline deep water: Late Paleocene reconstructions and global climate model simulations. *Bull. geol. Soc. Am.*, **108**, 270–284.
- Parrish, J.T. and Curtis, R.L., 1982. Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenozoic eras. *Paleogeogr. Palaeoclim. Palaeoecol.*, **40**, 31–66.
- Said, R., 1990. Cenozoic. In: *The Geology of Egypt* (R. Said, eds), pp. 451–486. Balkema, Rotterdam.
- Sautter, L.R. and Thunell, R.C., 1991. Planktonic foraminiferal response to upwelling and seasonal hydrographic conditions: Sediment trap results from San Pedro Basin, Southern California Bight. *J. Foramin. Res.*, **21**, 347–363.
- Schmitz, B., 1987a. Barium, equatorial high productivity, and the northward wandering of the Indian continent. *Paleoceanography*, **2**, 63–77.
- Schmitz, B., 1987b. The $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio in the Cenozoic Bengal Abyssal Fan sediments and its use as a paleostream energy indicator. *Mar. Geol.*, **76**, 195–206.
- Schmitz, B., 1994. The Paleocene Epoch: stratigraphy, global change and events. *GFF*, **116**, 39–41.
- Schmitz, B., Speijer, R.P. and Aubry, M.-P., 1996. Latest Paleocene benthic extinction event on the southern Tethyan shelf (Egypt). Foraminiferal stable isotopic ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) records. *Geology*, **24**, 347–350.
- Shimmield, G.B., 1992. Can sediment geochemistry record changes in coastal upwelling palaeoproductivity? Evidence from northwest Africa and the Arabian Sea. In: *Upwelling Systems. Evolution Since the Early Miocene* (C. P. Summerhayes *et al.*, eds). *Spec. Publ. Geol. Soc. London*, **64**, 29–46.
- Speijer, R.P., 1995. The late Paleocene benthic foraminiferal extinction as observed in the Middle East. In: *Paleocene-Eocene Boundary Events* (P. Laga, eds). *Bull. Soc. Belge Géol.*, **103**, 267–280.
- Speijer, R.P., van der Zwaan, G.J. and Schmitz, B., 1996a. The impact of Paleocene-Eocene boundary events on middle neritic benthic foraminiferal assemblages from Egypt. *Mar. Micropal.*, **28**, 99–132.
- Speijer, R.P., Schmitz, B., Aubry, M.-P. and Charisi, S.D., 1996b. The latest Paleocene benthic extinction event: Punctuated turnover in outer neritic foraminiferal faunas from Gebel Aweina, Egypt. *Isr. J. Earth Sci.*, **44**, 207–222.
- Steineck, P.L. and Thomas, E., 1996. The latest Paleocene crisis in the deep sea. Ostracode succession at Maud Rise, Southern Ocean. *Geology*, **24**, 583–586.
- Thompson, E.I. and Schmitz, B., 1997. Barium and the late Paleocene $\delta^{13}\text{C}$ maximum: Evidence of increased oceanic surface productivity. *Paleoceanography*, **12**, 239–254.
- Von Breymann M.T., Emeis K.-C. and Suess E., 1992. Water depth and diagenetic constraints on the use of barium as a palaeoproductivity indicator. In: *Upwelling Systems. Evolution Since the Early Miocene* (C. P. Summerhayes *et al.*, eds). *Spec. Publ. Geol. Soc. London*, **64**, 273–284.
- Wedepohl, K.H., 1995. The composition of the continental crust. *Geochim. Cosmochim. Acta*, **59**, 1217–1232.

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