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Paleoenvironment across the Cretaceous-Tertiary transition in eastern Bulgaria

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ABSTRACT

The Cretaceous-Tertiary (K-T) transition in eastern Bulgaria (Bjala) was analyzed in terms of lithology, mineralogy, stable isotopes, trace elements, and planktic foraminifera. The sequence represents a boreal-Tethyan transitional setting, spans from the last 300 k.y. of the Maastrichtian (zone CF1) through the early Danian (zones P0-Plc), and contains several short hiatuses. It differs from low-latitude Tethyan sequences primarily by lower diversity assemblages, pre-K-T faunal changes, a reduced K-T $\delta^{13}C$ shift, and the presence of two clay layers with platinum group element anomalies. The first clay layer marks the K-T boundary impact event, as indicated by an iridium anomaly (6.1 ppb), the mass extinction of tropical and subtropical planktic foraminifera, and cooling. The second clay layer is stratigraphically within the upper *Parvularugoglobigerina eugubina* (Pla) zone and contains a small Ir enrichment (0.22 ppb), a major Pd enrichment (1.34 ppb), and anomalies in Ru (0.30 ppb) and Rh (0.13 ppb) that suggest a volcanic source.

INTRODUCTION

Cretaceous-Tertiary (K-T) boundary studies have often concentrated on documenting the geochemical anomalies and the pattern of planktic foraminiferal species extinctions immediately below and above this boundary event in low latitudes (Fig. 1). Most of these studies reveal a major mass extinction of all tropical and subtropical species at or near the K-T boundary and iridium anomalies that have been variously attributed to the sole effects of an impact (e.g., Smit, 1990; D'Hondt et

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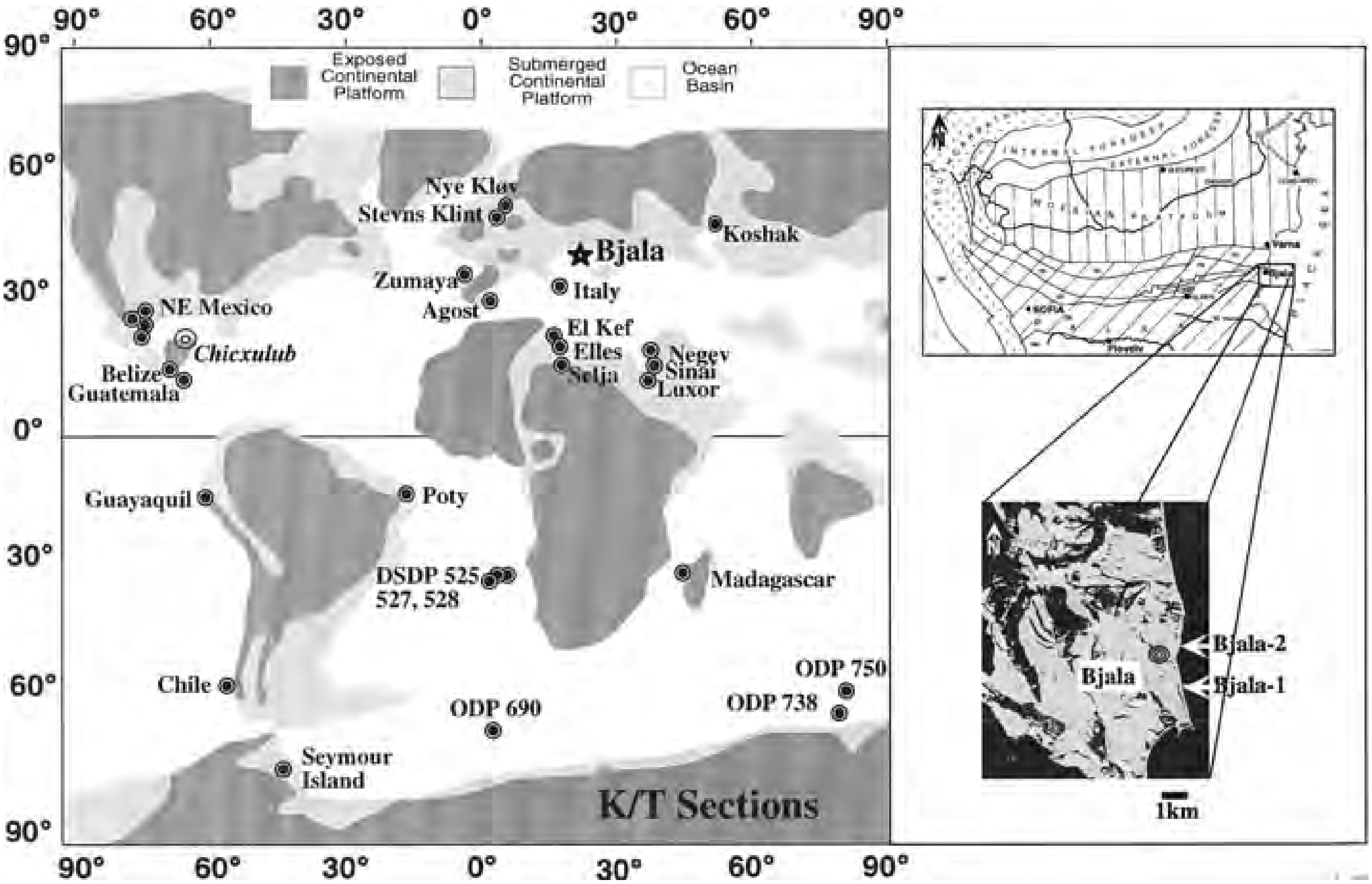

Figure 1. Paleolocations of Cretaceous-Tertiary (K-T) boundary sections that have good biostratigraphic control and relatively continuous sediment records. Note that current knowledge of K-T boundary event is primarily from sections in low-latitude northern Tethys, including Mexico, Spain, and Tunisia. Few K-T sections are currently known from middle and high latitudes. Bjala sections of Bulgaria provide critical information of this event in transitional environment between northern Tethys and boreal sea. Inset shows satellite photograph of Black Sea coast with Bjala locality, and simplified tectonic map of South Carpathian arc (modified from Preisinger et al., 1993a; Rögl et al., 1996). Ocean basins are white, continental platform is gray, continents are black (modified from MacLeod and Keller, 1991a). ODP is Ocean Drilling Program, DSDP is Deep Sea Drilling Project.

al., 1996; Apellaniz et al., 1997; Olsson, 1997), or long-term environmental changes followed by an impact (e.g., Keller, 1988, 1996; Luciani, 1997; Abramovich et al., 1998). Few studies have attempted to evaluate some aspects of the K-T event on a regional or global scale, including studies of hiatus distributions (MacLeod and Keller, 1991a, 1991b), species survivorship, and records of pre-K-T extinctions (MacLeod and Keller, 1994; Abramovich et al., 1998; Pardo et al., 1999). The absence of more comprehensive integrated summary studies is largely because most K-T sections are separated by large distances (Fig. 1), and direct comparisons across latitudes are difficult due to little known regional effects, particularly in middle to high latitudes.

The mass-extinction pattern of planktic foraminifera in high latitudes is quantitatively documented from a few localities in the southern ocean (e.g., Deep Sea Drilling Project [DSDP] Sites 690 and 738, Keller, 1993) and Northern Hemisphere (e.g., Denmark and Kazakhstan, Schmitz et al., 1992; Keller et al., 1993; Pardo et al., 1999; Fig. 1). These data suggest a diminished mass-extinction effect compared with low latitudes primarily because tropical and subtropical species are absent and assemblages are dominated by small species that tolerate environmental fluctuations, including *Guembelitria cretacea, G. danica, G. trifolia, G. dammula, Heterohelix globulosa, H. navarroensis, H. planate, Hedbergella holmdelensis, H. monmouthensis*, and *Globigerinelloides aspera* (MacLeod and Keller, 1994). Most of these species are also observed in Danian sediments of low latitudes, and between 4 and 12 species have been considered as survivors (e.g., Canudo, 1997; Keller, 1997; Masters, 1997; Olsson, 1997; Orue-etxebarria, 1997; Smit and Nederbragt, 1997; Luciani, 1997). Stable isotopes measured on some of these species in Danian sediments have been found to record Danian values, also suggesting that they are survivors (Barrera and Keller, 1994; Keller et al., 1993; MacLeod and Keller, 1994). Huber (1996) attributed the presence of these species in Danian sediments to reworking, citing relatively unchanged stable isotope values of *Globigerinelloides multispinus* across the K-T boundary at Site 738 as evidence (see also Huber et al., 1994; Keller and MacLeod, 1994). We do not argue that Danian sediments may contain reworked Maastrichtian species, as indeed any sedimentary interval may, but we disagree that the consistent presence of these small species in sections across latitudes can be attributed to reworking, and that the Danian isotopic signal of species can be explained as artifact of reworking.

We suggest that these species are K-T survivors for two major reasons. (1) They are ecological generalists able to survive the K-T environmental changes, whereas the larger complex tropical and subtropical species are not. (2) Environmental effects of the K-T impact diminished into higher latitudes, as suggested by $\delta^{13}C$ values that indicate a relatively minor decrease in primary productivity in high latitudes as compared with low latitudes (e.g., Keller and Lindinger, 1989; Zachos et al., 1989; Keller et al., 1993; Barrera and Keller, 1994).

Environmental changes and the nature of the mass extinction between the extremes of the northern boreal sea (Denmark and Kazakhstan) and the low-latitude Tethys are still relatively unknown. This shortcoming is because K-T sequences with nearly continuous sedimentation and good microfossil preservation are very rare and currently only reported from Bjala in eastern Bulgaria (Preisinger et al., 1993a, 1993b; Rögl et al., 1996). We chose to study the Bjala sections in order to obtain a quantitative record that would allow evaluation of the mass extinction and environmental changes in this transitional environment and permit comparison with both low- and high-latitude records. To this end we analyzed the biostratigraphy, stable isotopes, bulk rock compositions, clay minerals, trace element abundances, and quantitative changes among planktic foraminiferal assemblages.

PREVIOUS STUDIES IN BULGARIA

The K-T boundary in eastern Bulgaria was first recognized on the basis of planktic foraminifera from boreholes (Juranov and Dzhuranov, 1983), and a subsequent search for outcrops in the vicinity of Bjala revealed a relatively complete K-T transition based on calcareous nannoplankton (Stoykova and Ivanov, 1992; Ivanov and Stoykova, 1994; Sinnyovsky and Stoykova, 1995). Geochemical and planktic foraminiferal data were given in Preisinger et al. (1993a, 1993b) and Rögl et al. (1996).

In those publications the K-T biostratigraphy is based primarily on calcareous nannoplankton, the most complete sequences containing the *Micula prinsii* zone in the topmost 14–17 m of the Maastrichtian, and zone NP1, spanning the basal 4 m of the Danian. The K-T boundary was recognized on the basis of a 2–3-cm-thick dark clay layer containing an Ir anomaly of 6.1 ppb (Preisinger et al., 1993a). A second, smaller Ir and Co enrichment was recognized 7–8 cm above this interval in a marly limestone layer, and was considered reworked. The first Danian nannofossil species *Biantholithus sparsus* and *Cyclagellosphaera alta* are reported from this marly limestone layer that also contains blooms of *Thoracosphaera operculata* and *Braarudosphaera bigelowii* (Preisinger et al., 1993a, 1993b; Ivanov and Stoykova, 1994). Rögl et al. (1996) reported the range of four Maastrichtian planktic foraminifer species (*Hedbergella monmouthensis, Guembelitria cretacea, Racemiguembelina intermedia, Abathomphalus mayaroensis*) and six undifferentiated genera in the 90 cm below the K-T boundary. They observed the first Danian species (*Woodringina hornerstownensis, W. claytonensis, Globoconusa predaubjergensis*) 2 cm above the base of the K-T clay layer.

GEOLOGICAL SETTING AND LOCATION

The studied outcrops are exposed along the Black Sea coast, close to the town of Bjala (Fig. 1). Tectonically, this area belongs to the Luda Kamchia unit of the Stara Planica zone, which is part of the High Balkan mountain range (Ivanov, 1983, 1988). The Bjala area was a well-differentiated basin characterized by rhythmic sedimentation of hemipelagic marls and marly limestones during the Late Cretaceous. Deposition of more detrital and turbiditic sediment began in the early Paleocene and appears to reflect the first pulse of alpine tectonic activity. Subsequent tectonic activity resulted in the numerous nappes, thrust folds, and faults that can now be observed in the area (Ivanov, 1988).

Bjala-1 is located 800 m north of a trench leading down from the town of Bjala to the beach (Figs. 1 and 2). This section corresponds to the Bjala 2b section of Ivanov and Stoykova (1994) and Preisinger (1994), and can be observed laterally over 15–20 m. This locality represents the best exposure and structurally least disturbed outcrop of the K-T transition known to date in Bulgaria. The area surrounding Bjala-1 is strongly tectonized with steep east-west faults and vertical displacements of 10–20 m. The beds dip 20°–30° southwest (Figs. 2A and 3A). About 2 km to the north is the Bjala-2 section (Figs. 1 and 3B), located along the beach close to the Bjala River outlet (near the Bjala-2 locality of Ivanov and Stoykova, 1994; Preisinger, 1994). This section is more tectonically disturbed than Bjala-1, and small-scale faults cut the K-T boundary clay layer, making it difficult to trace laterally over any distance.

METHODS

We collected 107 samples at Bjala-1 (Fig. 3A) at 15–20 cm intervals for the first 5 m of the section, 5–10 cm intervals for the K-T transition, and 20–30 cm intervals for the 8 m of lower Paleocene sediments. Due to the tectonic disturbance at the Bjala-2 outcrop, only 15 samples were collected at that locality (Fig. 3B). In the field, the sections were measured and the lithology was examined and described with particular emphasis on structural disturbance (faults and folds), bioturbation, trace fossils, macrofossils, and erosion surfaces (e.g., undulating surfaces, clasts, truncated trace-fossil burrows).

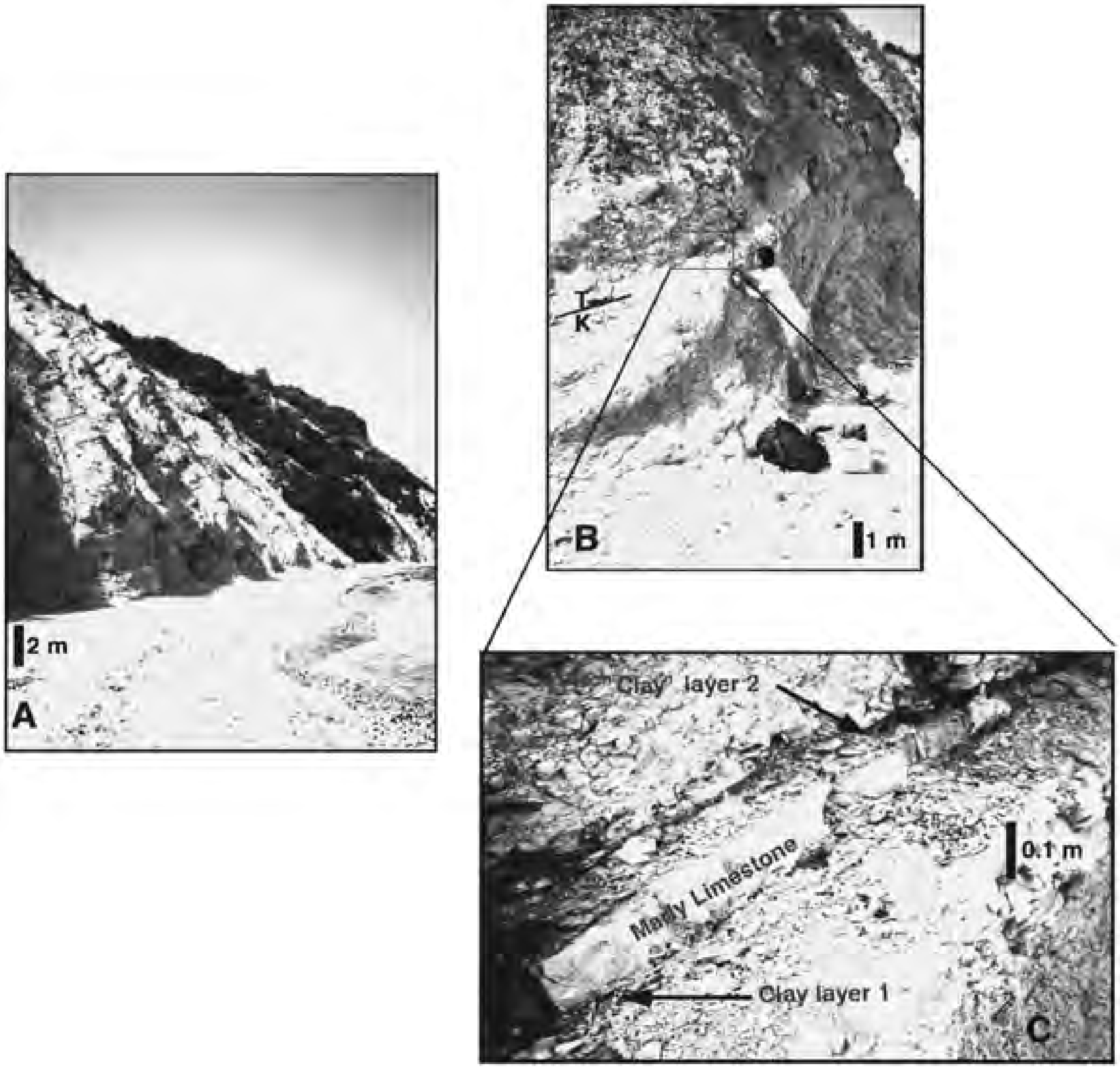

Figure 2. Photographs of Bjala-1 outcrop. A: Alternating marl and marly limestone layers of zone CF1, which spans last 300 k.y. of Maastrichtian. B: View of Cretaceous-Tertiary (K-T) boundary transition at Bjala-1. C: K-T boundary at Bjala-1 showing clay layer 1 (K-T) and clay layer 2 separated by 7–10-cm-thick marly limestone layer.

For foraminiferal studies, samples were processed following the standard method of Keller et al. (1995). Sediments were washed over a 63 µm sieve for the Maastrichtian samples and <38 µm sieve for the early Danian samples. The 38 µm sieve size was used for the early Danian because the first evolving Tertiary species in the boundary clay are usually smaller than 63 µm (see Keller et al., 1995). If necessary, foraminifera were further cleaned by ultrasonic agitation for 10–15 s, until a clean residue was obtained, and then washed again. The samples were oven dried at 50 °C. Planktic foraminifera are abundant and relatively well preserved, although recrystallized. From each sample, ~250–300 specimens were picked from random sample splits (using a microsplitter) from two size fractions, >63 µm and >150 µm. The two size fractions were analyzed in order to obtain statistically significant representations of the smaller and larger species populations. The entire sample was searched for rare species and these were included in the species range distributions and species richness data. The 38–63 µm size fraction was examined for small Danian species, but none were observed in the Bjala sections.

Major faunal assemblage changes noted in the quantitative analysis of washed residues were also examined in thin sections in order to evaluate potential preservation effects. Because identification of species in thin sections is more difficult than in washed residues, no quantitative abundance data were obtained from these samples. However, the overall species assemblages were evaluated on the basis of relative abundances of easily identifiable groups, such as heterohelicids, globotruncanids, and rugoglobigerinids, and compared with the quantitative counts.

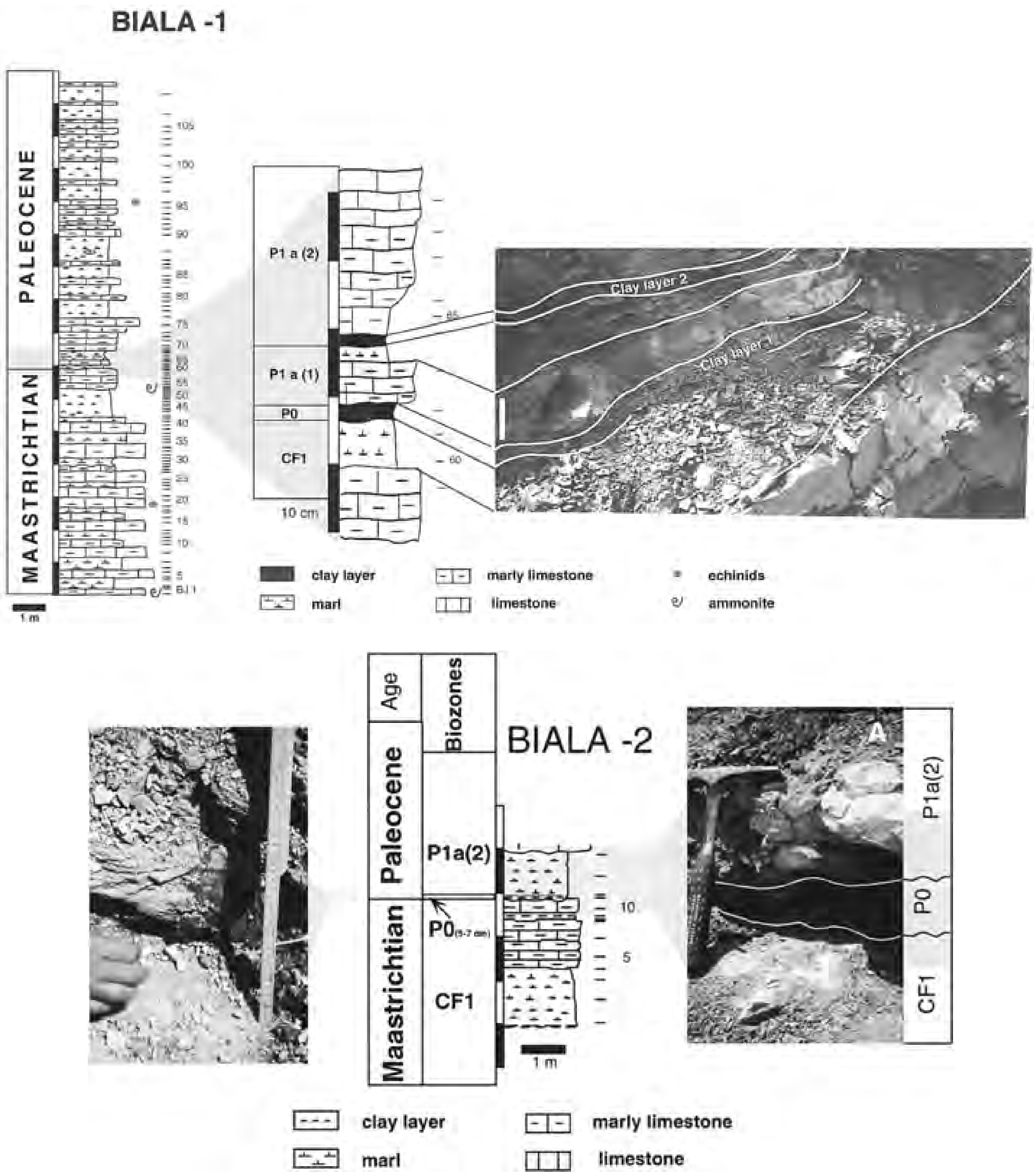

Figure 3. A. Lithology and biostratigraphy of Bjala-1 section and photo of Cretaceous-Tertiary (K-T) boundary transition showing presence of boundary clay layer 1 and second clay layer within zone Pla, ~10 cm above it. Note that two clay layers are separated by 7–10-cm-thick marly limestone layer with undulose erosional contact that marks hiatus. B: Lithology and biostratigraphy of Bjala-2 section. K-T boundary clay layer (P0) is ~2–3 cm thick (right side), but varies due to infilling of depressions and forms lenses as thick as 5–7 cm (left side). Note that this clay layer is between marly limestones with undulating, irregular erosional contacts that mark hiatuses at K-T boundary (CF1-P0) and in early Danian *P. eugubina* zone (P0-Pla[2]).

Whole-rock and clay mineral analyses were conducted at the Geological Institute of the University of Neuchatel, Switzerland, based on X-ray diffraction (XRD) analyses (SCINTAG XRD 2000 diffractometer). Sample processing followed the procedure outlined by Kübler (1987) and Adattey et al. (1996). Whole-rock compositions were determined by XRD (SCINTAG XRD 2000 diffractometer) based on methods described by Klug and Alexander (1974) and Kübler (1983). This method for semiquantitative analysis of the bulk-rock mineralogy (obtained by XRD patterns of random powder samples) uses external standards. The intensities of selected XRD peaks that characterize each clay mineral in the <2 µm size fraction (e.g., chlorite, mica, kaolinite, smectite) were measured for semiquantitative estimates. Therefore, clay minerals are given in relative percent abundances without correction factors. The percent smectite is estimated by using the method of Moore and Reynolds (1989).

We selected 10 samples for trace element analysis across the K-T transition. The very low trace element contents required preconcentration, and matrix elimination prior to detection with inductively coupled plasma-mass spectrometry (ICP-MS) was achieved by fire assay with NiS collection as described in detail in Cubelic et al. (1997). ICP-MS analysis was performed using platinum group element (PGE) multielement standards Claritas (SPEX Industries Grasbrunn, Germany) and Tm and Bi as internal standards. Accuracy was checked by means of WPR-1 and SARM-7 standard reference materials. Based on reference samples analyzed in the laboratory at the University of Karlsruhe over several years, recovery was estimated to be better than 85%, which is in the range of the efficiency usually obtained by NiS fire assay (Reddi et al., 1994; Zereini et al., 1994). Detection limits are 0.05 ng/g Ir, 0.1 ng/g Rh, 0.4 ng/g Pd, and 0.4 ng/g Pt. Detection limits are mainly dependent on blanks of the NiS fire assay.

Stable isotope analyses were conducted on the bulk-rock carbonate samples at the stable isotope laboratory of the University of Bern, Switzerland, using a VG Prism II ratio mass spectrometer equipped with a common acid bath (H_3PO_4). The results are reported relative to the Vienna Peedee belemnite standard reference material with a standard error of 0.1‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$.

LITHOLOGY

At the Bjala-1 locality, ~16 m of relatively undisturbed alternating gray marl and light yellow to beige marly limestone layers are exposed (Fig. 3A). The lower 5.5 m of the section are characterized by alternating marl and marly limestone layers of approximately equal thickness (30–40 cm). The upper surfaces of the marly limestone layers are undulating, frequently bioturbated (*Chondrites, Thalassinoides*), and occasionally slightly glauconitic. These surfaces are indications of nondeposition, or possibly erosion. Between 67 cm and 150 cm below the K-T boundary, the sediments are more marly and interbedded with discrete 2–3-cm-thick calcareous layers. Overlying this interval is a 60-cm-thick white to gray marly limestone with an undulating, bioturbated upper surface (Fig. 3A). This surface is overlain by a 7-cm-thick gray bioturbated marl with an undulating upper surface that marks the top of the Maastrichtian and suggests erosion prior to deposition of the K-T boundary clay. The boundary clay consists of a 2–3-cm-thick, dark gray to black clay layer that contains an Ir anomaly of 6.1 ppb (Preisinger et al., 1993a) and is labeled "clay layer 1" (Fig. 3A).

Above the K-T boundary clay layer is a 7–10-cm-thick, white to beige marly limestone layer with undulating surfaces at the bottom and top suggesting erosion, a conclusion supported by a strongly bioturbated (*Chondrites*) upper surface. This limestone layer is laterally continuous, although variable in thickness. Above this limestone layer is a 1–2-cm-thick marl layer, followed by a 2-cm-thick clayey marl layer which we labeled "clay layer 2" (Fig. 3A). The overlying sediments consist of alternating marl and marly limestone layers with occasional thin clayey intercalations. The upper part of the section consists of 30–50-cm-thick marl layers that are interbedded with thin, light gray, marly limestone layers.

The Bjala-2 section is significantly tectonically disturbed, and therefore only the K-T transition interval was examined. The first 1.20 m of the section consist of light gray marl (Fig. 3B). Above the marl are 1.1 m of marly limestone layers having strongly undulating and bioturbated surfaces. A 1–3-cm-thick dark brown to dark gray clay layer represents the K-T boundary clay and contains a 2.1 ppb Ir anomaly. The thickness of this clay layer is variable and may reach 6 cm, infilling depressions and cracks in the underlying marly limestone. A 1.05-m-thick gray marl layer with echinoid fragments overlies the K-T boundary clay. Above the marl is a light beige limestone with an undulating upper surface (Fig. 3B).

BIOSTRATIGRAPHY

Macrofossils are rare at Bjala-1. An unidentifiable ammonite mold was collected 60 cm below the K-T boundary. Ivanov (1993) noted common ammonites at 10 m below the K-T boundary, only very rare specimens in the last 10 m of the Maastrichtian, and the last ammonite at 40 cm below the K-T boundary. Echinoid fragments were observed in the lower 3.5 m of the section and in the Danian at 12 m (Fig. 3A).

In this study the biostratigraphy of the Cretaceous-Tertiary transition in the Bjala sections is based on quantitative analysis of planktic foraminifera. We use the biozonation of Keller (1993) and Keller et al. (1995), shown in Figure 4, in comparison with the zonal scheme and paleomagnetic correlation of Berggren et al. (1995), and the calcareous nannofossil zonation of Martini (1971). Zones P0 and Pα in the Berggren et al. (1995) zonal scheme are equivalent to zones P0 and Pla of Keller et al. (1995). However, it is difficult to correlate these two zonal schemes above this interval for reasons of methodology. Zones Pla, Plb, and Plc of Berggren et al. (1995) are

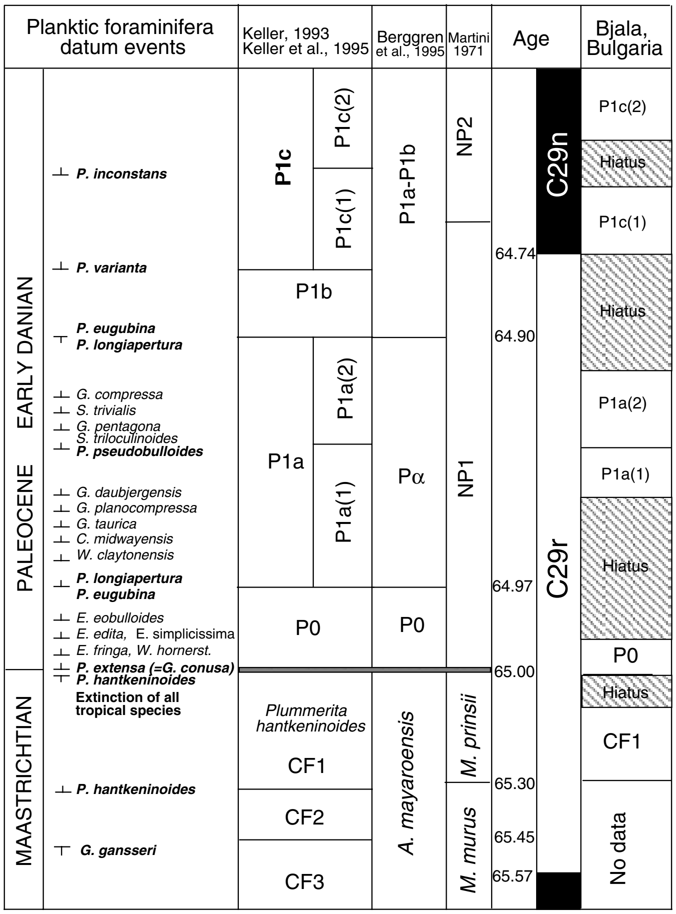

Figure 4. Late Maastrichtian–early Paleocene plankton zones and time scale. Correlation of commonly used planktic foraminiferal and calcareous nannofossil zonations as applied at Bjala, Bulgaria. Note presence of short intrazonal hiatuses recognized in upper part of CF1, at P0-Pla(1), Pla(2)-Plc, and Plc intervals. Lithologic observations (e.g., undulating erosional surfaces) indicate that additional short hiatuses may be present. See Figure 3A for rock unit symbols.

based on the successive first appearances of *Subbotina triloculinoides, Globanomalina compressa*, and *Praemurica inconstans*, all of which they reported to originate well above the extinction of *Parvularugoglobigerina eugubina*. However, *S. triloculinoides* and *G. compressa* have been observed to first appear in the upper part of the range of *P. eugubina* (see MacLeod and Keller, 1991a, 1991b; Keller et al., 1995). The difference in the reported first appearances is apparently due to the size fraction analyzed. Keller (1988, 1993; Keller et al., 1995, 2001) documented that early Danian species are very small (38–63 μm) and generally do not reach sizes larger than 100 μm until zone Plc (Fig. 4), ~500 k.y. after the K-T boundary. When only the >100 μm size fraction is analyzed, the first appearances of these species are delayed as a function of size, although these species are present earlier in the smaller size fraction (both 38–63 μm and >63 μm size fractions are analyzed in this study).

There is generally good agreement between nannofossil and planktic foraminiferal zones (e.g., Henriksson, 1993; Berggren et al., 1995; Pardo et al., 1996; Li and Keller, 1998a). The latest Maastrichtian *Micula prinsii* zone is an excellent marker species that first appears near the base of paleomagnetic chron 29R, ~500 k.y. before the K-T boundary. The *M. prinsii* zone thus encompasses planktic foraminiferal zones CF1 and CF2, which span the last 450 k.y. of the Maastrichtian (Li and Keller, 1998a). Zone CF1 spans the last 300 k.y. of the Maastrichtian (Pardo et al., 1996). The early Danian zone NP1 spans foraminiferal zones P0, Pla, and Plb of Keller (1993) and Keller et al. (1995), and zone NP2 begins near the base of zone Plc (Fig. 4). The stratigraphic resolution of calcareous nannoplankton is therefore not comparable to that of planktic foraminifera in the early Danian.

MAASTRICHTIAN

The nearly 7 m of Maastrichtian marl and marly limestone layers exposed at Bjala-1 contain diverse, abundant planktic foraminiferal assemblages indicative of zone CF1, and calcareous nannofossils (*Micula prinsii* zone; Ivanov and Stoykova, 1994). *Plummerita hantkeninoides*, the index species for zone CF1, is present but rare (Fig. 4). The undulating surface at the top of the Maastrichtian suggests the presence of a short hiatus in both Bjala-1 and Bjala-2 sections. However, very little of the latest Maastrichtian zone CF1 may be missing, as suggested by the thickness of this zone (7 m), compared to Tunisian sections (6 m, Abramovich and Keller, 2001). Other short hiatuses may be present in the lower part of the section, as indicated by the lithological changes and undulating and glauconitic surfaces. Current biostratigraphic resolution is insufficient to detect these short hiatuses.

A total of 53 species were identified, although most faunal assemblages contain between 30 and 40 species (Fig. 5). This species richness is significantly lower than the species diversity generally observed in the Tethys (e.g., 55–65 species in Tunisia, Israel, Italy, Spain; Keller et al., 1995; Apellaniz et al., 1997; Luciani, 1997; Abramovich et al., 1998), and reflects the location of Bjala in the northern Tethys. The assemblages observed are generally more characteristic of middle than low latitudes, as indicated by the high abundances of *Globotruncana arca* (to 40% in >150 μm) and *Heterohelix globulosa* (Fig. 6; see also Malmgren, 1991; Nederbragt, 1998; Li and Keller, 1998a), rarity of *P. hantkeninoides* and low-latitude globotruncanids, and the relatively low abundance of rugoglobigerinids (5%–10%). For most of zone CF1, species populations fluctuated, but in the 67 cm below the K-T boundary the relative abundance of all large-sized species decreased significantly and permanently (Fig. 6). All tropical and subtropical species disappeared at or below the K-T boundary. In contrast, the small (63–150 μm) ecological generalist species (Keller, 1993, 1996) increased during this time, suggesting a major environmental change and increased stress preceding the K-T boundary.

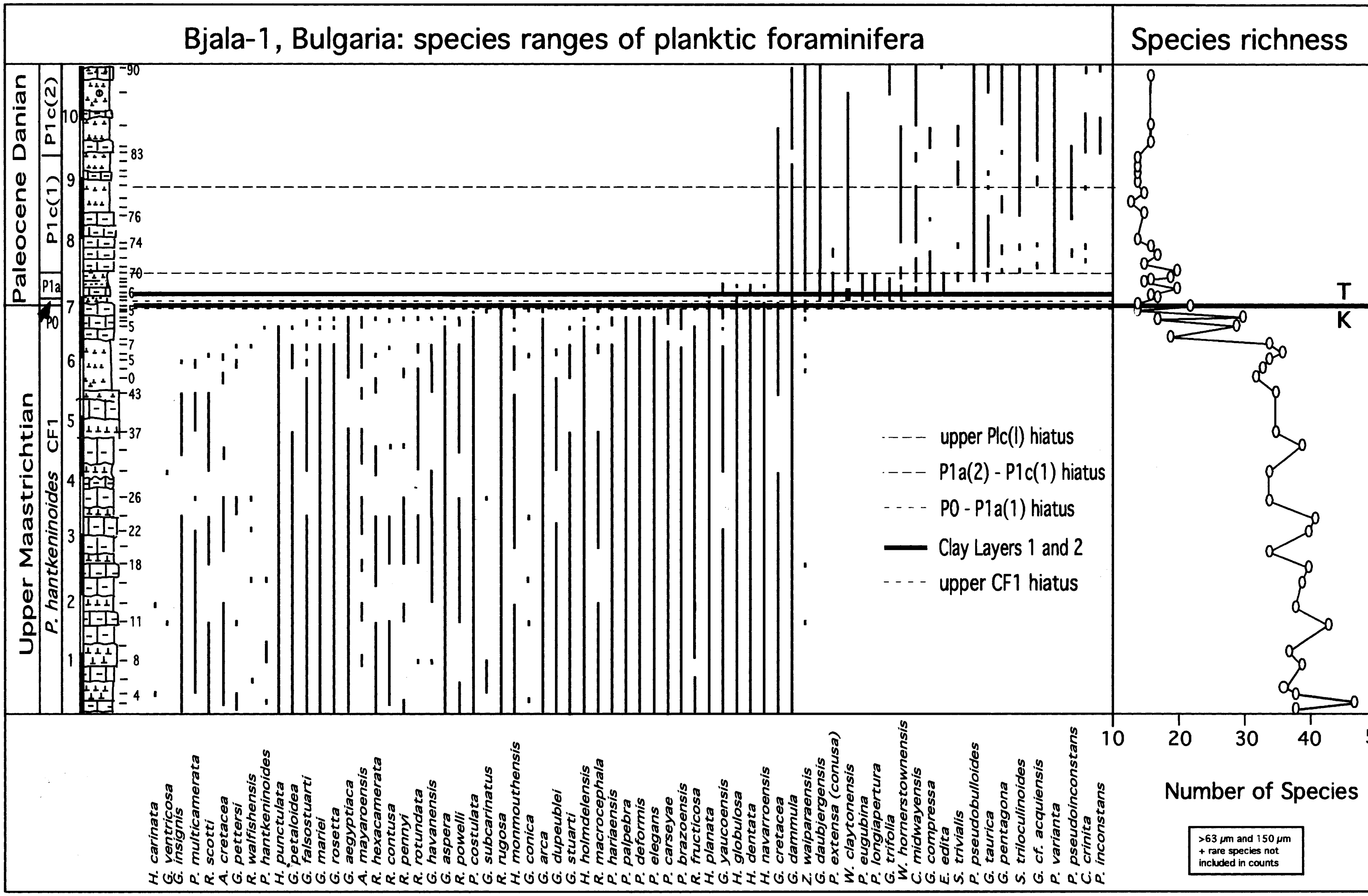

Figure 5. Species richness and biostratigraphic ranges of species across Cretaceous-Tertiary (K-T) boundary at Bjala-1, Bulgaria. Note decreased species richness in upper half of zone CF1, followed by rapid, but variable decrease in 67 cm below K-T boundary. Decreased diversity reflects environmental changes and increasing biotic stress that resulted in local species disappearances and migrations. See Figure 3A for rock unit symbols.

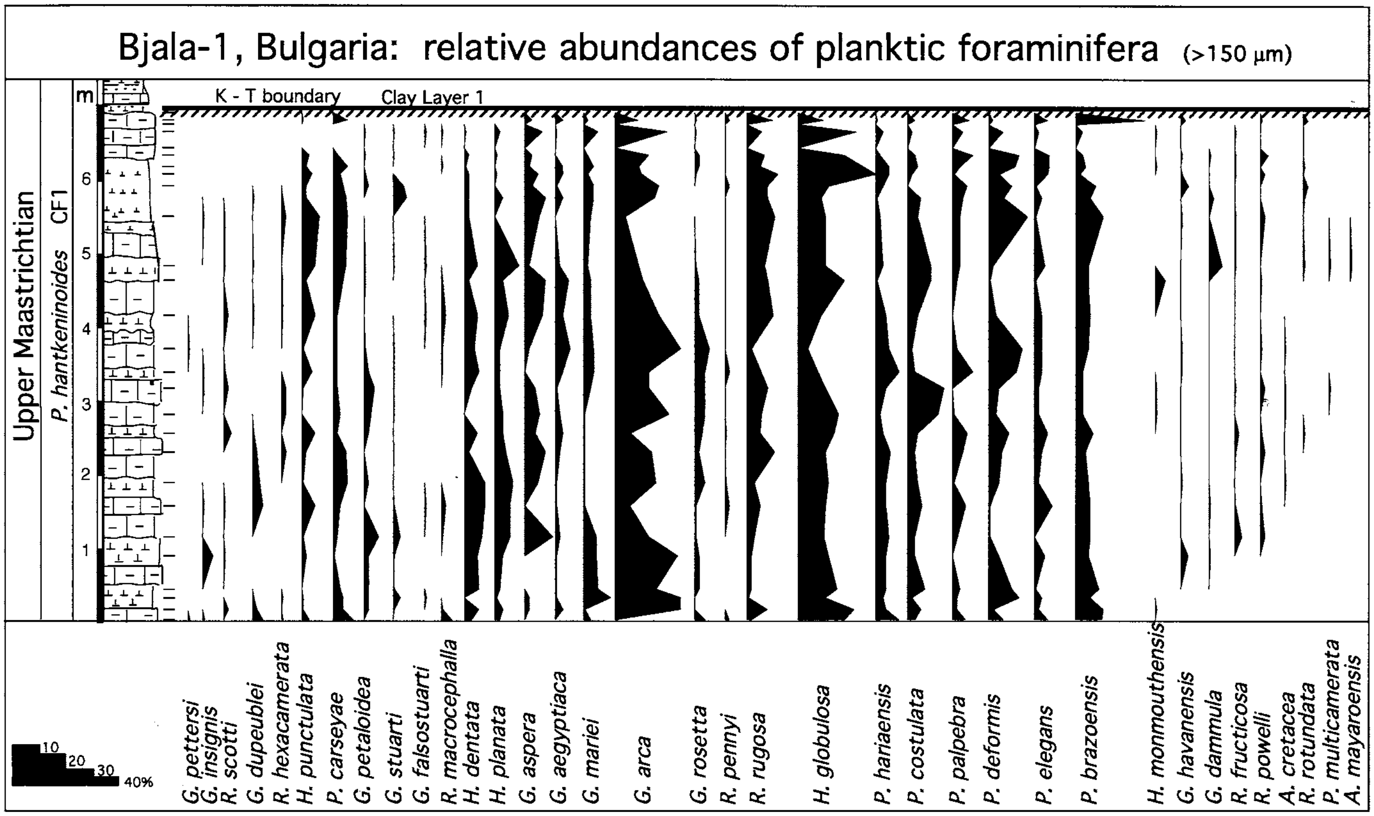

Figure 6. Relative abundance changes in species populations of planktic foraminifera (>150 µm) during last 300 k.y. of Maastrichtian at Bjala-1, Bulgaria. Note high abundance of *Globotruncana arca* and *Heterohelix globulosa*, species that thrived in relatively cool middle latitudes. Major environmental change is indicated by general decrease in all larger sized species in top 67 cm of Maastrichtian interval. See Figure 3A for rock unit symbols.

The most unique aspect of the latest Maastrichtian Bjala-1 fauna is the dominance (60%–80%) of *Guembelitria dammula*, which has not been reported elsewhere (Fig. 7). *Guembelitria dammula* is a very high spired and large triserial species that has a morphology similar to that of the smaller *G. danica*, which is common in northern boreal seas (e.g., Denmark, Kazakstan; Keller et al., 1993; Pardo et al., 1999). *G. dammula* has been observed in late Maastrichtian sediments of Madagascar, which also suggests that this species is endemic to higher latitudes (Abramovich, 2000, written commun.). Quantitative data from other localities are needed before environmental affinities of *G. dammula* can be interpreted.

Species richness

Species census data provide an estimate of the number of species present in a faunal assemblage. In this study, the species richness of each sample at Bjala-1 is based on three types of records: (1) the number of species present in a count of 250–300 individuals in the >150 µm size fraction of a random sample split (using a microsplitter), (2) the number of species present in a count of 250–300 individuals in the >63 µm size fraction of a random sample split (using a microsplitter), and (3) a careful search of the remaining sample residues of the >63 µm and >150 µm size fractions for rare species that were not observed in either of the two counts. The species richness curve in Figure 5 thus reflects the union of these three species tallies for each sample and therefore is not necessarily the same as the plotted species ranges, which are based on the two counts.

Species richness averaged 40 species in the lower 3.5 m of the Maastrichtian zone CF1, and decreased to an average of 35 species in the upper 3 m (Fig. 5). A major drop in species richness occurred in the top 67 cm of the Maastrichtian, coincident with decreased abundance of large species (Fig. 6). However, species variability is high (14–30 species) in this interval and suggests that at least part of the decrease is due to preservation bias. Thin sections from this interval show the presence of impoverished species assemblages dominated by small (63–150 µm) ecological generalists (e.g., small biserial species and guembelitria), similar to those observed in the >63 µm faunal counts, whereas species with larger morphologies (>150 µm) are generally few to rare (e.g., globotruncanids, rugoglobigerinids, and large heterohelicids). This suggests that a significant faunal change occurred prior to the K-T boundary that differentially affected more specialized large species, leading to decreased populations, whereas the inferred ecological generalist

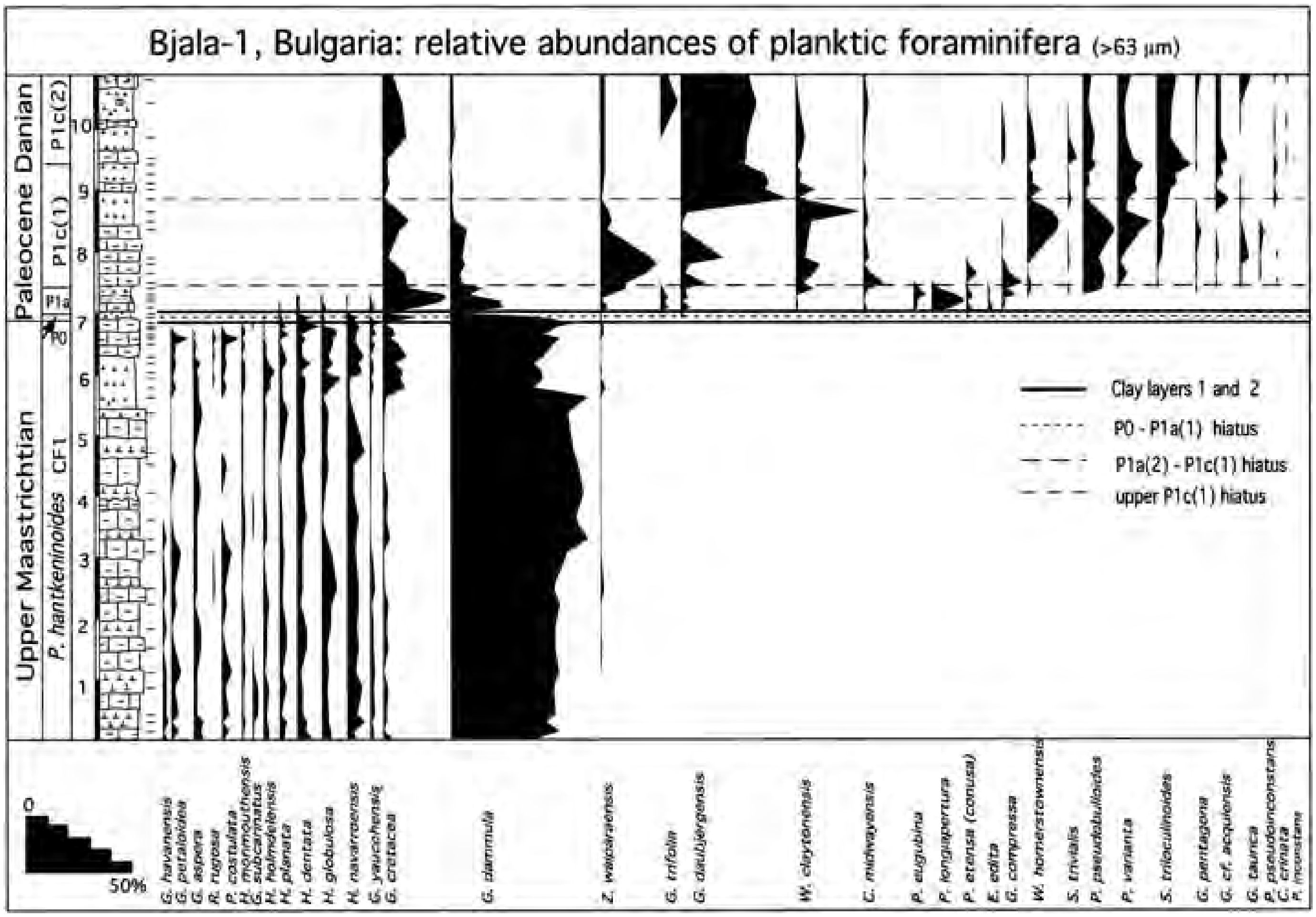

Figure 7. Relative abundance changes in species populations of planktic foraminifera in >63 μm size fraction across Cretaceous-Tertiary (K-T) boundary at Bjala-1, Bulgaria. Note that this size fraction contains only ecological generalists, many of which are known to be K-T survivors. What is unique to Bulgaria is dominance of triserial species *Guembelitria dammula* in late Maastrichtian. Ecological generalists thrived during biotic crisis that led to terminal decline of larger sized planktic foraminifera at end of Maastrichtian. Abrupt faunal changes in early Danian mark hiatuses. See Figure 3A for rock unit symbols.

species remained unaffected or thrived. The high species richness variability in this interval may reflect local species disappearances and reappearances due to migration from the Tethys during climate fluctuations.

K-T BOUNDARY

At Bjala-1, the K-T boundary clay consists of a 2–3-cm-thick clay layer (labeled clay layer 1) that contains a 6.1 ppb Ir enrichment (Preisinger et al., 1993a). This clay layer 1 contains a planktic foraminiferal assemblage dominated by *Guembelitria* (75% *G. dammula*) and common small biserial Maastrichtian species (*Heterohelix globulosa, H. dentata, H. navarroensis*, and *H. planata*, Fig. 8). A few large and possibly reworked Maastrichtian species are also present. Rögl et al. (1996) reported the first occurrence of Danian species *Woodringina hornerstownensis, W. claytonensis*, and *Globoconusa predaubjergensis* 2 cm above the base of the clay layer. In the overlying marly limestone layer, we observed abundant very small Danian planktic foraminifera, including *Parvularugoglobigerina extensa* (formerly *Globoconusa conusa), Globoconusa daubjergensis, G. predaubjergensis, Woodringina claytonensis, W. hornerstownensis*, abundant *Guembelitria dammula*, and *Parvularugoglobigerina eugubina* and *P. longiapertura*, the index species for the early Danian zone Pla (Figs. 4 and 8). However, the simultaneous first appearance of these species immediately above clay layer 1 indicates an interval of nondeposition or a short hiatus between the clay and overlying marly limestone (zone P0-Pla[l]); most of the lower part of zone Pla (*P. eugubina* zone) missing. A hiatus is also suggested by the abrupt lithologic change from clay to marly limestone with undulating surface.

Only one clay layer was observed at the nearby Bjala-2 section. This clay layer represents the boundary clay, as indicated by the presence of an Ir anomaly of 2.03 ppb. As at Bjala-

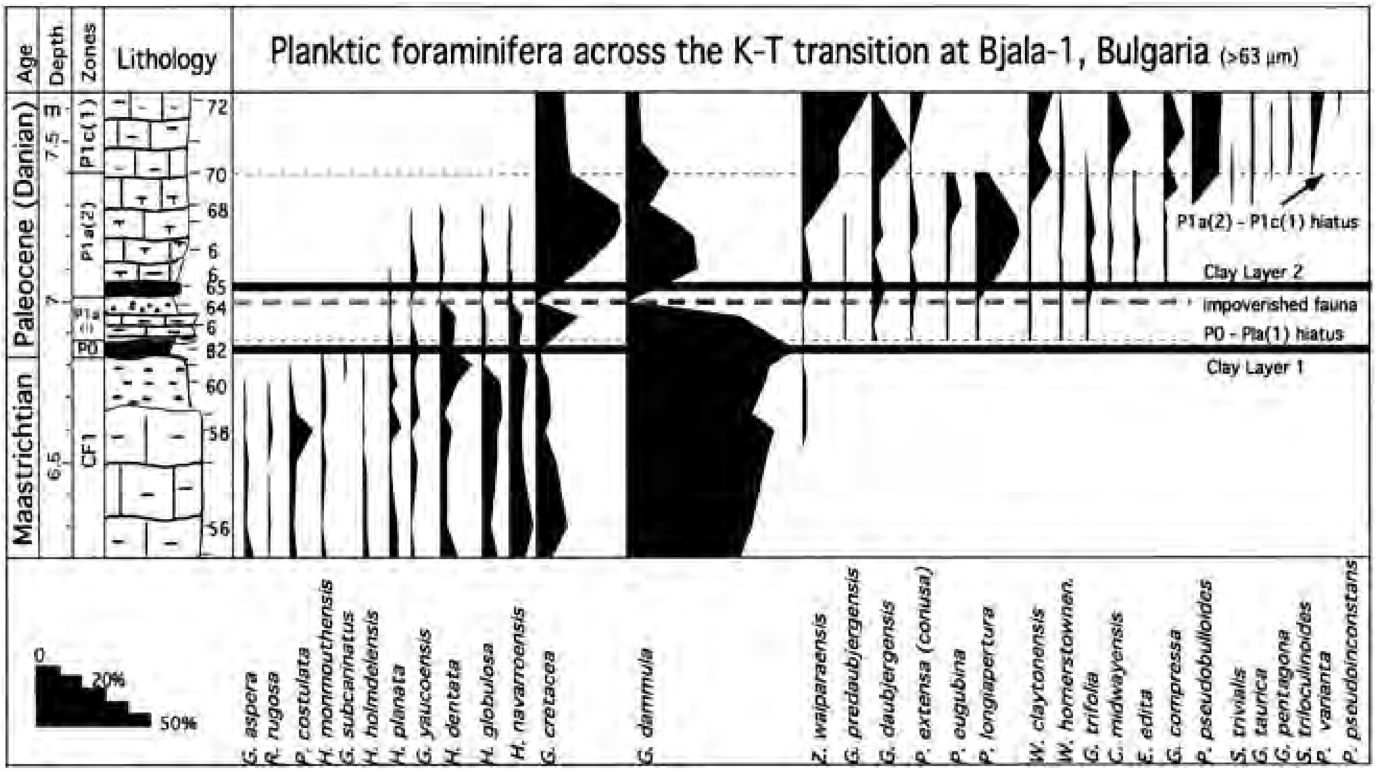

Figure 8. Details of relative abundance changes in planktic foraminifera across Cretaceous-Tertiary (K-T) boundary at Bjala-1, Bulgaria, in >63 µm size fraction. Note dominance of *Guembelitria dammula* and its decreased abundance in early Danian, and unusually high abundance of *Heterohelix navarroensis* in early Danian. First appearance of eight new Danian species above boundary clay layer marks hiatus; most of lower part of *P. eugubina* zone, or Pla(1) is missing. Note also that second clay layer in upper part of *P. eugubina* zone, or Pla(2), also marks hiatus, as indicated by abrupt disappearance of *P. eugubina* and *P. longiapertura*, and lithological change and undulating erosional surface. See Figure 3A for rock unit symbols.

1, this clay layer contains small Maastrichtian heterohelicids, guembelitrids, and hedbergellids, as well as rare reworked globotruncanids and rugoglobigerinids; however, it contains no Danian species. The first Danian species are observed in the overlying marl, which contains a well-developed early Danian assemblage with specimens predominantly in the >63 µm size fraction. The assemblage includes *P. eugubina, P. longiapertura, G. conusa, G. daujergensis, G. dammula, G. cretacea, P. pseudobulloides*, and *C. midwayensis*. This species assemblage and the relatively large size of the specimens indicate zone Pla(2) (upper part of *P. eugubina* zone). Zone Pla(1) is characterized by generally smaller size (>63 µm) and absence of *P. pseudobulloides*. Thus at Bjala-2, biostratigraphy indicates that an early Danian hiatus spans the interval from the boundary clay to Pla(2).

DANIAN

A second clay, clay layer 2, is present in the early Danian zone Pla of Bjala-1. This clay layer, separated from the boundary clay by thin limestone and marl layers (Fig. 3A), contains small Ir (0.22 ppb), Ru (0.30 ppb), and Rh (0.13 ppb) anomalies and a larger Pd anomaly (1.34 ppb). Although this clay layer was not mentioned by Preisinger et al. (1993a, 1993b), it is clearly visible in their photo of the section. The small Ir and Co anomalies noted by Preisinger et al. (1993a) are present in the marly limestone layer between the two clay layers (A. Preisinger, 2000, personal commun.). The lithology, biostratigraphy, and geochemistry of these two clay layers indicate that they are separate depositional events.

In clay layer 2, *G. compressa, Chiloguembelina midwayensis*, and *Eoglobigerina edita* first appear, followed by *Parasubbotina pseudobulloides, Subbotina trivialis*, and *G. taurica* (Fig. 8). This assemblage marks the upper part of the *P. eugubina* zone or Pla(2). Early Danian planktic foraminifera are more abundant and larger than in the interval below, particularly *P. longiapertura* and *P. eugubina*, whereas *Guembelitria dammula* decreased. These abundance and test size changes are characteristics of the upper part of the *P. eugubina* zone or Pla(2). A short hiatus is suggested by this abrupt faunal and lithological change from clay to limestone.

The Pla(2) assemblage continued for 27 cm (sample 70), where the Pla index species *P. eugubina* and *P. longiapertura* disappeared coincident with the first appearance of *G. penta-*

gona, Subbotina triloculinoides, and the Plc index species *Parasubbotina varianta* (Fig. 8). The juxtaposition of the Pla and Plc index species suggests another condensed interval or short hiatus. The abrupt faunal change at this interval is also evident in the decreased relative abundance in triserial species (*G. cretacea, G. dammula*) and subsequent increased abundance in biserial species (*Zeauvigerina waiparaensis, Woodringina claytonensis, Chiloguembelina midwayensis*), as well as *G. daubjergensis G. compressa*, and *P. pseudobulloides* (Figs. 7 and 8). Triserial species continued to decrease in Plc(1), and all biserial and trochospiral species nearly disappeared coincident with the onset of dominant *G. daubjergensis* just below the Plc(1)-Plc(2) boundary, which is marked by the first appearance of *P. inconstans*. An abrupt lithologic change from marl to limestone with an undulating surface marks this faunal change and suggests another short hiatus.

Interpretation

Planktic foraminiferal biostratigraphy and assemblage changes indicate that the early Danian at Bjala is very condensed and probably underwent significant erosion or intermittent periods of nondeposition at the P0-Pla, Pla-Plc, and Plc(1)-Plc(2) intervals. An incomplete sedimentary record for the Pla zone at Bjala-1 is also suggested by the fact that this zone interval spans only 40 cm, as compared with more than 4 m at El Kef and Elles in Tunisia (Keller, 1988; Karoui-Yakoub et al., 2001). Hiatuses are frequently observed in early Danian sections at these stratigraphic intervals in marine sections (MacLeod and Keller, 1991a, 1991b; Keller and Stinnesbeck, 1996).

Previous workers have argued that eastern Bulgaria has one of the most continuous sediment records across the K-T transition (Preisinger et al., 1993a, 1993b; Ivanov and Stoykova, 1994; Rögl et al., 1996). Our study indicates that these sections are far from complete. However, because each hiatus spans less than a biozone, they cannot be detected by biostratigraphy alone, and that is probably why they were not been detected earlier. In this study, the hiatuses were recognized by field observations (e.g., lithological changes, erosional surfaces, bioturbation), high-resolution sampling, and quantitative faunal analysis. In earlier studies, Ivanov and Stoykova (1994) considered the Bjala-1 (their Bjala 2b) section complete on the basis of the presence of early Danian calcareous nannofossil zones. However, because nannofossil zone NP1 corresponds to planktic foraminiferal zones P0, Pla(1), Pla(2), and Plb, and zone NP2 encompasses more than Plc(1) and Plc(2) (Fig. 4), the short early Danian hiatuses within these intervals could not be detected by nannofossil biostratigraphy. Preisinger et al. (1993a, 1993b) and Ivanov and Stoykova (1994) cited the presence of *Braarudosphaera* and *Thoracosphaera* blooms in the limestone immediately above the K-T boundary clay as evidence for continuous sedimentation. However, these blooms are not restricted to the basal Danian, but are characteristic of the early Danian zones Pla(1)-Plc(1) (Keller and v. Salis Perch-Nielsen, 1995; Keller et al., 2001).

MINERALOGY

Bulk rock

In the Bjala-1 section, sediments are generally dominated by calcite (50%–75%), phyllosilicates (10%–40%), and quartz (8%–20%), and there are sporadic occurrences of K-feldspar (0%–3%) and plagioclase (0%–2%, Fig. 9). The first 4.5 m of the analyzed uppermost Maastrichtian do not show significant fluctuations in the bulk-rock composition. With the exception of sample BJ3, plagioclase (low albite) averaged 2%. In the top 2 m of the Maastrichtian, calcite shows an overall increase from a mean value of 70% to 80%. These data suggest a brief period of proportionally higher calcite at the top of zone CF1, ~100 k.y. prior to the K-T boundary.

At the K-T boundary, calcite content dropped abruptly from 78% to 3% and detrital influx increased (Fig. 9). Immediately above the clay layer, calcite content increased to pre-K-T values (80%). In complete K-T transitions, calcite content remained low from zone P0 through at least the lower part of zone Plb (e.g., Zachos et al., 1989; Keller and Lindinger, 1989). The rapid return to higher values at Bjala-1 may reflect the hiatus at the P0-Pla(1) boundary that is recognized by abrupt changes in lithology and planktic foraminiferal assemblages. Calcite also decreased (from 84% to 66%) in the second clay layer and at the base of zone Plc (from 91% to 72%). These intervals coincide with increased detrital influx, abrupt changes in lithology, and faunal assemblages that mark short hiatuses. In the overlying marly limestone, calcite increased to 80%–87%, then decreased gradually to 55%–60%: at the same time, detrital minerals, such as quartz (10%–15%), phyllosilicates (20%–30%), and plagioclase (2%–3%) increased. This enhanced detrital influx prevailed into zone Pld (>20%) and reflects increased erosion due to tectonic activity in the area.

CLAY MINERALS

At Bjala-1, the main clay phases are smectite, illite, chlorite, and kaolinite. Random illite-smectite mixed layers (I/S) with a high percentage of smectite layers and smectite are the predominant clay minerals. We refer to I/S with a high percentage of smectite layers (85%) as smectite (Fig. 10). The constant presence of smectite throughout the section indicates the absence of a strong diagenetic overprint due to burial. The smectite presence implies that the clay minerals are not transformed, and therefore are mostly of detrital origin, and reflect local uplift and/or variations in weathering processes and soil formation in the bordering continental areas (Chamley, 1989; Weaver, 1989). Two types of smectite are present in the Bjala sediments: (1) an almost pure Mg smectite, crystallized and characterized by a high percentage of expandable layers

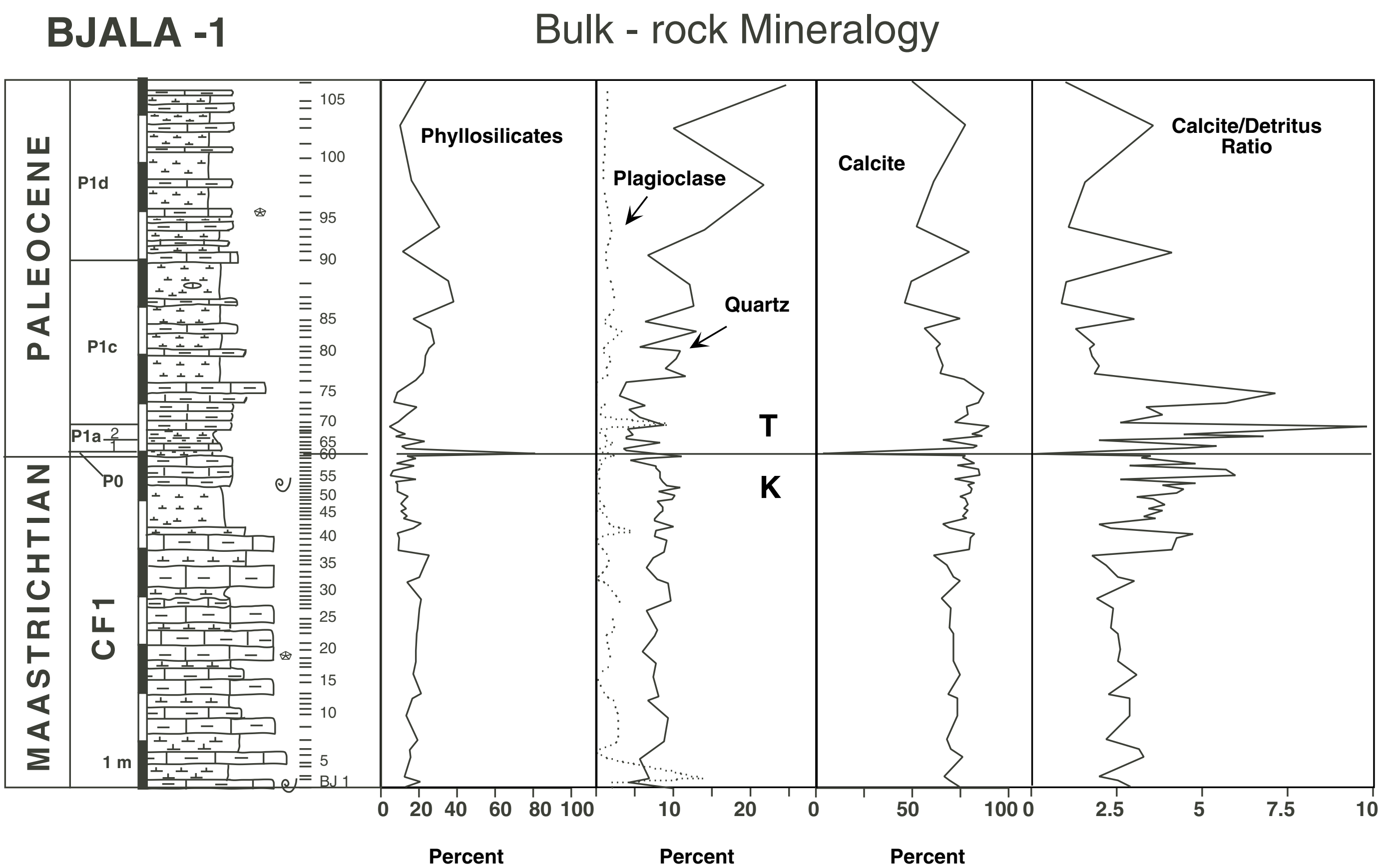

Figure 9. Bulk-rock composition at Bjala-1, Bulgaria. Note that detritus includes quartz, plagioclase, and phyllosilicates. Dominant sedimentary components are calcite and phyllosilicates with minor influx of quartz and plagioclase. Gradually increasing calcite/detritus ratio in upper part of CF1 is followed by decrease just below Cretaceous-Tertiary (K-T) boundary that suggests enhanced erosion and possible hiatus. Note that calcite is abundant directly above zone P0, contrary to more complete K-T sections (e.g., El Kef, Tunisia), and indicates presence of hiatus. See Figure 3A for rock unit symbols.

(>95%), and (2) a chemically more variable smectite characterized by broader XRD peaks and a lower percent of expandable layers (<80%). Environmental scanning electron microscope (ESEM) and energy dispersive X-ray (EDX) analyses of the type 1 (sample 65 from clay layer 2) reveal a weblike morphology and show that the major element is a typical Mg smectite (Si, Al, Mg, with minor Fe and K). Type 2 smectite is characterized by higher Al and K contents (sample 62 from K-T clay layer 1). The Mg smectite may be derived from a volcanic precursor (Elliot et al., 1989; Elliot, 1993), whereas smectite type 2 may be derived from alteration of soils under temperate to semiarid climate conditions (Gaucher, 1981; Hillier, 1995). Cool annual temperatures, low precipitation, and a short time for soil evolution restrict weathering and enhance the direct flux of illite and chlorite eroded from parent rocks. Note that detrital smectite in marine sediments increases during sea-level highstand periods, whereas chlorite, mica, and kaolinite increase during lowstand periods.

Smectite is abundant at the base of the section (80%), but decreased gradually to 60% by 3.5 m and increased to 80% by 6 m (Fig. 10). Rhythmic alternations between marl and marly limestone layers coincide with discrete, but repeated, changes in clay mineral assemblages. Marly limestones contain slightly increased smectite and decreased illite and chlorite (Fig. 10). The overall evolution of the clay mineral assemblages can be shown by the smectite/chlorite + illite (S/IC) ratio, which confirms the trends indicated by the bulk calcite/detritus ratio.

Interpretation

The S/IC ratio and the presence of kaolinite in the lower half of the Maastrichtian interval (Fig. 9) indicate enhanced erosion (due to low sea level and/or tectonic activity) under relatively warm and humid conditions. More temperate and arid conditions and possibly higher sea level prevailed shortly before (1–2 m below) the K-T boundary. The sharp decrease in the S/IC ratio near the top of the Maastrichtian marks a lower sea level and increased detrital input under cool and arid conditions (abundant illite and chlorite) that culminated in the boundary clay layer 1. Above the K-T boundary, the increased

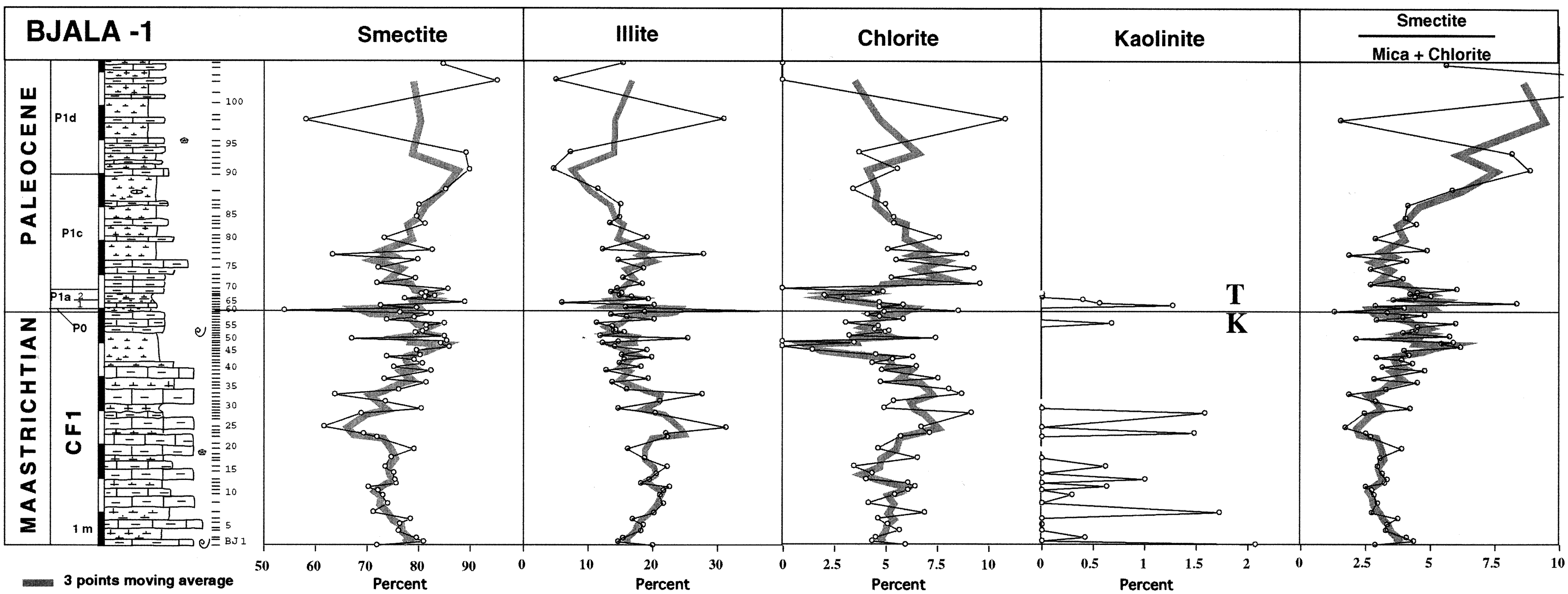

Figure 10. Clay mineral composition (relative percent) and smectite/mica + chlorite ratio (counts by seconds). Note that smectite is most abundant, followed by illite and chlorite, and reflect overall temperate-cool to arid conditions. Minor amounts of kaolinite in lower part of zone CF1 may indicate episodes of slightly warmer and humid conditions. Sharp decrease in smectite/chlorite + illite (S/IC) ratio near top of Maastrichtian marks lower sea level and increased detrital input under cool-arid conditions (abundant illite and chlorite) that culminated in boundary clay layer 1. Similar decrease in S/IC ratio is observed in lower Plc zone. See Figure 3A for rock unit symbols.

S/IC values in clay layer 2 could be due to deposition during a time of high sea level with increasing seasonality, or enhanced alteration of volcanic rocks. At the base of zone Plc, the significantly decreased S/IC and calcite/detritus ratios (Figs. 9 and 10) suggest a sharp sea-level drop. However, the change from a smectite-rich facies to a predominantly illite-chlorite assemblage may be due to increased erosion from a closer source (due to uplift or lower sea level). Beginning in the middle part of zone Plc (Figs. 9 and 10), the detrital input and smectite increased gradually and sediments changed from marl and marly limestone layers to more siliciclastic sediments. This suggests increased tectonic activity in the region, although alteration of volcanic rocks may have contributed to the increased smectite.

STABLE ISOTOPES

During the last 300 k.y. of the Maastrichtian at Bjala-1 (zone CF1), bulk carbonate $\delta^{13}C$ values narrowly fluctuated (1.9‰–2.3‰) for the first 5 m, and slightly increased in the upper meter of the Maastrichtian. At the K-T boundary, there is a relatively small (0.6‰) $\delta^{13}C$ negative shift in clay layer 1, and a small 0.2‰ decrease in clay layer 2. The $\delta^{13}C$ values continued to decrease through the early Danian into zone Plc (Figs. 11 and 12). Assuming that these values are original and that the shape of the curve has not been compromised by hiatuses, the $\delta^{13}C$ values suggest relatively high productivity during the Maastrichtian zone CF1 with a slight increase prior to the K-T boundary. The unusually small (0.6‰) $\delta^{13}C$ shift at the K-T boundary, as compared with 2‰–3‰ in low latitudes, indicates that the characteristic productivity crash did not extend to this middle latitude locality. However, productivity appears to have continued to decrease through the early Danian. A similar $\delta^{13}C$ pattern has been observed in other middle- and high-latitude localities (Keller et al., 1993; Barrera and Keller, 1994).

During the last 300 k.y. of the Maastrichtian at Bjala-1, $\delta^{18}O$ values fluctuated between −2.1‰ and −2.6‰, then decreased to a steady −2‰ in the 1.5 m below the K-T boundary (Fig. 11). In the 10 cm below the K-T boundary, the $\delta^{18}O$ values increased from −2‰ to −1.5‰ in the boundary clay and increased to −1.3‰ in clay layer 2 (Fig. 11). Thereafter, $\delta^{18}O$ values narrowly fluctuated between −1.1‰ and −1.4‰ in zone Plc(1). Assuming that these $\delta^{18}O$ trends reflect paleoenvironmental conditions, they suggest a relatively warm but fluctuating climate with increased cooling near the end of the Maastrichtian. Support for rapid cooling coincident with the K-T boundary and continuing into the early Danian is provided by the marked increase in illite and chlorite (e.g., increased detrital influx). These climate trends are consistent with those observed in low and high latitudes (Zachos et al., 1989; Barrera and Keller, 1994).

DISCUSSION

Paleoenvironment

Planktic foraminiferal assemblages of Bjala-1, eastern Bulgaria, reflect their depositional environment between the Tethys and northern boreal sea and are most similar to middle-latitude assemblages, as indicated by their relatively low species diversity (32–40 species), high abundance of *Globotruncana arca* and *Heterohelix globulosa*, and low abundance of species endemic to low latitudes (Li and Keller, 1998a; Nederbragt, 1998). A strong boreal influence is reflected by the dominance of *Guembelitria dammula*, which has been observed in faunal assemblages from Madagascar (S. Abramovich, 2000, written commun.).

The K-T mass extinction in planktic foraminifera at Bjala is similar to that in low latitudes in that all morphologically complex, large (>150 μm) species disappeared at or before the K-T boundary and only small, morphologically simple species survived (e.g., guembelitrids, heterohelicids, and hedbergellids). However, there are major differences in the patterns of pre-K-T species disappearances. About one-third of the large morphotypes that are known to range up to the K-T boundary in low latitudes disappeared within 1 m below the boundary clay at Bjala-1. Because most of these species are rare, their early disappearance may be partly due to the Signor-Lipps effect, and partly to increasingly unfavorable environmental conditions.

Stable isotope and clay mineral data indicate a cooling climate correlative with the disappearance of tropical and subtropical species. Evidence for late Maastrichtian climate changes were recorded from middle to high latitudes in the Northern and Southern Hemispheres (e.g., Barrera, 1994; Kucera and Malmgren, 1998; Li and Keller, 1998a, 1998b). At DSDP Site 525 in the middle-latitude South Atlantic, a 3–4°C climate warming occurred in deep and surface waters between 65.2 and 65.4 Ma, followed by a 3°C cooling during the last 100 k.y. of the Maastrichtian (Li and Keller, 1998b). At Bjala-1, this warming may be reflected by high calcite content and the presence of kaolinite in the lower 5 m of zone CF1, the maximum abundance in globotruncanids (43%), and maximum average species richness (40 species). The end-Maastrichtian cooling is reflected by the decreased relative abundances of all larger species (>150 μm), decreased abundance of globotruncanids (10%–28%), and increased abundance of small (63–150 μm) morphologically simple taxa (Figs. 5 and 6), increased detrital minerals, chlorite, and mica at the expense of calcite and smectite, respectively.

Humid Tethys-cool middle latitudes

Climate and sea-level changes at Bjala can best be interpreted in comparison with clay mineral data from K-T sections of the Tethys and northern middle to high latitudes. Overall,

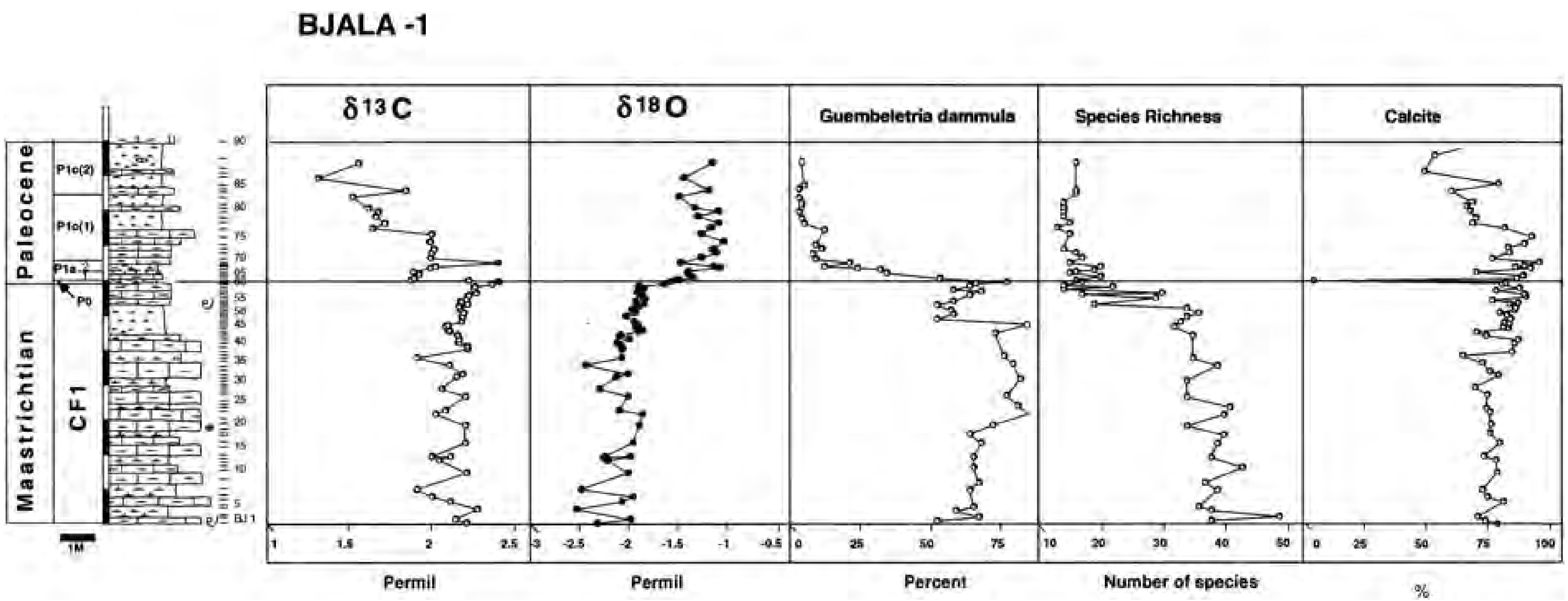

Figure 11. Stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) of bulk rock at Bjala-1, correlated with *Guembelitria dammula* populations, planktic foraminiferal species richness, and calcite content. Note gradual increase in $\delta^{13}C$ values in late Maastrichtian, relatively small (~0.6‰) negative shift at Cretaceous-Tertiary (K-T) boundary, and major decrease in early Danian all suggest long-term changes in productivity and absence of sudden productivity crash at K-T boundary. $\delta^{18}O$ data indicate that cooling began in latest Maastrichtian (upper part of CF1) and continued across K-T boundary into early Danian.

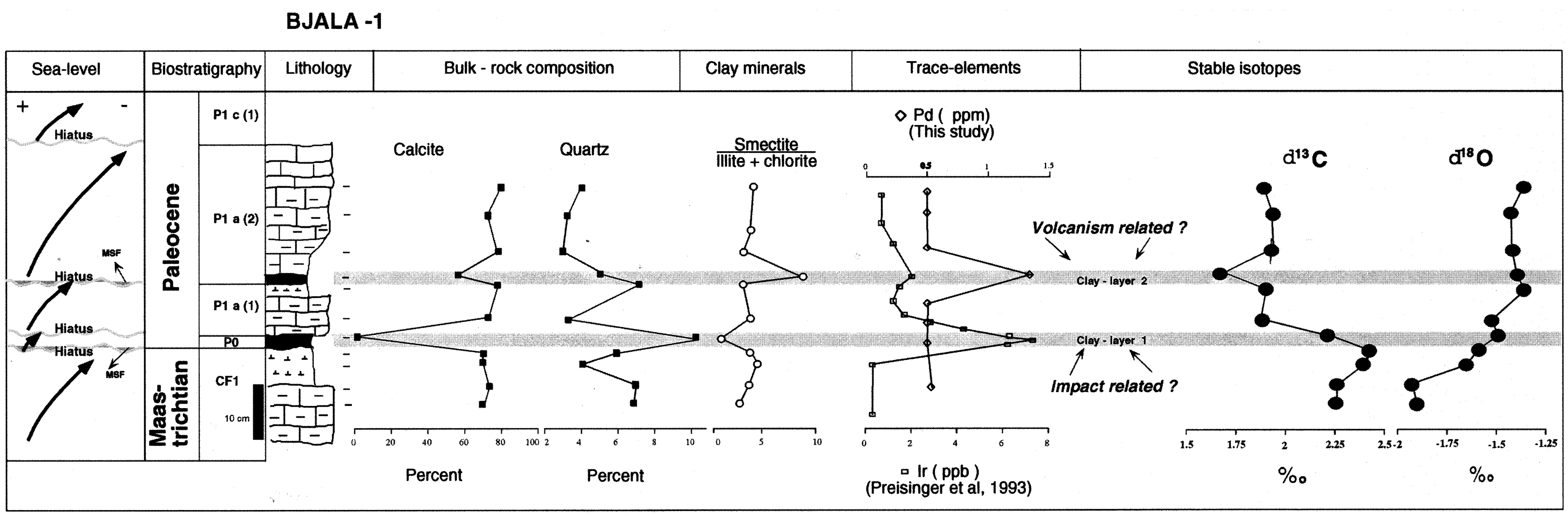

Figure 12. Summary of changing parameters across Cretaceous-Tertiary (K-T) transition at Bjala-1. Relatively small negative $\delta^{13}C$ shift and increasing $\delta^{18}O$ values mark environmental changes at Bjala that are more similar to higher latitudes than low-latitude Tethys. Two clay layers are present; K-T boundary clay with relatively high Ir anomaly marks cosmic event, whereas Pd-dominated early Danian clay layer in *P. eugubin* a zone suggests volcanic origin. See Figure 3A for rock unit symbols. MSF: Maximum flooding surface.

these data indicate that the low-latitude Tethys region underwent a time of increased humidity (Chamley, 1989), whereas the middle and higher latitudes underwent cooling (Adatte et al., 2001) coeval with the late Maastrichtian to early Danian climate cooling observed in the oxygen isotope record. For example, in Tunisia kaolinite increased from the late Maastrichtian into the early Danian, reflecting overall increased humidity. Smectite peaked just below the K-T boundary and again near the base of zone Pla and marks sea-level rises linked with drier climatic conditions (Adatte et al., 2001). Throughout the early Danian a series of warm humid periods alternated with seasonal temperate periods in the tropical and subtropical Tethys, from Tunisia to Haiti (Keller et al., 2001). However in higher latitudes, such as the east boreal paratethys of Kazakstan, the predominance of mica and smectite and minor amounts of kaolinite indicate a relatively cool and seasonally variable climate during the late Maaastrichtian and a cooler climate during the earliest Danian (Pardo et al., 1999). Similar cool climatic conditions are also inferred from clay minerals and stable isotopes for the Denmark K-T sections (Elliott, 1989, 1993; Schmitz et al., 1992). The source of the Mg smectite in the boundary clay of Stevns Klint was interpreted as volcanic, deposited under a temperate seasonal climate.

Productivity crash limited to low latitudes

The $\delta^{13}C$ record across the K-T boundary transition at Bjala-1 is very different from that of coeval records from low latitudes. Global stable isotope records across the K-T boundary in marine sediments show a major negative $\delta^{13}C$ excursion in surface waters of 2‰–3‰ in low latitudes (Zachos et al., 1989, 1992; Keller and Lindinger, 1989; Hsü and McKenzie, 1990), but only 0.5‰–1.0‰ in middle to high latitudes, such as Denmark, Kazakhstan (Schmitz et al., 1992; Keller et al., 1993; Oberhänsli et al., 1998), and DSDP Sites 738, 690, and 527 (Shackleton et al., 1994; Barrera and Keller, 1994). In low latitudes, low $\delta^{13}C$ values persisted through zones Pla and Plb; recovery is recorded in Plc, ~500 k.y. after the K-T boundary (Keller, 1988; D'Hondt et al., 1996). However, in middle to high latitudes $\delta^{13}C$ values continued to decrease through zones Pla and Plb and to the base of zone Plc (Fig. 11). This decreasing $\delta^{13}C$ effect into higher latitudes indicates that the productivity crash was highest in low latitudes and diminished into higher latitudes. This latitudinal difference in surface productivity is likely due to increased upwelling and proximity to a deep-water source in higher latitudes, which may also explain the high rate of species survivorship. The Bjala-1 section defines the productivity crash in the Tethys ocean as south of ~30°N (Fig. 1), in agreement with the conclusion reached by Pardo et al. (1999) based on a summary of faunal assemblages.

Multiple events

Bjala-1 also differs from most other K-T boundary sequences in that it has two clay layers. A single clay layer generally enriched in iridium of cosmic origin characterizes the K-T boundary globally. At Bjala-1 and Bjala-2, the K-T boundary has Ir anomalies of 6.1 ppb and 2.3 ppb, respectively, and coincides with the mass extinction in planktic foraminifera. However, there is a second clay layer stratigraphically within the upper part of zone Pla (*P. eugubina*). This clay layer has a high of Mg smectite content, a small iridium enrichment (0.22 ppb), a major enrichment in palladium (Pd, 1.34 ppb), and anomalies in Ru (0.30 ppb) and Rh (0.13 ppb, Fig. 11). These PGE anomalies suggest a probable volcanic source for this early Danian event. Volcanic rocks in Bulgaria are of Santonian and early Campanian age. However, volcanism related to the Balkan tectonic activity occurred in the early Paleocene in northern Turkey and in Georgia (Senel, 1991; Tzankov and Burchfiel, 1993).

A second event in the early Danian zone Pla with similar PGE anomalies has been documented in a number of sections, including Haiti (Stinnesbeck et al., 2000; Keller et al., 2001; Stueben et al., this volume), Guatemala (Fourcade et al., 1998; Keller and Stinnesbeck, 1999), and Mexico (W. Stinnesbeck, 2000, written commun.). The origin of this second event is still speculative. In Haiti, the PGE anomaly is present in a clayey layer rich in Fe, and has a basalt-like pattern, suggesting a volcanic source (Stinnesbeck et al., 2000; Stueben et al., this volume). In Mexico, a small Ir anomaly of 0.5 ppb correlates with the highest Pt content (1.7 ng/g^{-1}) and minor enrichments of Rh and Pd. The Pt/Ir ratio is nearly chondritic and suggests a cosmic origin (Stinnesbeck 2000, written commun.). Thus there is evidence of a cosmic event and a volcanic event in the early Danian zone Pla. These data suggest that, in addition to the K-T boundary event, at least one and possibly two major events resulting in PGE anomalies occurred in the early Danian Pla (*P. eugubina*) zone. Further studies are needed to determine the origin and nature of these events.

CONCLUSIONS

The K-T sections at Bjala, Bulgaria, provide critical information that help define the extent and distribution of the environmental effects and the K-T boundary mass extinction across latitudes.

1. The K-T mass extinction in planktic foraminifera at Bjala is similar to that in low latitudes in that all morphologically complex, large (>150 μm) species disappeared at or before the K-T boundary. However, Bjala differs in its pre-K-T decreased species richness, decreased abundance of all low-latitude species, and increased abundance of ecological generalists, all of which suggest unfavorable environmental conditions.

2. Clay mineral data indicate that the low-latitude Tethys region underwent a time of increased humidity during the late Maastrichtian, whereas the middle and higher latitudes under-

went cooling. Temperate to cool conditions prevailed across latitudes during the early Danian.

3. Oxygen isotope data indicate that climate cooling occurred during the last 100 k.y. of the Maastrichtian and accelerated across the K-T boundary, with generally cool climate across latitudes in the early Danian.

4. There is a decreasing $\delta^{13}C$ effect into higher latitudes across the K-T boundary, which indicates that the productivity crash was highest in low latitudes and diminished into higher latitudes. This latitudinal difference in surface productivity is likely due to increased upwelling and proximity to a deep-water source in higher latitudes, which may also explain the possibly high rates of species survivorship in these regions.

5. There are two clay layers with PGE anomalies at Bjala-1 that suggest multiple events. Clay layer 1 marks the K-T boundary and contains an Ir anomaly of 6.1 ppb. Clay layer 2 is in the early Danian *P. eugubina* (Pla) zone and contains a small Ir anomaly, and a major Pd anomaly that suggests a volcanic origin.

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