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The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia — Original definition and revision

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The Cretaceous/Paleogene (K/Pg) Working Group, after many years of studies, voted to define the Global Stratotype Section and Point (GSSP) for the base of the Danian Stage at the base of the boundary clay at a section near El Kef, Tunisia. The GSSP was approved by the International Commission on Stratigraphy (ICS) and ratified by the International Union of Geological Sciences (IUGS) in 1991. Nevertheless, the GSSP was not officially published, although some papers dealing with geological aspects of the K/Pg boundary at El Kef have been published and this is quite well known. In April 2006, the GSSP was revisited, a marker was put in place and protection of the site was requested. Many correlation criteria are present at the GSSP of which the most useful are the meteorite impact evidence (iridium anomaly, Ni-rich spinel, etc.) and the mass extinction of planktic micro- and nannofossils. This event coincides with the GSSP, allowing us to propose that the K/Pg boundary is marked exactly by the moment of the meteorite impact, which implies that all the sediments generated by the impact belong to the Danian. This definition solves problems of correlation in the Yucatan peninsula (Mexico) and its surroundings.

Introduction

The Cretaceous/Paleogene (K/Pg) boundary marks the base of the Danian Stage and consequently the Paleocene Epoch, the Paleogene Period, the "Tertiary" Subera and the Cenozoic Era. It is more popularly known as the Cretaceous/Tertiary (K/T) boundary, but the term "Tertiary" has become informal and is not used in the Geologic Time Scale edited by Gradstein et al. (2004). This important boundary was discussed intensively at the International Geological Conference in 1960 in Copenhagen and attracted increased attention of the scientific community since Luterbacher and Premoli Silva (1964) defined the *Globigerina eugubina* Biozone in the Central Apennines and it was calibrated to magnetostratigraphy by Alvarez et al. (1977). It has been studied even more intensively since Alvarez et al. (1980) found the Ir anomaly at Gubbio (Italy) and Smit and Hertogen (1980) at Caravaca (Spain). Nevertheless, the boundary needed a precise definition, as some geologists continued to include the Danian in the Cretaceous. An International Working Group, chaired by Katharina von Salis Perch-Nielsen, was established under the auspices of the International Commission on Stratigraphy (ICS) to formally define a GSSP for the K/Pg boundary.

The first step was achieved in 1982 when all but one of the members of the Working Group voted in favour of placing the K/Pg boundary between the Maastrichtian and the Danian, thus ending the old tradition of including the Danian in the Cretaceous. Several sections were studied for consideration to site the GSSP and after narrowing down the choice of localities to four in 1988, a postal ballot resulted in the following distribution of votes: 10 for El Kef (Tunisia), 6 for Zumaya (Spain), 2 for Brazos (USA) and 2 for Stevns Klint (Denmark). A final postal ballot in 1989 gave the following result: 26 in favour of El Kef, 8 against, 1 abstention and 4 members gave no reply. For the exact point, at which the GSSP should be defined, the result was the following: 11 for the base of the Boundary Clay, 3 for the first occurrence of *Danea californica* (dinoflagellate), 3 for the Iridium maximum, 1 for the base of the tsunamite and 1 for another. Consequently, the chairwoman, von Salis Perch-Nielsen, on behalf of the K/Pg Boundary Working Group submitted a written proposal to the ICS defining the GSSP of the K/Pg boundary at **the base of the boundary clay at the section near El Kef, Tunisia**. This proposal was approved by the ICS in 1990 after obtaining an 80% majority and was ratified by the International Union of Geological Sciences in 1991.

The final step in the definition of a GSSP is its publication in a prestigious stratigraphical journal of wide distribution. The chairwoman promised to shorten the original proposal in order to make it an article for *Episodes*. However, this final step has not yet been made. Only a very short note was published in *Episodes* by Cowie et al. (1989), in a report on activities of the ICS from 1984 to 1989. Since them, certain problems have arisen as the detailed proposal was unknown to many scientists working on the K/Pg boundary, new sections were found in Mexico and controversial interpretations were proposed. Therefore, in order to resolve these problems, the ICS has requested the International Subcommission on Paleogene Stratigraphy (ISPS) to finally publish the proposal. The chairman of

ISPS (E.M.) in collaboration with Tunisian colleagues again visited the GSSP at El Kef, in order to place an artificial marker ("golden spike"), and to request the Tunisian authorities to protect the site. At the same time, the present status of the site has been documented by a series of photographs. The aim of this paper is to publish the abbreviated original proposal to review the studies since the original proposal and to revise the main criteria defining the K/Pg boundary.

The abbreviated original proposal

The approved and ratified proposal of the GSSP consists of 8 pages of text and more than a dozen pages with photographs of the site and figures and tables mainly taken from publications. It contains many details and many of the figures need revision after over 15 more years of research in Tunisia and around the world. Consequently, the original proposal that follows is a shortened version, maintaining most of the text and eliminating the figures that can be found in the cited papers older than ca. 1989.

Geographical location and geology

The location of the El Kef section was indicated in three figures after Lindinger (1988), showing a general map of Tunisia, a map of the El Kef area and a detailed map of the section (Figure 1). The GSSP site is located at a distance of between 5 and 6 km from the crossroad of the El Kef city. It can be reached by taking the exit towards the town of Tadjerouine and following the road which leads to Hammam Mellegue. The GSSP section is located 3 km from the road sign to Hammam Mellegue between a small village and a recent artificial lake. The GSSP was indicated on a topographic map of the area, but the precise coordinates were not given. In addition, two photographs were also included plus an overview of the access to the proposed GSSP locality and an overview of the proposed GSSP locality.

The GSSP lies in the upper Maastrichtian to Paleocene El Haria Formation, which is underlain by the upper Campanian/lower Maastrichtian Abiod Formation and overlain by the lower and middle Eocene Bou Dabbous/El Garia Formation (attributed to the Metlaoui Formation in the original proposal).

The lithology of the boundary interval can be subdivided into 5 units:

A: white-grey marls in the uppermost 4.5 m of the Maastrichtian. These have an average $CaCO_3$ content of 40%. The uppermost Maastrichtian contains burrows of darker Danian sediments. These burrows furnished the extremely negative $\partial^{18}O$ value of –4.93 and are also enriched in Ir, Os and Au (Perch-Nielsen et al., 1982).

B: 0.5 m black clay = Boundary Clay with an average $CaCO_3$ content of 5%. At its base, a 1–3 mm thick rust coloured ferruginous layer marks the boundary event (s). This layer is composed of reddish hematitic and goethitic laminae (Lindinger, 1988). According to the same author, it contains less than 1% $CaCO_3$, and a maximum in TOC (Total Organic Carbon). Kuslys and Krähenbühl (1983) found enrichments in Ir and Os and depleted La, Eu, Yb and Lu. The maximun Ir content of 16.25 ppb is restricted to the rusty layer of the basal Boundary Clay.

C: 0.5 m dark grey clay with slightly higher $CaCO_3$ content (6-10%).

D: ca. 1 m grey, clay-rich shale with an average $CaCO_3$ content of 14 %.

E: > 10 m white-grey clayey marls, with an increasing $CaCO_3$ content of 20–25 % between 2.5 m and 3.0 m above the boundary.

Details of the boundary section

The proposed GSSP is at the base of the Boundary Clay. At El Kef, this base is characterised by a rust coloured layer. It is this layer which in many K/Pg boundary sections includes geochemical anomalies, spherules, shocked quartz, and is considered to be isochronous all over the world, in marine as well as in continental sections.

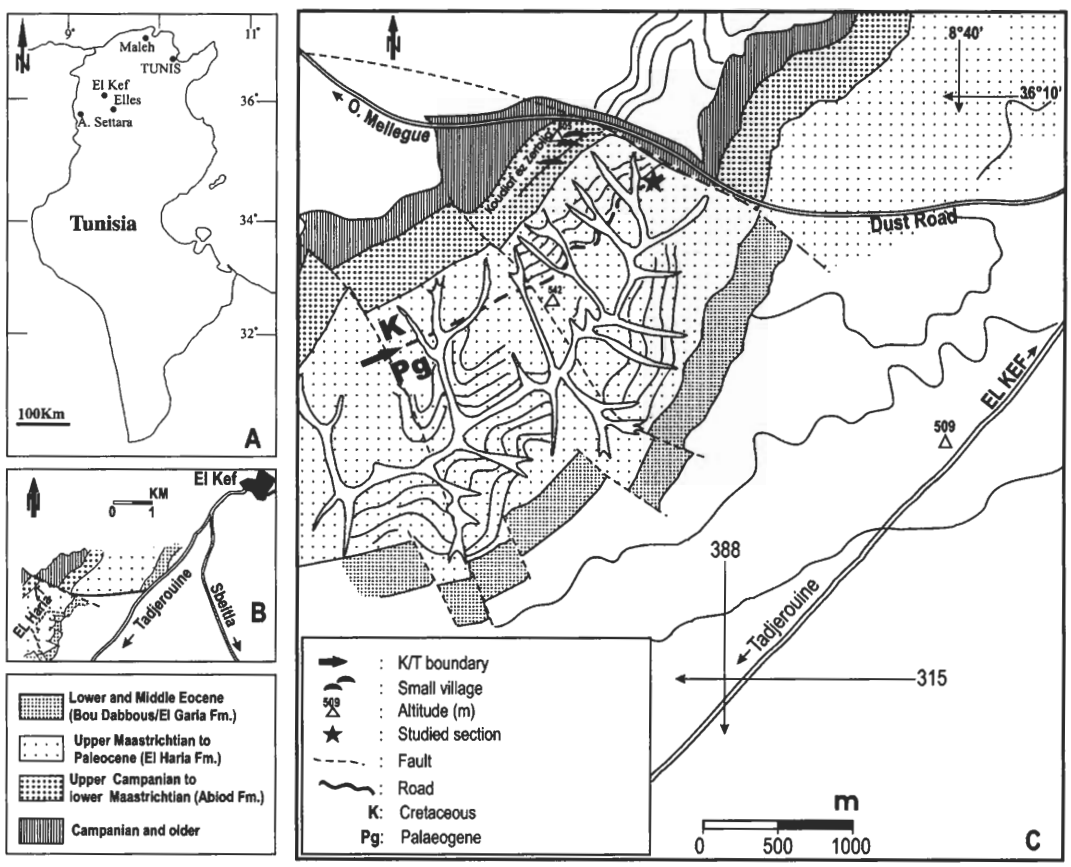

Figure 1 Geographical and geological location of the El Kef section. Modified from Lindinger (1988).

Reasons for the choice of the GSSP

The El Kef is a thick section including the sequence of events across the boundary. The section contains markers that are also known from many other sections, including continental ones, and can thus be easily correlated to El Kef: Boundary Clay, Ir anomaly, TOC maximum, stable isotope shift, decrease of $CaCO_3$ content. Also, calcareous microfossils and nannofossils as well as dinoflagellates are common and well preserved above and below the boundary and allow for wide correlation. The choice of the geographic location was based on the quality of the section.

Method of marking the GSSP: The marker ("golden spike") is placed where the hill is relatively steep so that it is in an area of cleaner, fresher sediment. An iron rod will be put inserted into the cliff at the appropriate level and the site will be protected by our Tunisian colleagues.

Continuity of sedimentation: The section contains marine sediments and sedimentation was as continuous as it could be at a K/Pg boundary. There is a facies change from a grey marl to a black clay (Boundary Clay), at the base of which is a thin rusty layer. This is the fingerprint of continuous sedimentation over the K/Pg boundary interval. The Boundary Clay at El Kef is thicker than at the other sections (Brazos, Stevens Klint and Zumaya).

Completeness of exposure: The section can easily be followed above and below the GSSP and can also be followed laterally. The boundary is also to be found at various other hills in the area. Some earlier reports about calcareous nannofossils from El Kef were from other sites in the area (Verbeek, 1977, Sissingh 1977, Perch-Nielsen 1979, 1981). Also Salaj (1974, 1980) and Donze et al. (1981, 1982) described faunas and floras from another section in the El Haria area.

Adequate thickness of sediments: Over 50 m of sediments outcrop in the section that contains the GSSP. In the area around the GSSP, some 400 m of section (Campanian through Eocene, see Salaj, 1980) is available for study.

Abundance and diversity of well-preserved fossils: The section is rich in micro- and nannofossils as well as dinoflagellates, pollen and spores. The rich assemblages allow easy correlation to sites richer in macrofossils such as Brazos, Mangyshlak, Stevns Klint and Zumaya.

Favourable facies: The marine facies of the GSSP is favourable to the preservation of both calcareous and organic-walled micro- and nannofossils. Thus, correlations can be accomplished with such fossils. The presence of the Boundary Clay with the basal rusty layer containing an Ir anomaly suggests easy correlation to other marine sections and to continental sections.

Freedom from structural complication: The El Kef section is free from structural complication, with the layers dipping gently. In the wider area, however, there are faults, but no metamorphism has affected the section.

Freedom from unconformities: No measurable time break is evident at the point in the section to contain the GSSP. Despite this, the site of the GSSP is obvious thanks to the event(s) that led to the deposition of the Boundary Clay and the rusty layer at its base. In the case of the K/Pg boundary, this is an asset rather than a reason to view the section as suspect.

Amenability to magnetostratigraphy and geochronometry: Neither magnetostratigraphy nor geochronometry are available at the section near El Kef.

Correlation of the GSSP with elsewhere

Correlation by planktic foraminifera: After Salaj (1980) and Donze et al. (1981), who gave summary accounts of Maastrichtian and Danian species from El Kef, Smit (1982) presented more detailed investigations. Salaj (1986), Keller (1988a,b, 1989), Keller and Lindinger (1989) and Brinkhuis and Zachariasse (1988) placed the K/Pg boundary following different criteria. While Keller and Smit used the base of the Boundary Clay, Brinkhuis and Zachariasse chose the extinction of Cretaceous planktic foraminifera, which coincides with the first appearance of the dinoflagellate *Danea californica*. Due to the reduced thickness of the lowermost planktic foraminifera Zone P1 in the El Kef, this zone can not only be subdivided more than in other sections, but subzones P0a and b, which are present only in a few sections, have been added below it.

Correlation by calcareous nannofossils: Bramlette and Martini (1964) first studied calcareous nannofossils from Tunisia in a K/Pg context. Verbeek (1977) and Sissingh (1977) gave the first account of a series of samples from El Kef. Perch-Nielsen (1979, 1980, 1981, 1982) and Jiang and Gartner (1986) studied the K/Pg boundary interval in more detail. At the GSSP section, the uppermost Maastrichtian is characterized by a rich assemblage and the presence of the marker *Micula prinsii* and relatively high numbers of *Prediscosphaera quadripunctata*. Just above the basal, barren and rusty part of the Boundary Clay, the abundance of calcareous nannofossils decreases dramatically. Above, the assemblage changes: Thoracosphaera increases and the first new coccolith, *Neobiscutum romeinii* appears. There is a slight increase in *Braarudosphaera bigelowii* at the top of the Boundary Clay. *Biantholithus sparsus*, a very rare form, the first occurrence of which has often been used to define the base of the Danian, was found only about 3 m above the basal Boundary Clay.

Correlation by palynology: Donze et al. (1981), Brinkhuis and Leereveld (1988) and Brinkhuis and Zachariasse (1988) have published their studies of dinoflagellates, acritarchs, pollen and spores from boundary sections near El Kef. There is no mass extinction of dinoflagellates across the K/Pg boundary. The first occurrence of *Danea californica*, while occurring at the base of the Boundary Clay in Scandinavia, was only found some 10 cm above the base of the Boundary Clay in El Kef.

Correlation by ostracodes: Donze et al. (1982) presented investigations of the ostracodes across the K/Pg boundary from the upper Campanian through the upper Paleocene and basal Eocene. They did not study the K/Pg boundary to the level of detail that has been accomplished with the other microfossil groups. Some 7 species seem to have their extinction at or near the K/Pg boundary, while some 14 cross it.

Correlation of marine to continental sections: The GSSP section near El Kef contains one main feature that allows for a direct correlation of this marine section with continental sections: the Ir anomaly at the base of the Boundary Clay. Since the first discovery of the Ir anomaly at the K/Pg boundary in a non-marine section, many localities have been reported on the North American continent. The boundary is usually identified by the pollen extinction horizon in association with the Ir anomaly and, at many localities, the presence of shock-metamorphosed minerals. The disappearance of the dinosaurs and the *Aquilapollenites* assemblage just below the Ir anomaly is followed by plant microfossil assemblages characterized by anomalous abundances of fern spores (Tschudi et al., 1984) just above the boundary. Such a fern-spike has also been found in the marine realm by Saito et al. (1986) and correlated with the planktic foraminiferal zone P0. Hollow spherules as much as 1 mm in diameter have been found in many K/Pg boundary layers in continental and marine sections. Some are thought to represent melt droplets formed during an impact.

Accessibility and conservation

The GSSP site is easily accessible. It is an area far enough away from a major town (El Kef, ca. 8 km) to be an unlikely site of development in the near or distant future. It is close enough to a small village to be within short walking distance of a paved or dirt road. The local farmers have their fields on the top of the hills, where the land is relatively flat, but leave the steeper sides of the ravines unused. Alteration will continue to produce scree that will cover the hillside, but can be removed with a hoe.

Discussion and conclusion

It has been pointed out by some members of the Working Group, the section does have some weak points and is not ideal. It is generally recognized, however, that it is unlikely that an ideal section will ever be found. Most members of the Working Group obviously decided, that the weaknesses of El Kef were minor compared to those of the other sections, or that its strengths were more important than those of the other sections. The K/Pg boundary is unique in

that it has a marker bed, the Ir anomaly, that allows the correlation from the marine to the continental realm, from low to high latitudes. This bed is well developed in El Kef and in many K/Pg boundary sections. It has been suggested to use it as defining the K/Pg boundary, but a substantial majority of the members of the working group decided against this. They felt more comfortable with a definition that would allow the recognition of the boundary in the field. We foresee no problems with the correlation of the GSSP to other areas.

Studies since the original proposal

Geochemical and mineralogical analyses: At the El Kef section, many criteria allow a worldwide correlation of the GSSP (Figure 2). The most useful ones are the meteorite impact evidence (Ir anomaly, Ni-rich spinels, etc.), which is concentrated in the basal part of the Boundary Clay (see above). Robin et al. (1991) and Rocchia and Robin (1998) confirmed the high concentrations of iridium and other PGEs in K/Pg boundary sediments at the El Kef GSSP, already described by Kuslys and Krähenbühl (1983). Although delivered by a very brief event, Ir is observed over a sizeable thickness of sediments simulating a long duration phenomenon. The Ir distribution shows a millimetre thick pulse-like feature occurring in perfect coincidence with the beginning of the biological crisis. This feature is superimposed to a diffuse component extending over about two metres of sediments from the upper Maastrichtian to the Danian *Parvularugoglobigerina eugubina* Zone. As far as the diffuse component in the Danian is concerned, its duration agrees with the estimated residence time of Ir in sea-water.

The pulse-like feature is associated with crystals of Ni-rich spinel, a mineral derived from meteoritic material. This pulse, reminiscent of the brevity of the K/Pg event, results from the rapid deposition of a large amount of impactor debris dispersed worldwide as a result of the impact event. Robin and Rocchia (1998) observed that the stratigraphic distribution of spinels is confined to a 1–3 mm rust coloured layer that coincides with a drastic decrease of the carbonate fraction. This observation clearly shows that the cosmic event and the biologic crisis took place abruptly and developed rapidly, in less than 100 years, consistent with the hypothesis of a large asteroid impact triggering the mass extinction at the end of the Cretaceous. The Ir content analyses from the GSSP in the El Kef section and in other Tunisian sections reveal that it changed according a random pattern (Robin et al., 1998).

Moreover, chemical analyses of spinels from El Kef reveal that they differ from spinels from other sites, even close to El Kef, suggesting the accretion of several objects. This result can be explained by the fragmentation of the bolide, either before the impact (comet break-up) or upon the impact (oblique impact), with dispersion of debris in both cases all over the Earth. Consequently, it has been generally assumed that the K/Pg boundary is marked by the evidence of the meteorite impact and more precisely by the horizon equivalent to the moment of the impact, i.e., the base of the millimetre-thick airfall layer. This millimetric key-bed represents the dust and fine ejecta that covered the atmosphere after the K/Pg impact event and deposited slowly probably over months or a few years after the impact. For this reason, all deposits or stratigraphic units containing K/Pg impact material around the Gulf of Mexico were considered Danian in age (Smit et al., 1996, Arz et al., 2001, 2004; Alegret et al. 2001, 2003, 2004, 2005; Arenillas et al., 2002; Molina et al., 2002).

The use of the iridium anomaly as the main criterion for correlation was proposed by Odin (1990). It is an excellent criterion for correlation, except for the areas proximal to the meteorite impact on the Yucatan Peninsula, Mexico. In the Gulf of Mexico and its surroundings, there is a thick clastic unit containing the impact breccias, tektites, microtektites, and sands generated by the tsunami, gravity flows and turbidite currents. The thickness of this clastic unit varies from about 15 cm at Blake Nose (Norris et al., 1999), to tens of meters in southeastern Mexico (Grajales et al., 2000) and hundreds of meters around La Havana in Cuba (Molina et al. 2002), but its "normal" thickness is generally a few meters (Smit et al., 1996; Arz

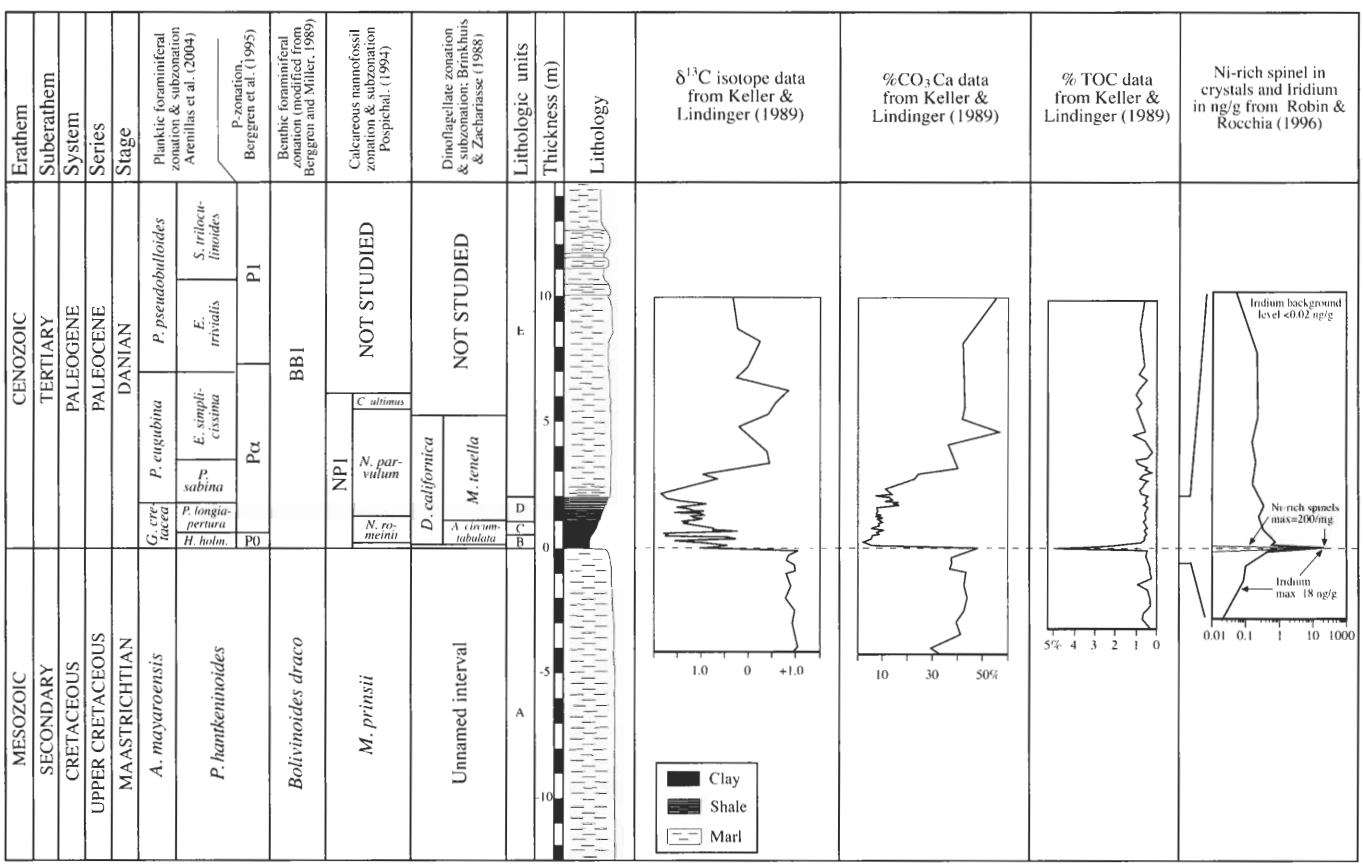

Figure 2 Integrated stratigraphy across the K/Pg boundary in the El Kef section.

et al., 2001; Soria et al., 2001; Alegret et al., 2001, 2005). This clastic unit was generated very rapidly, the rate of sedimentation was very high and the Ir became concentrated when the sedimentation rate decreased (Smit, 1999). Consequently, in the region close to the impact the Ir anomaly is found above the clastic unit and its use as an indicator of the K/Pg boundary could be confusing. Wherever present, the ejecta layers mark exactly the sudden mass-mortality horizon of the K/Pg boundary, but the fossils present in it are reworked from the Cretaceous and cannot be used for dating this unit as Maastrichtian. Most of the geologists working around the Gulf of Mexico place the K/Pg boundary at the base of the clastic unit (Smit et al., 1996, Arz et al., 2001, 2004; Arenillas et al., 2002, among others), whereas few others (e.g., Keller, 1989) place the boundary above it. In order to solve this dispute, we propose that the K/Pg boundary is precisely marked by the horizon representing the moment of the meteorite impact, which implies that all the sediments generated by the impact belong to the Danian.

Planktic foraminifera: This micropaleontological group has been studied by different authors and the interpretation of the planktic foraminiferal extinction pattern across the K/Pg boundary in the El Kef section has been a matter of controversy. The El Kef section was studied by Keller (1988a) and Keller et al. (1995) who reported an extended gradual pattern of extinction. Two very close sections were studied by Keller et al. (1995) namely El Kef I, which is the stratotype section that she also studied in 1988, and El Kef II, about 600 m north of the stratotype. A comparison of the stratigraphical distribution of planktic foraminifera shown in the two papers reveals that they are very inconsistent and contradictory. Only two species (*Planoglobulina carseyae* and *Globotruncanita stuarti*) coincided to become extinct at the K/Pg boundary in El Kef I as well as in El Kef II, but in her previous paper (Keller, 1988a) P. carseyae became extinct in the terminal Maastrichtian and *G. stuarti* in the lower Paleocene. On the contrary, other micropaleontologists found a sudden pattern of extinction compatible with the meteorite impact theory (Smit, 1982, 1990, Haslett, 1994, Olsson and Liu, 1993, etc.). In order to solve this long-standing controversy, mainly between Keller and Smit, a blind test was organized (Lipps, 1997) and four "blind" specialists (Canudo, Master, Olsson and Orue-Etxebarria) examined six unlabelled samples across the K/Pg boundary of the El Kef section.

The results were analysed by Arenillas et al. (2000b), who also carried out an independent test, and found a catastrophic mass extinction pattern. These authors suggested that the controversy among specialists is due to several problems in the biostratigraphic study, such as the Signor-Lipps (1982) effect and the possibility of reworking. In the conclusions, Arenillas et al. (2000b) suggested: First, there are no significant pre-K/Pg changes either in the number of extinctions or assemblages turnover at El Kef. Second, Cretaceous specimens are present in the lowermost Danian, but it is not clear whether they are reworked or indigenous. Third, apparent Cretaceous survivors are always smaller in size and lower in absolute abundance in the lower Danian than in the upper Maastrichtian. Fourth, the planktic foraminiferal evolutionary radiation occurs above the K/Pg boundary and never below. Consequently, this last suggestion is yet another proof of the catastrophic mass extinction at the K/Pg boundary, since if the mass extinction had been gradual, the evolution of new species would have occurred during the entire Cretaceous-Paleogene transition. Therefore, Arenillas et al. (2000b) concluded that the K/Pg catastrophic mass extinction constitutes the largest and most sudden extinction event in the history of planktic foraminifera and is very compatible with the catastrophic effects caused by the impact of a large extraterrestrial bolide.

Most of the apparent disappearances below the boundary are due to the Signor-Lipps effect and most of the species that seem to "survive" are in fact reworked. Reworking is particularly frequent if the samples are taken at very close intervals and the sediments are affected by bioturbation. As stated in the original proposal for the definition of the GSSP, the uppermost Maastrichtian contains burrows filled with darker Danian sediments (Perch-Nielsen et al., 1982). Nevertheless, Keller and Lindinger (1989) claimed that stable isotope values of the lowermost Tertiary "Cretaceous" planktic foraminifera are incompatible with an interpretation that they are reworked from the Cretaceous. But, Kaiho and Lamolda (1999) also using isotope analyses concluded that the Cretaceous planktic species in lower Danian sediments at Caravaca are in fact reworked. At present, most micropaleontologists agree that there were few or no significant plankton extinctions before the K/Pg boundary, a sudden major mass extinction event at the boundary, and some unimportant survivorship above it (Smit, 1994; Molina et al, 1996, 1998, 2005; Peybernès et al., 1996; Apellaniz et al., 1997; Kaiho and Lamolda, 1999; Arz et al., 1999, 2000, 2001, 2004; Arenillas et al., 2000a,b,c, 2004; Zaghbib-Turki et al., 2000, 2001, Zaghbib-Turki and Karoui-Yaakoub, 2004, etc.).

Calcareous nannofossils: After the initial proposal of the K/Pg boundary at El Kef, the record of calcareous nannofossils was studied by Pospichal (1994). A detailed quantitative study revealed no extinction of calcareous nannoplankton in the uppermost 4 m of the Maastrichtian marls. Nannofossil assemblages below the boundary show no trends to indicate that ecologic stresses such as temperature change foreshadowed the K/Pg event. Cretaceous nannofossil specimens present above the K/Pg boundary at El Kef are interpreted to have been reworked, rather than having survived the K/Pg event. Abundance patterns of common Cretaceous species and a correlation with short-term sea-level lowstands, suggest redeposition of these specimens in Tertiary sediments. There is evidence of very limited survivorship of species of the Cretaceous assemblage into the Tertiary. According to Gardin and Monechi (1998) latest Maastrichtian assemblages are abundant and diverse and coccolithophores did not seem to be in decline in the latest Maastrichtian. At the K/Pg boundary there was a drastic decrease in almost all Cretaceous species, and blooms of Thoracosphaera, followed by acmes of few opportunistic survivors and new Tertiary dwarf species. Most Cretaceous species occurring above the K/Pg boundary are mainly considered as reworked.

Small benthic foraminifera: Their turnover across the K/Pg boundary at El Kef has been intensively studied by several authors (e.g., Keller, 1988b; Speijer, 1994; Speijer and Van der Zwaan, 1996; Kouwenhoven et al., 1997; Galeotti, 1998; Coccioni and Galeotti, 1998; Galeotti and Coccioni, 2002; Alegret, 2003; Alegret et al., 2004). All these studies agree with an outer neritic-upper bathyal depth of deposition. Although Keller (1988b) interpreted a shallowing trend to middle shelf depths from the K/Pg boundary to Zone P1b, benthic foraminiferal assemblages seem to indicate paleoenvironmental changes at the seafloor rather than paleobathymetrical changes, and such changes in depth of deposition have not been supported by most other authors. Benthic foraminiferal assemblages did not suffer a major extinction at the K/Pg boundary, but they did undergo a significant faunal turnover. At El Kef, the diverse and heterogeneous assemblages from the uppermost Maastrichtian were suddenly replaced by low diversity assemblages belonging to an "epifaunal domain", Cibicidoides pseudoacutus being the most abundant species in the lowermost Danian. This species was misidentified by Keller (1988b) and Keller and Lindinger (1989), who classified it as *Anomalinoides acuta*. According to Galeotti and Coccioni (2002), *C. pseudocautus* developed a preference for sinistral coiling that might be related to a short-term cooling, which occurred during the earliest Danian, lasted for some 7 ky and is regarded as a potential marker for the K/Pg boundary.

Benthic foraminiferal assemblages from the lowermost part of the *G. cretacea* Biozone (P0) indicate oligotrophic conditions at the seafloor; such a decrease in the nutrient supply to the seafloor has been related to the collapse of surface-water productivity as the result of the mass extinction of primary producers. The collapse of the food web is thought to have been the main factor that determined the benthic foraminiferal turnover directly at the K/Pg boundary (Alegret et al., 2004), although some authors have inferred a decrease in oxygenation as well as in organic flux to the seafloor immediately after the K/Pg boundary (Keller, 1988b, Speijer and Van der Zwaan, 1996). Nevertheless, such a period of decreased oxygenation has not been found at El Kef (Alegret, 2003; Alegret et al., 2004), or at the nearby Aïn Settara section (Peryt et al., 2002). Benthic foraminifera indicate a slow recovery of the nutrient flux

and more stable conditions at the seafloor towards the *Ps. pseudobulloides* Biozone; assemblages seem to recover some 200-300 ky after the K/Pg boundary (Galeotti and Coccioni, 2002; Alegret, 2003; Alegret et al., 2004).

Ostracodes: Their record at the El Kef section was first studied by Donze et al. (1982), who recognised 45 species from the Late Campanian to the Ypresian. Although several species range through the K/Pg boundary, 11 became extinct around the K/Pg boundary. Many species are common with those recognized by Saïd-Benzarti (1998) at the Elles section.

Palynology: Palynological studies of the Cretaceous-Paleogene interval at the El Kef outcrop were carried out by Méon (1990) who suggested that in the late Maastrichtian time, Northern Africa was at the boundary between the African-South American and European provinces. During the transition to the Tertiary, palynofloral variety decreased and only European taxa remained. It is possible that a somewhat abrupt event did occur and its record is superimposed on that of climate change and regression. Donze and Méon (1997) studied the extinctions of microfauna and palynomorphs across the El Kef K/Pg boundary, concluding that it coincides with the beginning of a major biological crisis. A sudden disturbance in the chemical conditions of ocean superficial waters, linked to the meteoritic event, seems to have been the most active parameter in this crisis, preventing the normal test building processes for the calcareous chlorophyllian algae and inducing strongly anoxic conditions in the ocean. At the boundary and in the first centimetres above it, Donze and Méon (1997) found a strong acceleration of taxa disappearances; nevertheless, at least two thirds of the late Maastrichtian taxa cross the boundary.

Ammonites: This group was described for the first time by Goolaerts et al. (2004) from the terminal Maastrichtian at El Kef. A rich assemblage, consisting of at least 17 taxa, occurs in the interval from meters 7 to 2 below the K/Pg boundary. They co-occur with a diverse macrofauna, which also includes rudists. All these fossils are pyritic, and the ammonites are all nuclei, mostly <20 mm in diameter. The dominance of *Indoscaphites* suggests open connections with southern India along the Southern Tethys. No ammonites have been recovered from the 2-m interval below the K/Pg boundary in the Tunisian basin. This absence could be due to the Signor-Lipps effect or more probably to taphonomic problems of preservation, since only nuclei of ammonites were found. Furthermore, a similar problem was evidenced in the Biscay region (southwestern France, northern Spain), where initially no ammonites were found in the uppermost Maastrichtian, but finally ammonites were found in several sections up to the K/Pg boundary by Ward et al. (1991).

Revision of the GSSP

Since the K/Pg Working Group finished its studies and the GSSP was approved and ratified in 1991, ICS and ISPS were alerted that the site of El Kef is poorly preserved and the exact location of the GSSP could not easily be identified. During the International Workshop on the Cretaceous-Tertiary Transition (May, 1998) in Tunisia, the El Kef section and two other apparently complete K/Pg sections (Elles and Aïn Settara) were visited. According to Remane and Adatte (2002) the field inspection showed that the El Kef section is indeed badly overgrown, they had difficulty in finding the K/Pg boundary. However, it can be located as it is placed a few meters below a tree, 20 m downstream of an electric line.

The best solution nevertheless, seems to be to maintain the GSSP at the El Kef section and eventually designate auxiliary sections. Zaghbib-Turki et al. (2001) proposed the Elles section as a new stratotype or at least a parastratotype for the K/Pg boundary, because the Elles section exposes a better K/Pg interval outcrop than the El Kef section. Nevertheless, a small hiatus has been identified by Arz et al. (1999) 6.5 meters above the K/Pg boundary at the base of the *Parasubbotina pseudobulloides* Zone, but it is an excellent auxiliary section as the K/Pg boundary is continuous. The three Tunisian sections, Elles, Aïn Settara and El Maleh, constitute excellent auxiliary sections situated in the same paleogeographic context (Arenillas et al., 2000a, Dupuis et al., 2001; Gardin, 2002; Karoui-Yaacoub et al., 2002; Luciani, 2002; Stüben et al., 2002; Zaghbib-Turki and Karoui-Yaacoub, 2004; Gallala, 2004).

In April 2006, preparation efforts in the field by Zaghbib-Turki and the members of her research team while excavating a trench ended successfully with the discovery of the Ir-rich rust layer and the dark boundary clay at the El Kef section. Furthermore, the K/Pg boundary was unequivocally identified by means of planktic foraminiferal species identification using a microscope. A few days later, during another field trip to the El Kef section, the chairman of ISPS and the Tunisian team placed an artificial marker (1 m-long iron-staff), at the base of the Boundary Clay, marking the GSSP (see photographs in Figure 3 and 4). The precise coordinates were measured with a GPS. Lambert coordinates calibrated from Carthago point: N36°09'13.2", E008°38'54.8". UTM coordinates: N32, N4001314, E468675.

Consequently, the Global Stratotype Section and Point for the base of the Danian, which by definition is also the base of the Paleocene, the Paleogene, the "Tertiary" and the Cenozoic, has been offi-

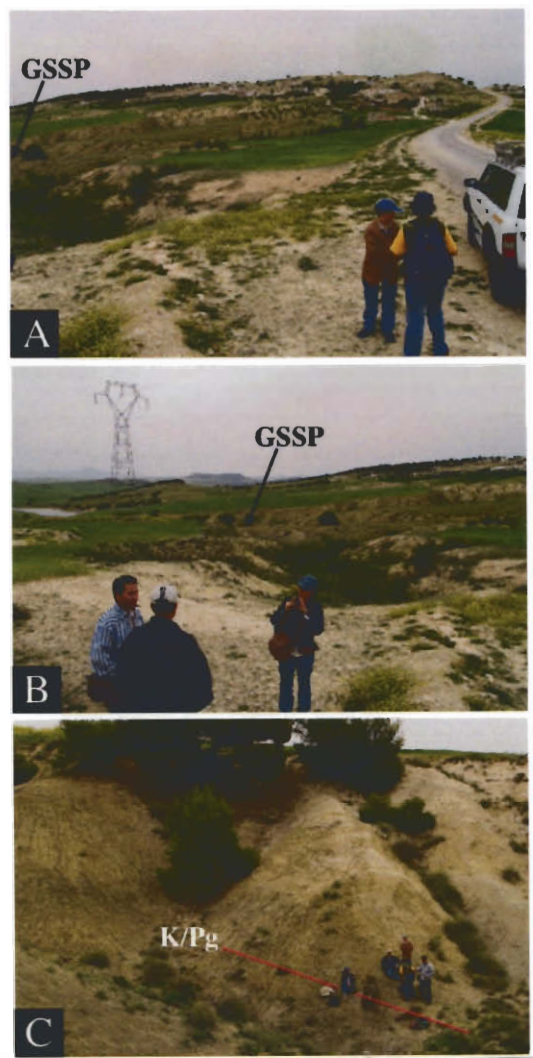

Figure 3 Photographs of the GSSP. A—Overview of the access to the GSSP from the road to Mellegue, the small village on the right and the section on the left. B—Overview of the GSSP locality, small village on the right, artificial lake and electric line on the left and the section in the middle C—Overview of the GSSP site where the trench was excavated.

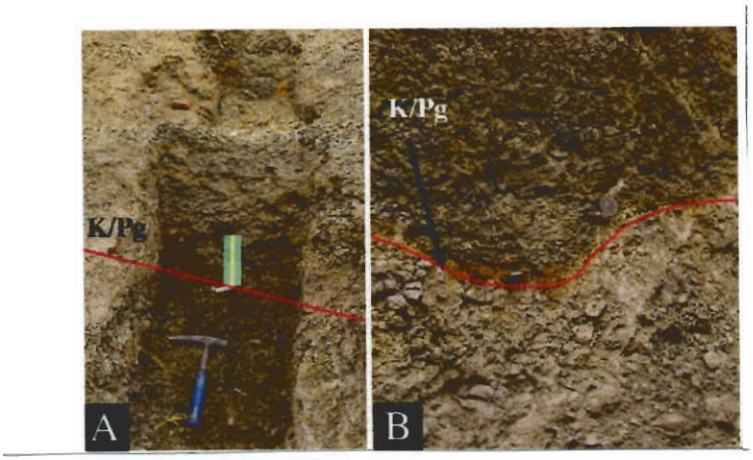

Figure 4 Photographs of the K/Pg boundary. A: Trench across the K/Pg with a hammer, a scale and the marker put in place at the boundary. B: Detail of the K/Pg boundary with a Tunisian coin as scale on the rusty layer.

cially reestablished at the base of the Boundary Clay, a very distinct and precise lithological level, in the section near El Kef, Tunisia. Also, the chairman of the ISPS has sent an official letter to the Tunisian authorities requesting the protection of the site. Several geologists of the Tunisian Geological Survey recently visited the GSSP in order to prepare for its protection.

The GSSP for the base of the Danian, corresponding to the Cretaceous/Paleogene boundary as defined at the base of the Boundary Clay in the section near El Kef, Tunisia fulfils most of the requirements for a GSSP set out by Remane et al. (1996). According to the data in the original definition and in the many papers published subsequently to it on different aspects of the El Kef section, the GSSP is characterized by the following criteria useful for correlation:

The K/Pg boundary is marked and overlain by a 1–3 mm thick rust coloured ferruginous layer composed of reddish hematitic and goethitic laminae. This layer contains less than 1% $CaCO_3$, a maximum in TOC (Total Organic Carbon), distinct excursions in the stable isotope ^{18}O and ^{13}C and the meteorite impact evidence (Ir anomaly, Ni-rich spinels, etc.). This key-layer only a few millimetres thick is the result of the meteorite impact, and concentrates all its evidence in distal areas. The K/Pg boundary is precisely defined by the horizon corresponding to the moment of the meteorite impact. This implies that in the proximal areas of the Chicxulub crater (Yucatan Peninsula) the K/Pg boundary must be placed at the base of the metre thick impact-linked clastic unit, which is therefore Danian in age.

The K/Pg boundary coincides with the most significant extinction in the history of the planktic foraminifera. The mass extinction suddenly affected more than 70% of the species, which may well reach 90% of the species considering most of the globotruncanids present in the Boundary Clay as reworked (Figure 5). The uppermost Maastrichtian belongs to the *Abathomphalus mayaroensis* Zone, but this species is very rare in the El Kef section. *Plummerita hantkeninoides*, which became extinct at the same time and is more abundant and restricted to the uppermost Maastrichtian, can be used alternatively (Arenillas et al., 2000b). The first Danian planktic foraminiferal assemblages are dominated by *Guembelitria*, disaster taxa that bloomed immediately after the K/Pg boundary. The lower Danian is characterized by the *Guembelitria cretacea* Zone, followed in succesion by the *Parvularugoglobigerina eugubina* Zone and the *Parasubbotina pseudobulloides* Zone. A high-resolution planktic foraminiferal subzonation was proposed and applied to the El Kef section by Arenillas et al. (2004).

A similar major mass extinction event at the K/Pg boundary is also observed in the calcareous nannoplankton. According to

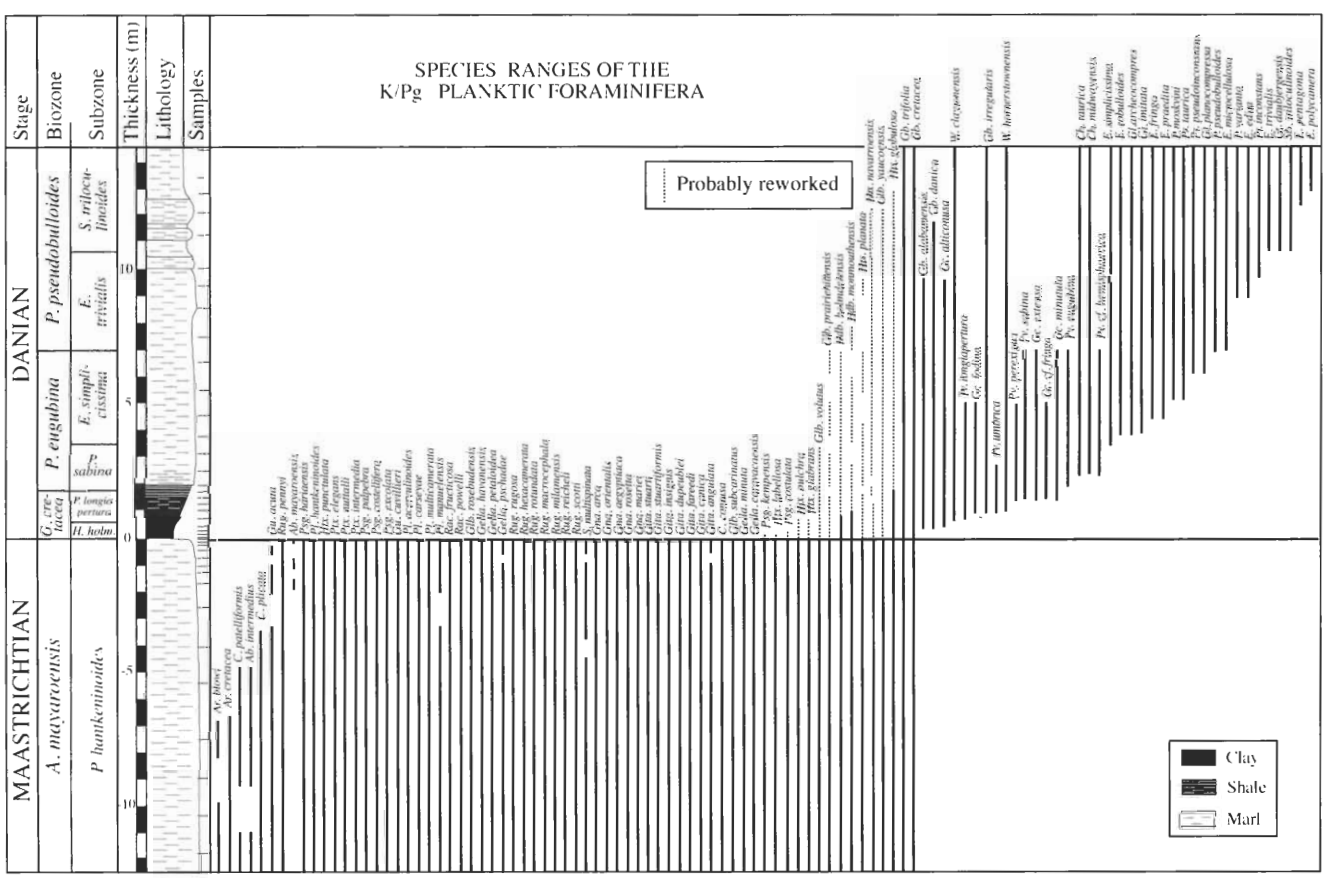

Figure 5 Planktic foraminifera species ranges in the El Kef section (modified from Arenillas et al., 2000b).

Pospichal (1994) the uppermost 4 m of Maastrichtian marls reveal no extinctions and show no trends to indicate that ecologic stresses such as temperature change foreshadowed the K/Pg event in the Tethyan region. Cretaceous nannofossil specimens present above the K/Pg boundary at El Kef are interpreted to have been reworked, rather than having survived the K/Pg event. The uppermost Maastrichtian belongs to the *Micula prinsii* Zone and the lower Danian to the zone NP1, characterized by *Neobiscutum romeinii* at the base, *Neobiscutum parvulum* in the middle and *Ceratolithoides ultimus* at the top.

In contrast to planktic nanno- and microfossils, the small benthic foraminiferal assemblages did not suffer a mass extinction at the K/Pg boundary; extinctions were fewer in deeper than shallower water settings. However, the outer shelf, upper bathyal sections of Aïn Settara and El Kef record a dramatic change in the structure of benthic foraminiferal assemblages across the K/Pg boundary (e.g. Speijer, 1994; Peryt et al., 2002 and Alegret et al., 2004). Diverse and heterogeneous assemblages from the uppermost Maastrichtian were suddenly replaced at the K/Pg boundary by taxonomically impoverished assemblages, strongly dominated by epifaunal morphogroups. The extinction or temporary emigration of most infaunal morphogroups was the result of a sudden breakdown and a decrease in the nutrient food supply resulting from a sudden mass extinction of the primary producers, triggered by the impact of the K/Pg asteroid. The extinction of *Bolivinoides draco* at the K/Pg known worldwide from many sections allows recognition of the base of the Cenozoic bathyal BB1 Zone of Berggren and Miller (1989) also in the El Kef section (Figure 6).

In conclusion, the main criteria defining the K/Pg boundary and the correlation among them are shown in Figure 2. The GSSP for the base of the Danian Stage defining the K/Pg boundary at the base of the boundary clay is overlain by a rusty red layer containing a peak of Ni-rich spinel, which is more concentrated than the iridium anomaly. This implies that all the sediments generated by the meteorite impact belong to the Danian. This millimetre thick layer, containing the evidence of the meteorite impact and other significant geochemical changes, coincides with a sudden catastrophic mass extinction event, which strongly affected the planktic environments. This mass extinction defines the top of the *Abathomphalus mayaroensis* Zone (*Plummerita hantkeninoides* Subzone) of the planktic foraminifera and the top of the *Micula prinsii* Zone of the calcareous nannofossils.

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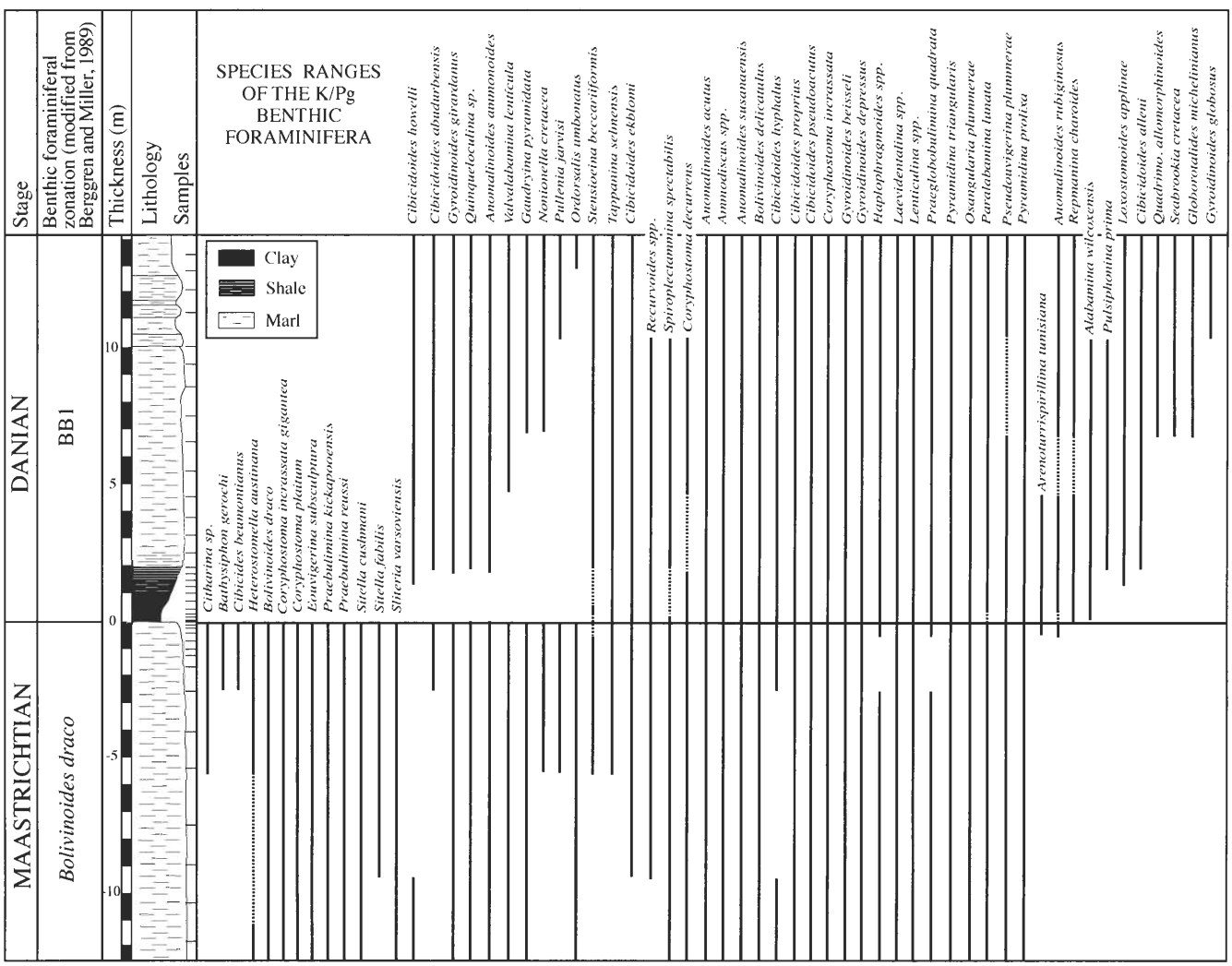

Figure 6 Benthic foraminifera species ranges in the El Kef section. (Modified from Alegret, 2003)

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