Comparative analysis of K/T boundary sites

Sørensen, Anne Mehlin

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Prepared by

Anne Mehlin Sørensen

Department of Geography and Geology, University of Copenhagen

in cooperation with Stevns Museum

Preface

The K/T boundary event, with the interpreted extraterrestrial impact and associated mass extinction, 65.5 million years ago, is an "outstanding example representing major stages of Earth's history, including the record of life" leading to the life we know on Earth today. This important geological time period is not currently represented on the World Heritage List.
This report provides a comparison of 17 K/T boundary sites based on seven independent, quantitative criteria to assess which geological site is the most commendable as representing the finest example in world of the K/T boundary event as a UNESCO World Heritage Site.

A first step was to create a list of sites that could be potential World Heritage Sites. A data base containing more than 500 K/T boundary sites already exist. To short list these many sites, three main criteria was developed. The potential K/T boundary sites should be perfect concerning completeness of the succession, should include a boundary layer showing evidence of the extraterrestrial impact, and be well described to be able to compare them. These main criteria where meet by 17 localities.

The checklist of ten questions developed by the IUCN for evaluating fossiliferous sites and nine recommendations presented by Well (Appendix B) were used as much as possible but since the compared sites represents an event across the K/T boundary and not a fossiliferous site the checklist and recommendations was of minor importance and criteria more suitable for this comparative analysis was developed. Seven criteria which taken together, and given points after importance, are used to compare the 17 K/T boundary sites and determine their relative importance.

Each of the 17 compared sites is described, followed by the quantified, comparative evaluation. These data are compiled in a cumulative table which makes it possible to determine the site most representative of the K/T boundary event.

On the basis of the comparative analysis this report completely supports the enclosure of Stevns Klint on the Danish list of potential World Heritage Sites.

It has been discussed whether Stevns Klint should be nominated by it self, as a K/T boundary site, or should be nominated with other Late Cretaceous and Early Tertiary localities in Scania as a serie.

After evaluating IUCN guidance for identifying natural heritage of potential outstanding value the K/T boundary event itself is an important time interval which stands out and can be observed at Stevns Klint without any connections with other localities.

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1. Significance of the transition from the Cretaceous to the Tertiary Period, the K/T boundary

During the Late Cretaceous period the oceans were ruled by large swimming reptiles and the land by dinosaurs. The Earth experienced greenhouse conditions associated with one of the highest known sea-level stands and shallow seas covered much of the continents (Fig. 1). Suddenly, 65.5 million years ago the Earth's ecosystems changed, the sea-level fell, the atmosphere cooled, and more than 50% of all species on Earth, including the dinosaurs, disappeared and a new era started. This extinction is one of the "Big Five" mass extinctions the Earth has experienced during the Phanerozoic – the past 550 million years. The transition from the Cretaceous to the Tertiary Period marks the end of the Mesozoic Era and the beginning of the Cenozoic Era and represents a major stage of Earth's history and a key event in the evolution of life. The transition period was associated with major global sea-level and climate fluctuations. A sea-level rise at the end of the Maastrichtian and an early Danian sea-level fall has been identified world wide. The climate changes precisely across the K/T boundary is still a unknown, mainly because the oxygen isotope records are unclear due to diagenetic alteration of carbonates (Adatte et al., 2002).

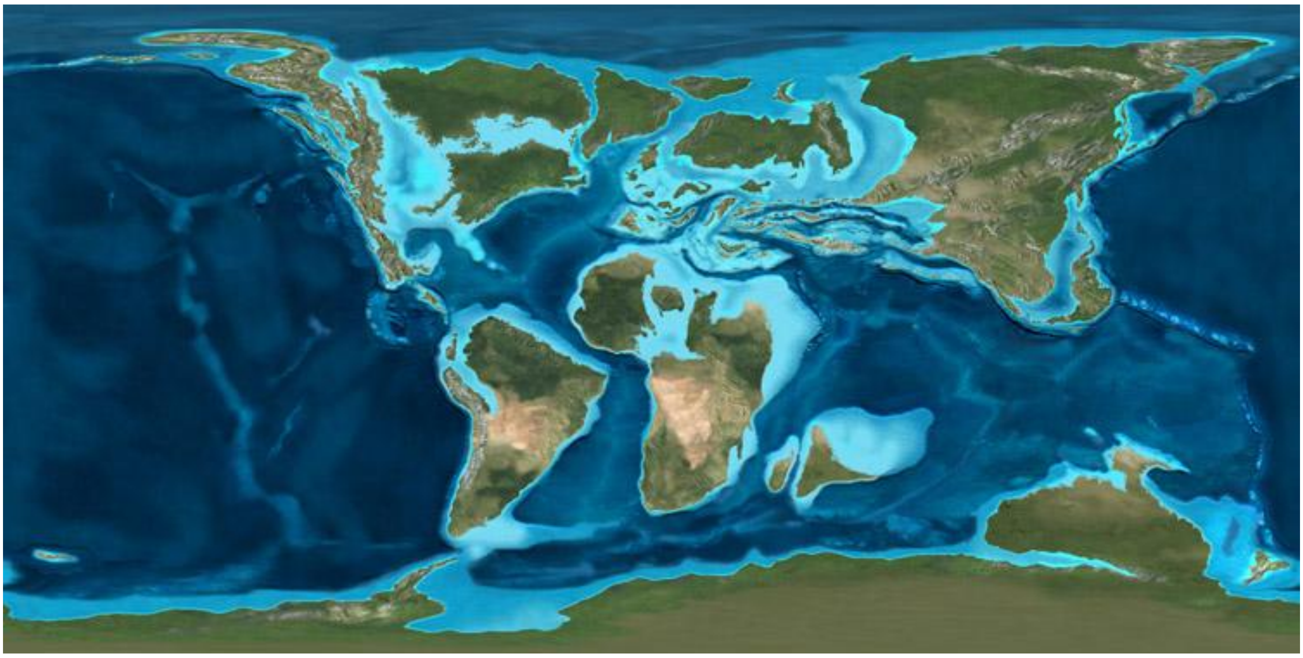


Figure 1. Palaeogeographical map of the world during the Late Cretaceous showing the high sea level stand and shallow seas covering the continents.

Much scientific work has been done on the transition from the Cretaceous to the Tertiary Period since it represents the only known mass extinction and change of the global ecosystems which has been related to an extraterrestrial impact. The discovery of an iridium anomaly, Ni-rich spinel, a mineral formed by fusion and oxidation in the atmosphere of meteoritic objects, and shocked quartz grains in the Cretaceous/Tertiary (K/T) boundary layers around the world formed the basis for the hypothesis of an enormous asteroid impact causing the mass extinction. The Chicxulub crater in Mexico (ca 200 km in diameter) is the best candidate for a K/T impact site (Hildebrand et al., 1991, Dupuis et al., 2001; Hollis, 2003). After almost 30 years of intensive research, debate and controversy about what caused the anomalous high iridium concentrations and the mass extinctions recorded in many floral and faunal groups at the K/T boundary, the Alvarez impact hypothesis (Alvarez et al., 1980) has been widely accepted. Other events, such as major volcanic activity releasing large amounts of ashes and gasses and major sea-level changes, have also been suggested as a cause for the mass extinction (Keller 1988 a, b, 1993, 2003; Smit, 1999; Dupuis et al., 2001; Gallagher, 2002; Hollis, 2003).

It is known that the mass extinction is closely linked to the impact event but it is still not clear how the impact event is linked to the extinctions. Alvarez et al. (1980) originally suggested that an extraterrestrial impact would leave a dust cloud in the stratosphere for several years, resulting in darkness on Earth. The temporary absence of sunlight would shut down photosynthesis followed by a food chain collapse and in combination with a prolonged period (> 3 kyr) of global warming it could explain most of the biotic events. The pattern of extinction and survival across the K/T boundary does provide a model for a collapse of the marine ecosystems generated by large-scale environmental disturbance (Smit, 1999; Gallagher, 2002).

The great majority of K/T boundary sections are located in the marine environments and most complete K/T boundary successions were deposited in the deep sea and thus accessible only through drilling programs which, in most cases, excludes information about macrofossils (Ward et al., 1986; Kiessling and Claeys, 2001). Microfossils have therefore primarily been used for investigating the nature of the mass extinction, the global change around the K/T boundary, and the recovery patterns. Especially planktonic foraminifers has been used since they are sensitive of environmental changes such as shifts in water temperatures, salinity, oxygen, nutrients, and water depth and generally are abundant in relative shallow to deep marine environments across latitudes (Canudo et al., 1991; Luciani, 2002).

The K/T boundary Global Stratotype Section and Point (GSSP) was officially defined at the El Kef section in Tunisia at the base of the boundary clay layer anomalously rich in iridium. The GSSP is an instant in time represented by this bedding plane. All other criteria such as mass-extinction level, last occurrence of Maastrichtian fossils, first occurrence of Paleocene fossils, irridium anomaly, Ni-rich spinels, soot, and negative shift of $\delta^{13}C$ and $\delta^{18}O$ are closely associated and can be used for correlation but are not part of the K/T boundary definition (Smit, 1999). Criteria which can be used for identifying the K/T boundary in terrestrial sites are the abrupt disappearance of numerous species of plant microfossils; the presence of an iridium anomaly, and the presence of shocked mineral grains, primarily quartz (Nichols, 2007).

The K/T boundary coincides with one of the most pronounced faunal turnovers known in the geological record, a turnover that affected both terrestrial and marine faunas, leading to the life we know on Earth today. It represents the only change of the global ecosystems and a mass extinction which has been related to an extraterrestrial impact, and the K/T boundary event therefore represents a major event in Earth's history and in the evolution of life. Even though it is an important period of the Earth's History the Cretaceous/Tertiary transition is not yet represented by a UNESCO World Heritage Site.

Geological sites, which are already inscribed as a UNESCO World Heritage Site represents different periods of geological time including the Cambrian (Burgess Shale), Ordovician (Gros Morne), Devonian (Miguasha National Park), Carboniferous (Mammoth Cave, Joggins Fossil Cliffs), Permian (Grand Canyon), Mesozoic (Dorset and East Devon Coast), Triassic (Talampaya Natural Parks, Monte San Giorgio), Cretaceous (Dinosaur Provincial Park), Eocene (Messel Pit, Wadi Al-Hitan), Miocene (Riversleigh), and Recent (Naracoorte) (Fig.2).

The aim of this comparative study is to document that the nominated K/T boundary site, Stevns Klint, is the very best and most outstanding site to present the unique record of the geological significant Cretaceous−Tertiary boundary interval.

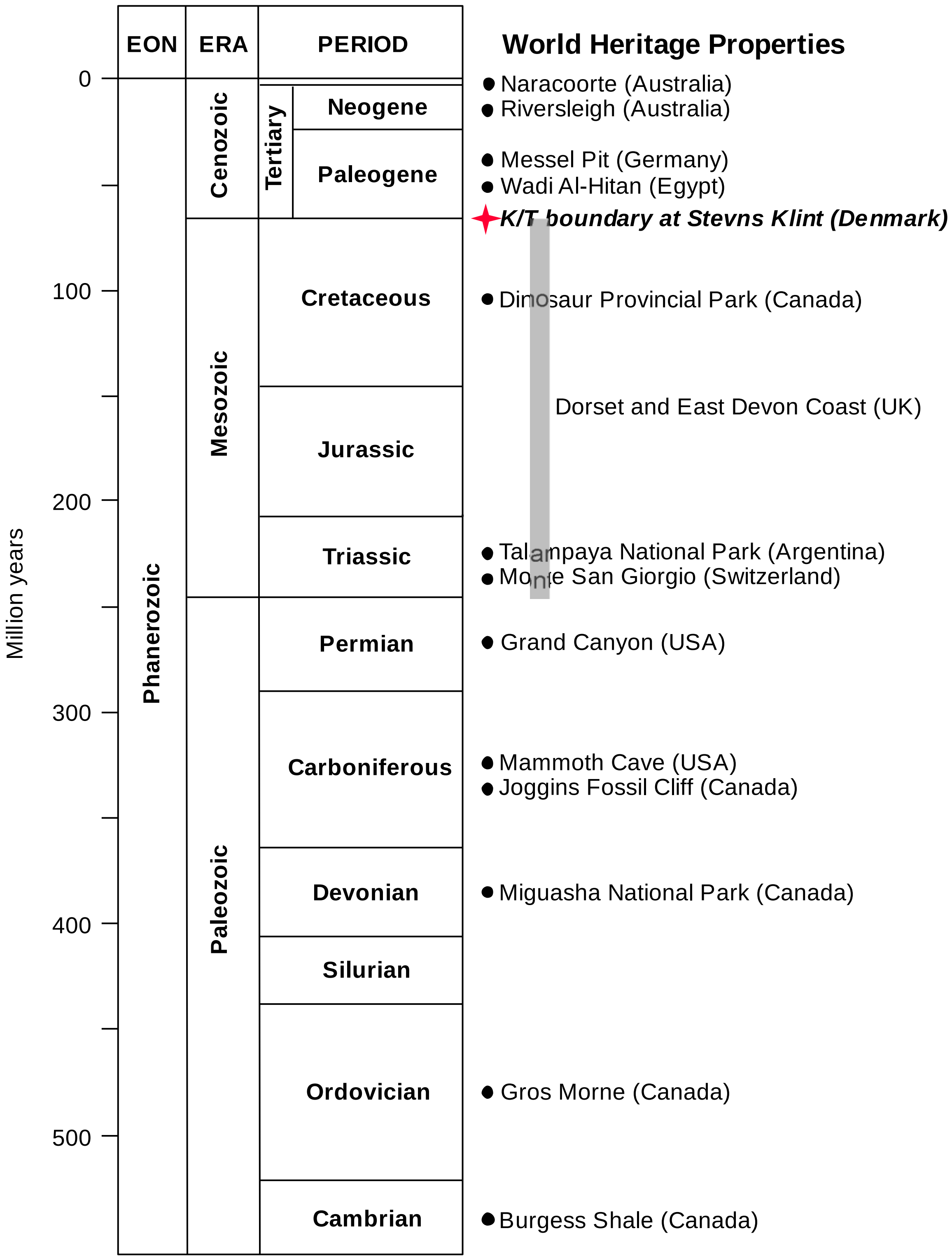


Figure 2: Stratigraphic scheme showing the major time intervals of the Phanerozoic Era and the geological interest of the K/T boundary at Stevns Klint in relation to the age of geological sites inscribed on the World Heritage list. The Stevns Klint site is written in bold and italics.

2. Problems in choosing a geological World Heritage Sites

Dorset County Council (2000) and Falcon-Lang (2002) explained in their comparative analysis of Mesozoic and Pennsylvanian fossil sites, respectively, the problems in attempting to choose a single geographical site as representative of a period of geological time. One problem is that the Earth today exhibits great variability in its environments and ecosystems and has done so throughout its history. It may be a problem to compare marine and terrestrial sections since the fossil contents and lithologies are very different. The fundamental nature of a nomination is thus the character of the nominated site as comprising a whole assemblage of significant features. Together these features result in a resource, which is both of global importance to the Earth Science, and lies within a beautiful and accessible setting.

The K/T boundary interval represents a stratigraphic site, showing the evolution of life before and after a mass extinction and not a fossil site where the surrounding environment plays a significant role. In this comparative study all environmental settings are thus included and all sites which meet the main criteria are compared.

3. Assessment criteria proposed for evaluating K/T boundary sites

The nominated K/T boundary site is considered as having outstanding universal value by meeting the criterion viii from the "Operational Guideline" to the World Heritage Convention which states that "Nominated properties shall be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features". Within criterion viii the IUCN recognises four different natural elements relevant to geological and geomorphological science (Dingwall et al., 2005). These are: Earth´s history; The record of life; Significant on-going geological processes in the development of landforms; Significant geomorphic or physiographic features. The nominated K/T boundary site belongs to Earth´s history which is defined by IUCN as a subset of geological (as opposed to geomorphological) features which are represented by phenomena that record important events in the past development of the planet such as:

- The record of crustal dynamics and tectonism, linking the genesis and development of mountains, volcanoes, plate movements, continental movement and rift valley development.
- Records of meteorite impacts.
- Records of glaciations in the geological past.

Sites in this category would be of outstanding universal value in the exhibiting elements of Earth history through rock sequences or association rather than fossil assemblages (Dingwall et al., 2005). Furthermore, thirteen geological themes, under criteria viii, are proposed by Dingwall et al. (2005) (Appendix A) and of these, the nominated K/T boundary site fits into proposal 4, stratigraphic sites, and 13, meteorite impact. Until now (2009) three stratigraphic sites are inscribed, the Grand Canyon National Park, Dorset and East Devon Coast, and Joggins Fossil Cliffs, and one meteorite impact site, the Vredefort Dome, is inscribed. The Vredefort Dome meteorite impact site represents an actual impact crater. No inscribed sites represent the physical evidence of meteorite impact together with the major changes that have resulted from the impact which can be recognised through a stratigraphic site such as the K/T boundary succession at Stevns Klint.

Criteria for selecting palaeontological World Heritage sites have been presented in different publications (Cloutier and Leliévre, 1998; IUCN, 1994; Well, 1996)). Not all these are relevant for evaluating K/T boundary sites since they were primarily developed for fossil sites of a very different nature. Falcon-Lang (2002) presented some considerations of these criteria, in the comparative analysis of Pennsylvanian fossil sites, and ended up subdividing the World Heritage Site criteria into three categories.

1. *Fossil record of biodiversity*
   The site should contain abundant fossil specimens and a large number of species, which represents the broadest possible range of major taxonomic groups.
2. *Nature, quality and variability of fossil archive in the rock section itself*
   The time interval represented by the sites; is it a "snapshot" of an ecosystem or million years of history?. Sites where ecosystems are preserved over a sustained time period are to be preferred, because they will likely better record the typical range of ecosystems types, and the community's dynamic response to changing environments and climates. Sites should encompass the greatest variety of depositional environments to paint the broadest picture of the world at a particular time interval. The sites should record aspects of the palaeobiology of the ecosystems for example evidence concerning food chains (such as coprolites or bite marks). The sites should additionally have a good fossil preservation quality.
3. *Permanency (integrity) and scientific impact of site*

Significance of the site itself. One subject is to which degree the site has been investigated and discoveries curated. Another item is that geological sites continuously under natural erosion (e.g. sea-cliffs) are to be preferred over artificial excavations because they are of greater permanency and are most likely to continuously yield new fossils in the future.

These three categories, representing previous criteria for selecting palaeontological World Heritage sites, will be used in the comparative analysis of K/T boundary sites to include all formerly used criteria for geo-sites.

3.1 Main criteria to put up a short-list of sites

Since there are more than 500 known K/T boundary sites around the world (Kiessling and Baron-Szabo, 2004) three main criteria are put together to produce a short list of K/T boundary sites for the comparative analysis. Only sites that meet these criteria are described in greater detail.

Criterion 1. The succession should be complete across the boundary representing the latest Cretaceous and the earliest Danian to represent the entire event, the nature of the mass extinction, and the subsequent recovery of life after the extinction.

Criterion 2. The potential K/T boundary sites should be well studied and described, allowing comparison.

Criterion 3. Since the K/T boundary represents an impact event, the site should include the presence of a boundary layer enriched in iridium and other elements considered to be mainly or partly of meteoritic origin. The boundary layer should be lithological different from the underlying Cretaceous sediments and the overlying Danian sediments.

These three criteria makes sure that sites used for the comparative analysis tell the complete story of the extraterrestrial impact and the time-equivalent extinction by the presence of impact traces in the boundary layer and the presence of both Cretaceous and Danian sediments to prove the faunal turnover across the K/T boundary.

3.1.1 Sites meeting the three main criteria

Details about more than 500 K/T boundary sites around the world have been collected in a comprehensive database (KTbase) designed to evaluate the causes and mechanisms of the K/T boundary event (Kiessling and Claeys, 2001; Kiessling and Baron-Szabo, 2004). The KTbase is not public assessable but Professor Wolfgang Kiessling filtered the database and recorded 43 boundary sites which are exposed sections (ODP sites were excluded), complete across the boundary, includes the presence of a boundary layer enriched in iridium and other elements, and provide good data quality (Table 1). The 43 sites together with eight well known, possibly complete localities were tested for their scientific impact by making searches of K/T, C/P or K/P together with the locality name on the standard databases Web of Science and GeoRef (Table 1). Of the 51 K/T boundary sites analysed for scientific impact, 17 sites turned out to be well described with more than 10 scientific papers in either of the databases (Table 1). The 17 sites do all have a boundary layer which is lithological different from the underlying Cretaceous sediments and the overlying Danian sediments and is enriched in iridium. These 17 K/T boundary sites are therefore used for the comparative analysis of potential K/T boundary sites (Table 2). The 17 sites are distributed in 13 countries and on six continents, only missing a site on the South American continent (Fig. 3).

Table 1: K/T boundary sites which are complete across the boundary. The table show the scientific impact of each site found on the online databases; web of Science and GeoRef. The impact is found by searching for K-T, K-P or C-P together with the site name. Only the highest impact found on either Web of Science or GeoRef are listed.

K/T boundary sites	Country	Scientific impact
El Kef	Tunesia	97
Stevns Klint	Denmark	53
Hell Creek	USA, Montana	53
Caravaca	Spain	45
Raton Basin	USA, New Mexico	25
Brazos River	USA, Texas	24
Beloc	Haiti	22
Mimbral	Mexico	22
Geulhemmerberg	Netherlands	22
Agost	Spain	22
Gubbio	Italy	19
Hokkaido	Japan	17
Nye Kløv	Denmark	11
Seymour Island	Antarctica	11
Elles	Tunesia	11
Flaxbourne River	New Zealand	11
Aïn Settara	Tunesia	11
Woodside Creek	New Zealand	10
Zumaya	Spain	8
Koshak	Kazachstan	6
Sopelana	Spain	3
Poty, Paraiba Basin	Brazil	6
Moody Creek	New Zealand	2
Kjølby Gaard	Denmark	2
Lattengebirge	Germany	2
Sumbar	Turkmenistan	2
Erto	Italy	2

Actela	Guatemala	2
Herrera	Spain	2
Dania	Denmark	1
Rotwandgraben	Austria	1
Malyi Balkhan	Turkmenistan	1
Gamba	China	1
Millers Ferry	USA, Alabama	1
Trinitaria	Mexico	1
Moscow Landing	USA, Alabama	1
Canon San Fernando	Mexico	1
Via Perimetral	Equador	0
Urrutxua	Spain	0
Irurtzun	Spain	0
Matisgraben	Switzerland	0
Elendgraben	Austria	0
Rio Minho	Jamaica	0

Table 2: K/T boundary sites meeting the general criteria, their palaeoenvironments, palaeolatitudes, and current locations.

K/T boundary sites	Country	Scientific impact	Environment / depth	Palaeolatitude	Location
El Kef	Tunesia	97	Upper bathyal 300−500 m	ca. 25˚N	Valley
Stevns Klint	Denmark	53	Epicontinental sea 100−200 m	ca. 50˚N	Coastal cliff
Hell Creek	USA, Montana	53	Terrestrial		Valleys
Caravaca	Spain	45	Middle bathyal 600−1000 m	ca. 30˚N	Valley
Raton Basin	USA, New Mexico	25	Terrestrial		Road cut
Brazos River	USA, Texas	24	Middle−outer shelf < 100 m	ca. 30˚N	River bank
Beloc	Haiti	22	Deep marine 1500−2000 m		Road cut
Mimbral	Mexico	22			Stream bank
Agost	Spain	22	Middle bathyal	ca. 30˚N	Road cut
Gubbio	Italy	19	Lower bathyal 1500−2500 m	ca. 35˚N	Road cut
Hokkaido	Japan	17	Upper bathyal (300−600 m) shallowing to 150−300 m	ca. 50˚N	Stream bank
Nye Kløv	Denmark	11	Inner neritic	ca. 50˚N	Abandoned quarry
Seymour Island	Antarctica	11	Shallow mid shelf	ca. 65˚S	Valleys and coastal cliff
Elles	Tunesia	11	Middle to outer neritic shelf	ca. 25˚N	Valley
Flaxbourne River	New Zealand	11	Mid-bathyal		Quarry
Aïn Settara	Tunesia	11	Middle to outer neritic shelf	ca. 25˚N	Along a channel
Woodside Creek	New Zealand	10	Upper bathyal		Creek

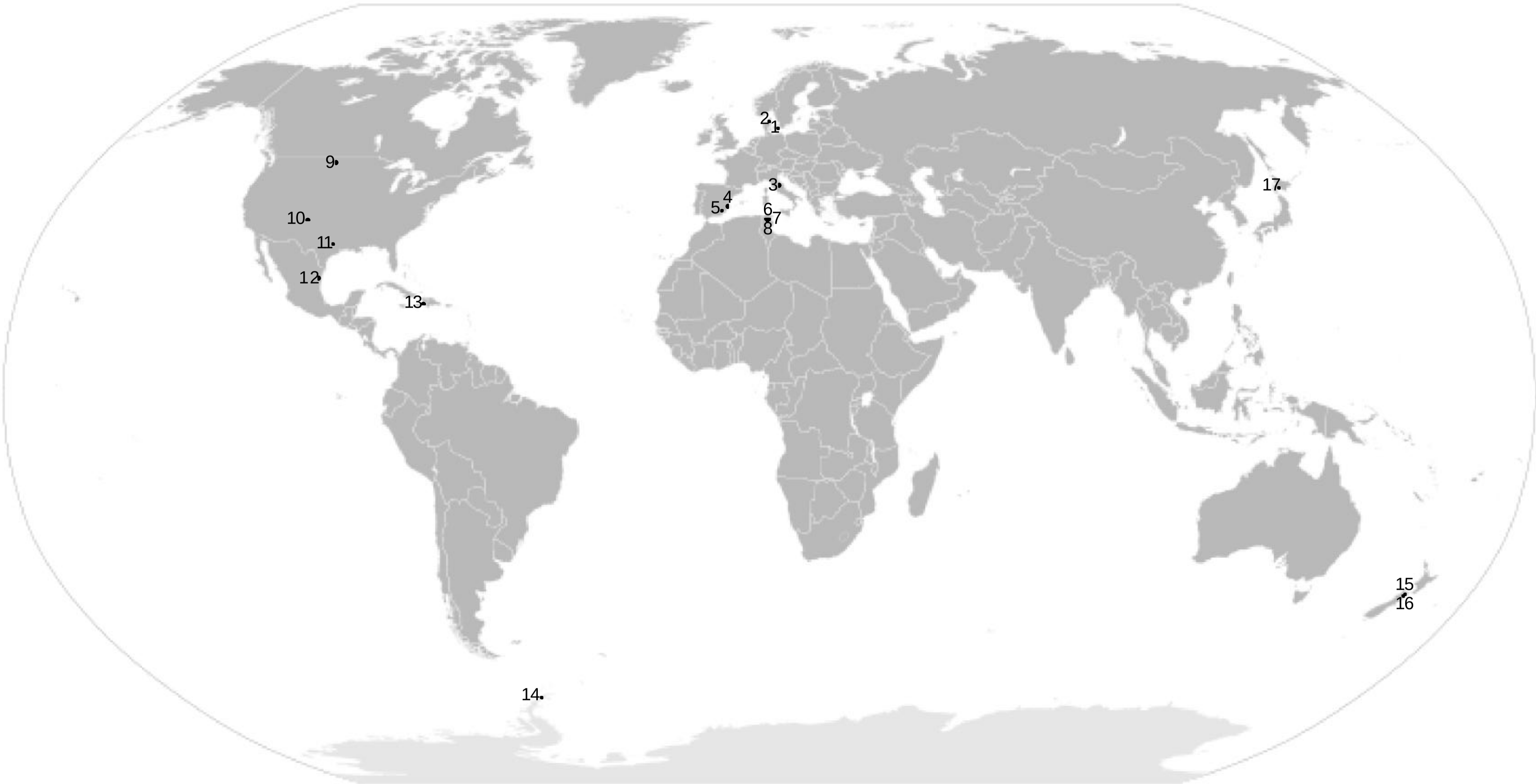


Figure 3: Sketch map showing locations of K/T boundary sites meeting the general criteria. 1 − Stevns Klint, 2 − Nye Kløv, 3 − Gubbio, 4 − Agost, 5 − Caravaca, 6 − El Kef, 7 − Elles, 8 − Aïn Settara, 9 − Hell Creek, 10 − Raton Basin, 11 − Brazos River, 12 − Mimbral, 13 − Beloc, 14 − Seymour Island, 15 − Flaxbourne River, 16 − Woodside Creek, 17 − Hokkaido.

4. Description of K/T boundary sites meeting the main criteria

4.1 Stevns Klint, Denmark – Marine section

Geographic description of the site

The Stevns Klint site is located about 45 km south of the Danish capital, Copenhagen on the east coast of the Danish island of Sjælland. The site comprises a 14.5 km long coastal cliff which can be easily reached by taking road 261 from Strøby Egede to Rødvig where access can be made from different places along the road.

Lithology and palaeoenvironment

The site is 14.5 km long and the exposed succession is up to 41 m thick. The lower parts of the cliff expose upper Maastrichtian chalk with bryozoan chalk wackestone at the top outlined by thin layers of nodular flint. The chalk is overlain by the K/T boundary clay, the Fish Clay, which is generally about 5–10 cm thick and enriched in iridium. The position of the boundary layer varies from about 5 m below to about 30 m above present day sea level. The irregular relief represents a depositional sea-floor topography (Lykke-Andersen and Surlyk, 2004). The Fish Clay passes gradually upwards into the strongly burrowed lowermost Danian Cerithium Limestone. A hardground surface truncates the top of the Cerithium Limestone and the intervening crests of the uppermost Maastrichtian mounds. This surface is overlain by lower Danian bryozoan limestone mounds outlined by thick black flint bands which illustrates the geometry, dimensions and architecture of one of the finest cool-water carbonate mound complexes in the world (Surlyk et al., 2006).

Fossil content

The site contains a rich and varied microbiota of foraminifers, dinoflagellates, and calcareous nannofossils. It is one of the few K/T boundary sites where the macrofauna is diverse and well preserved, comprising bivalves, echinoids, brachiopods, solitary corals, bryozoans, polychaetes, gastropods, asteroids, sponges, crinoids, tracefossils, and vertebrate remains.

Significance of the site

The beautiful coastal cliff Stevns Klint is one of the most famous, scenic and best exposed K/T boundary sites in the world where the exceptional K/T boundary layer is easily recognised just beneath the topographic overhang of the younger and harder Tertiary limestone. It is a classical K/T boundary site and constitutes the type locality of the Danian Stage. It is one of the three discovery localities of the famous iridium anomaly, which formed the basis for the asteroid impact hypothesis of Alvarez et al. (1980) to explain the mass extinction at the end of the Cretaceous. Stevns Klint is therefore a key locality in the ongoing debate about the K/T boundary and international researchers have flocked to Stevns Klint to sample the famous iridium-rich boundary clay. It is also visited by numerous student excursions, school classes and tourists every year. Furthermore, the Stevns Klint site shows an excellent exposure of one of the finest examples in the world of a cool water, sub-photic carbonate mound complex (Surlyk et al., 2006).

The K/T boundary at Stevns Klint immediately beneath the ovehang at the middle of the cliff (photo: Anne M. Sørensen).

4.2 Nye Kløv, Denmark − Marine section

Geographic description of the site

The Nye Kløv site is located in a small abandoned chalk quarry with an average dimension of 40 m in length and 20 m in height. The quarry is situated few kilometres north of Lønnerup Fjord in the northern part of Jylland (Johansen, 1987). The exposure is at present covered by talus and it is necessary to excavate a trench to locate the boundary.

Lithology and palaeoenvironment

The exposed site across the K/T boundary is about 20 m thick, including 8 m of Maastrichtian and 12 m of Danian chalk. The Maastrichtian sediments consist of white chalk with scattered flint nodules and macrofossils. The K/T boundary is marked by a 3 cm thick brownish-grey marly clay with rust at its base and an enrichment in iridium. The Danian sediments consist of 0.5 m thick greyish marly chalk layer topped by 8.5 m white bryozoan limestone, containing as much as 25 wt % bryozoans, interbedded with 10 to 20 cm thick flint nodule layers (Johansen, 1987). Macrofossils in the bryozoan limestone increasing in abundance and diversity upwards (Håkansson and Hansen, 1979; Surlyk and Johansen, 1984).

Fossil content

The site contains microbiota of dinoflagellates, foraminifers, and calcareous nannofossils. Furthermore, it is one of the few K/T boundary sites where the macrofossils are well preserved and contains bryozoans, echinoids, bivalves, brachiopods, and trace fossils (Surlyk and Johansen, 1984; Johansen, 1987; Keller et al., 1993; Kiessling and Claeys, 2001)

Significance of the site

The Nye Kløv site is one of the few complete K/T boundary sites with a high quality record of the K/T extinction pattern for macrofossils.

The K/T boundary at Nye Kløv is exposed behind people in each side of the site (photo: Anne M. Sørensen).

4.3 El Kef, Tunesia – Marine section

Geographic description of the site

The El Kef site is located 7 km west of the town of El Kef. The site is reached by taking an unpaved road leading to the village of Hamman Mellégue located near the site. About 2 km along this unpaved road is a small cement water reservoir overlooking a large valley formed in Maastrichtian to Eocene limestones and marls. From this location the K/T boundary site can be found by descending into the valley for about 1.5 km on a gentle slope within the soft grey marl of the El Haria Formation (Keller et al., 1995).

Lithology and palaeoenvironment

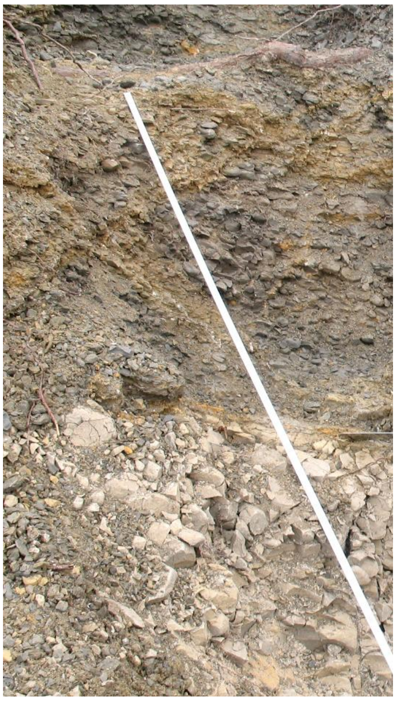
The K/T boundary site of El Kef is contained within the El Haria Formation. The Maastrichtian sediments consist of relative carbonate rich grey marl with about 40% $CaCO_3$ and with common burrows about 2−3 cm long (Keller, 1988b). The K/T boundary is marked by a 50 cm black, organic-rich clay layer with about 3−4% $CaCO_3$ and an overlying 50−60 cm marly clay layer with about 10% $CaCO_3$. A 2−3 cm oxidised thin rust-red layer at the base of this clay unit marks the boundary event and define the K/T boundary. The thin rust-red layer shows a drop in $CaCO_3$, a maximum of organic carbon, and a negative excursion in $\delta^{13}C$. It contains the iridium anomaly and other impact evidence such as the Ni-rich spinels, shocked quartz grains, Os anomaly and spherules of sanidine and hematite (Arenillas et al., 2000). The red layer is continuous and can be followed over several hundred metres (Abdelkader et al., 1997). No burrows are observed through the red layer or in the black clay (Keller, 1988b). The Danian sediments consist of relatively carbonate rich grey marls with about 40% $CaCO_3$. The upper Maastrichtian − Danian succession is more than 500 m thick and consist predominantly of hemipelagic calcareous marls with few micritic limestone intervals. Obvious breaks in sedimentation or hardgrounds are absent in the entire interval (Smit, 1999)

Fossil content

The site contains a rich and varied microbiota of foraminifers, ostracods, coccoliths, and dinoflagellate cysts but spores and pollen from the hinterland are also found. Insignificant amounts of macrofossils, mainly echinoids, inoceramid bivalves, and ammonites are found, whereas tracefossils are abundant. The absence of bioturbation across the boundary makes a very precise biostratigraphic study possible (Abdelkader et al., 1997; Smit, 1999).

Significance of the site

The El Kef site was officially designated the K/T boundary global stratotype site and point (GSSP) in 1989 at the 28th International Geological Congress in Washington (Arenillas et al., 2000). The selection is based on the abundant presence of well-preserved microfossils and the unusually complete and expanded sedimentary succession where the litho- and biostratigraphic units used to recognise the K/T boundary are thicker than in other pelagic sites (Dingus, 1984). Furthermore, the absence of bioturbation and the high sedimentation rate in quiet conditions preserve a high resolution record of the K/T transition where hiatuses have not been identified (Abdelkader et al., 1997). Due to selection to the global stratotype site and point for K/T boundaries the El Kef stratotype is endangered by oversampling and on top of this agricultural encroachment also threat the site (Karoui-Yaakoub et al., 2002).



The K/T boundary at El Kef (From http://images.google.com/imgres?imgurl=http://www.panoramio.com/photos/original/12358292.jpg&imgrefurl=http://www.panoramio.com/photo/12358292&usg=__fY7fJJf-r0u8AtK3n-U4dbE-dD8=&h=1200&w=1600&sz=1533&hl=fr&start=4&itbs=1&tbnid=TFf8kmS0KdH8sM:&tbnh=113&tbnw=150&prev=/images%3Fq%3DKT%2Bboundary%2Bel%2Bkef%26gbv%3D2%26hl%3Dfr).

4.4 Elles, Tunesia – Marine section

Geographic description of the site

The Elles site is located 75 km southeast of the El Kef GSSP site in a valley near the small town of Elles. The site is reached by driving about 7 km along an unpaved road leading to the village of Elles where a wide, ca. 4 km long valley begins. The valley is cut by the usually dry Karma River. The valley continuously exposes sediments spanning from the Campanian to the lower Eocene. The K/T boundary outcrops in numerous places and can be traced over hundreds of metres along the slopes of the valley. The location of the K/T boundary is based on the same lithological changes and planktonic foraminiferal extinctions and evolutions as at the El Kef stratotype (Karoui-Yaakoub et al., 2002).

Lithology and palaeoenvironment

The Maastrichtian succession consists of grey shales and several thin marly limestone layers. The K/T boundary is well marked by a 5−30 cm thick bioclastic packstone. Above this layer is a 0.5−1.0 cm thick clay layer followed by a 3−4 mm thick rust-red layer associated with two thin gypsum layers. This red layer marks the K/T boundary event and contains altered spherules, Ni-rich spinels and maximum concentrations of iridium. The red layer is overlain by a 50−60 cm thick dark grey to black clay layer followed by 6 m of gradually lighter coloured clayey shales. The Danian succession consists of 7.5−12 m grey shales interbedded with several thin marly limestone layers, overlain by another 8 m of marly shales which grade into interbedded limestone and marl layers (Karoui-Yaakoub et al., 2002)

Fossil content

The site contains a rich and varied microfauna and nannoflora, including foraminifers, ostracods and coccoliths. No macrofossils are recorded from the Elles site around the K/T boundary.

Significance of the site

The Elles site is complete with all the indicated foraminifer zones and subzones being slightly more expanded than elsewhere. The Elles site thus exposes a better K/T interval outcrop compared to the El Kef site. This supports the proposal of the Elles site to be designated as a new sratotype or at least parastratotype (Zaghbib-Turki et al., 2001). Furthermore, due to the many outcrops oversampling is not a concern, like at El Kef, and there is no danger of destruction due to agricultural encroachment because of the steep valley slopes (Karoui-Yaakoub et al., 2002).

The K/T boundary at Elles (Photo: Nicolas Thibault)

4.5 Aïn Settara – Marine section

Geographic description of the site

The Aïn Settara site is located in the Atlas Mountains about 50 km southeast of the El Kef site. The K/T boundary is exposed in the 100 m high, very steep flank of a deeply incised gully at about 80 m above the base of the gully. The boundary can be traced horizontally over more than 200 m. The exposure of the boundary is excellent since there is almost no vegetation on the steep slope (Dupuis et al., 2001; Luciani, 2002).

Lithology and palaeoenvironment

The uppermost Maastrichtian succession consists of grey silty marls with a strongly burrowed upper boundary and carbonate content of 35−45%. Few bivalves, brachiopods, and solitary corals occur at about 14 cm below the top of the marls. The K/T boundary is marked by a thin dark clay layer with a 0.5 cm thick red oxidized layer at its base containing maximum iridium concentrations and Ni-rich spinels. The entire dark boundary clay is about 60 cm thick with a carbonate content of 4−5%

which increases upwards to about 5−20%. The Danian succession consists of light grey marl with a marked upward increase in carbonate content to 35% (Dupuis et al., 2001; Luciani, 2002).

Fossil content

The site contains a rich and varied microfauna including foraminifers, calcareous nannofossils, and dinoflagellate cysts and invertebrates such as bivalves, brachiopods, and solitary corals (Dupuis et al., 2001).

Significance of the site

The Aïn Settara site is more complete in the uppermost Maastrichtian than the El Kef site (Dupuis et al., 2001).

4.6 Agost, Spain – Marine section

Geographic description of the site

The Agost site is located about 1 km north of the village of Agost in the Alicante provins, in SE Spain ca. 100 km east of the Caravaca K/T boundary site. The K/T boundary is well exposed along a roadcut near the 13 km marker post of the Agost-castalla road (Molina et al., 2005).

Lithology and palaeoenvironment

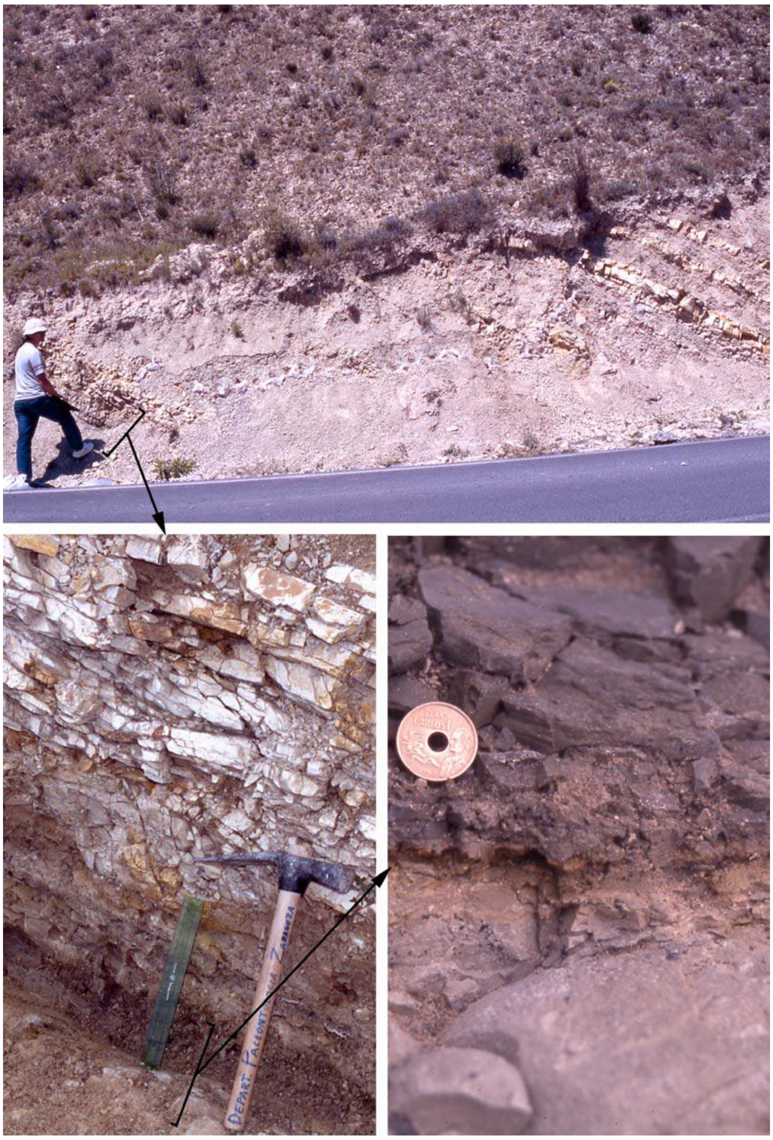
The Maastrichtian succession consists of grey marls, interbedded with marly limestones; the latter are very scarce in the uppermost Maastrichtian. The K/T boundary is marked by a 12 cm thick layer of black clay, with a 2−3 mm thick, red layer at its base. The red layer marks the K/T boundary and contains spherules, Ni-rich spinels and maximum concentrations of iridium. Furthermore, it contains goethite, hematite, glauconite clasts, scarce foraminifers and a sharp decrease in carbonate content compared to the immediately underlying beds. The black clay is overlain by a 10 cm thick layer of massive grey clay. The Danian succession consists of two decimetre-thick tabular bodies of marly limestones with a decimetre-thick intercalated layer of marls. The upper part of the site consists mainly of marly limestones. Trace fossils are abundant across the boundary (Molina et al., 2005).

Fossil content

The site contains a rich and varied foraminiferal and ostracod fauna, nannofossil cocclith flora and insignificant amounts of macrofossils, mainly echinoids, inoceramid bivalves, ammonites, and abundant tracefossils (Smit, 1999; Molina et al., 2005).

Significance of the site

The Agost section is one of the most continuous and expanded K/T boundaries in the Tethys region and is therefore considered a classical K/T boundary site which has been studied from different points of view, such as micropaleontology, paleoichnology, magnetostratigraphy, mineralogy, and geochemistry (Molina et al., 2005). The site is exposed in a roadcut where the succession is tilted and the K/T boundary can therefore only be studied in a limited area.



The K/T boundary at Agost. Top: General view of the uppermost Cretaceous and lower Tertiary. Left: Detail of the lower Danian dark clay layer. Right: Detail of the red rusty layer at the K/T boundary (From Molina et al., 2005).

4.7 Caravaca, Spain – Marine section

Geographic description of the site

The Caravaca site is located 4 km SE of the village of Caravaca and about 100 km vest of the Agost site in SE Spain.

Lithology and palaeoenvironment

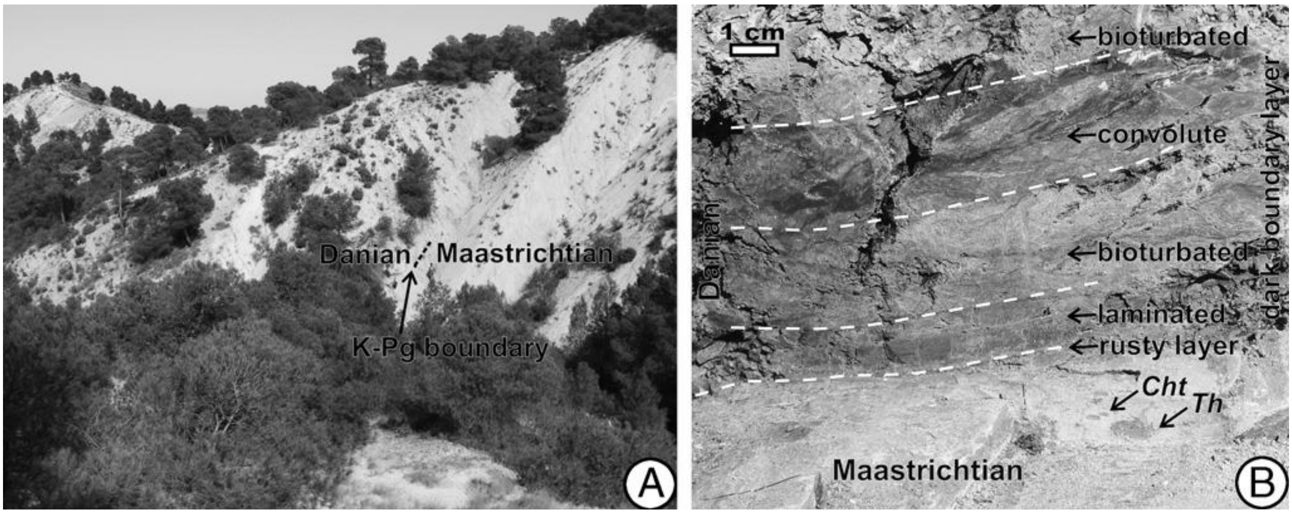
The site belongs to the Jorquera Formation (lower Maastrichtian – lower Danian), which is about 225 m thick and made up of intercalated marls, marly limestones and occasional turbidites. No turbidites are present from 1 m below to 2 m above the K/T boundary (Canudo et al., 1991). The Maastrichtian succession consist of marlstones. The K/T boundary is well marked by a dark 7−10 cm thick dark clay layer which has a sharp decrease in carbonate from 80% in the immediately underlying bed to 20%. A 1−2 mm thick rust-red layer is found at the base of the clay and contains maximum concentrations of iridium and spherules. The Danian sediments consist of marlstones (Robin et al., 1991; Arinobu et al., 1999).

Fossil content

The site contains a rich and varied foraminifer fauna and nannofossil cocclith flora and insignificant amounts of macrofossils, mainly echinoids, inoceramid bivalves, ammonites, and abundant trace fossils (Smit, 1999; Rodríguez-Tovar and Uchman, 2006).

Significance of the site

The Caravaca site is characterized by high completeness, probably preserving sediment during each 10,000 yr interval of chron 29R, as well as an exceptional foraminifer record (Dingus, 1984; Rodríguez-Tovar and Uchman, 2006). Unfortunately urban and road-building development has threatened the excellent exposures, and the lower 100 m of the upper Maastrichtian are already not longer accessible (Smit, 2004).



The K/T boundary at Caravaca (A) View of the eastern slope of the valley, where the boundary is located. (B) The dark boundary layer with its subdivisions; *Chondrites targionii* (Cht) and *Thalassinoides* (Th) in cross-site (From Rodriguez-Tovar and Uchman, 2006).

4.8 Gubbio, Italy – Marine section

Geographic description of the site

The Gubbio site is located within 1 km north of the town of Gubbio along the road to Scheggia in the Bottaccione Gorge in the Umbria-Marche Apennines, central Italy (Arthur and Fisher, 1977; Cronholm and Schmitz, 2007).

Lithology and palaeoenvironment

The K/T boundary site of Gubbio is contained within the Scaglia Rossa Formation which consists predominately of pink to red homogeneous limestone and marly limestone that have been thoroughly bioturbated and compacted prior to cementation (Cronholm and Schmitz, 2007) The limestones generally contain about 5% clay. The K/T boundary is marked by a 1−2 cm thick dark clay layer and is further marked by a 20−50 cm thick zone of white bleached limestone underlying the clay (Alvarez et al., 1980; Cronholm and Schmitz, 2007). The boundary clay is enriched in iridium and contains about 50% $CaCO_3$ but this is coarse-grained calcite that probably crystallised during deformation long after deposition (Alvarez et al., 1980).

Fossil content

The site comprises a rich foraminifer fauna and calcareous nannofossils.

Significance of the site

The Gubbio site is one of the three classic discovery locations for the of the iridium anomaly (Alvarez et al., 1980). The succession is tilted and the K/T boundary can therefore only be studied in a limited area.

The K/T boundary at Gubbio. The boundary layer is located in the deep fissure (Photo: Anne M. Sørensen)

4.9 Woodside Creek, New Zealand – Marine section

Geographic description of the site

The Woodside Creek site is located in the eastern Marlborough on the northern South Island of New Zealand and can be reached by a 15 minute walk up the creek, past some patchy outcrops of Eocene mudstone. The K/T boundary is exposed on both banks about 50 m into the gorge and is easily recognised by the many drill holes from a palaeomagnetic study.

Lithology and palaeoenvironment

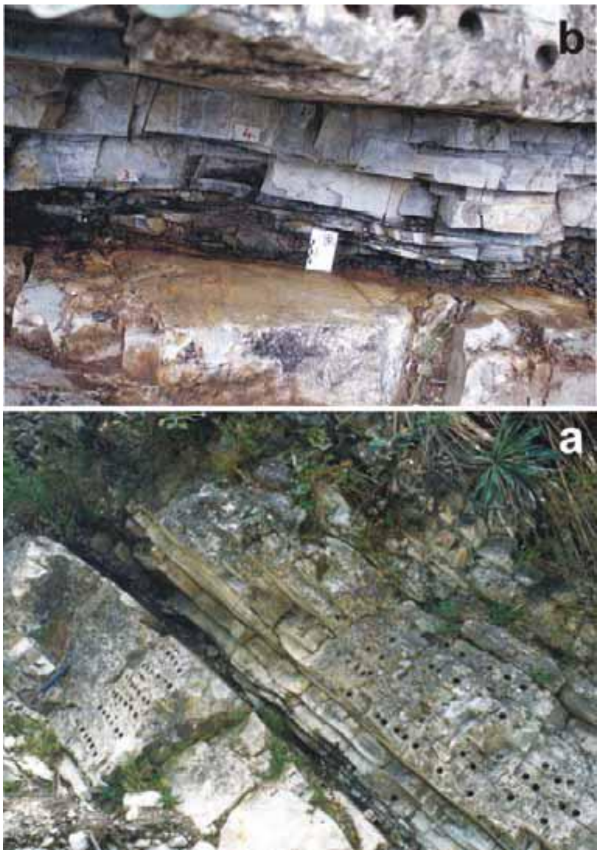
The Maastrichtian succession consists of 30 m of light green-grey, bedded, siliceous limestone with thin marl interbeds. The K/T boundary is marked by a 25 mm thick boundary clay with anomalous enrichment in iridium, shocked quartz and microtektites, abundant soot-like carbon, and a negative excursion in bulk carbonate and kerogene $\delta^{13}C$. The Danian succession consists of a 0.15 m dark green-grey, bedded, clay-rich, porcellanite overlain by 9.2 m light green-grey, bedded, clay-poor, porcellanite; 18.5 m light green-grey, bedded, clay-poor siliceous limestone; 7 m pink, bedded limestone and 8 m yellow-brown, quartz-rich limestone with rare chert nodules (Hollis et al., 2003).

Fossil content

The site contains common planktonic foraminifers and radiolarians throughout, whereas benthic foraminifers and diatoms are common in some intervals. Dinoflagellate cysts and other palynomorphs are present in the uppermost Maastrichtian and lowest Danian. Most of the calcareous nannofossils are too poorly preserved for confident identification (Hollis et al., 2003). No macrofossils are recorded from Woodside Creek.

Significance of the site

The Woodside Creek site is one of the three classic locations for the discovery of the iridium anomaly (Alvarez et al., 1980) and is the stratotype for the radiolarian RK 9 and RP1−RP4 biozones (Hollis et al., 2003). The succession is tilted and the K/T boundary can therefore only be studied in a limited area.



The K/T boundary at Woodside Creek. The boundary layer is located in the deep fissure (From Strong and Hollis, 2009: Photo a C. Hollis, Photo b B. Field).

4.10 Flaxbourne River, New Zealand – Marine section

Geographic description of the site

The Flaxbourne River site is located on the northern South Island of New Zealand within the Chancet Quarry. A guide is needed to locate the K/T boundary (Strong and Hollis, 2009).

Lithology and palaeoenvironment

The Maastrichtian succession consists of 13.2 m light green-grey limestone with thin marl partings overlain by 2−3 cm white marl, with an irregular upper contact. The K/T boundary is marked by a 1−3 cm thick layer which consists of a 3−5 mm thick basal red brown clay layer enriched in iridium, an 8−10 mm thick grey layer, and an uppermost 8−10 mm thick grey brown layer. The overlying Danian succession consists of 48 cm thick, dark grey, laminated, bedded, clay-rich porcellanite alternating with calcareous, siliceous claystone and 10.5 m yellow-grey, bedded, clay-poor porcellanite to siliceous limestone (Hollis et al., 2003).

Fossil content

The site contains common planktonic foraminifers and radiolarians throughout, whereas benthic foraminifers and diatoms are common in some intervals. Dinoflagellate cysts and other palynomorphs are not found at the Flaxbourne site and no macrofossils are recorded (Hollis et al., 2003)

The K/T boundary at Flaxbourne River, Chancet Quarry (From Strong and Hollis, 2009: Photo C. Hollis).

4.11 Mimbral, Mexico – Marine section near the impact area

Geographic description of the site

The Mimbral site is located in northeastern Mexico on the southwestern flank of the isolated mountain range Sierra de Tamaulipas. It is located on the southern bank of the Mimbral creek approximately 10 km east of the main road from Ciudad Victoria to Tampico (Keller et al., 1994). The site is 152 m long and of variable height, ranging from 1 m to 36 m. It is reached by a rough, unpaved, and often poorly graded dirt road (Keller et al., 1994).

Lithology and palaeoenvironment

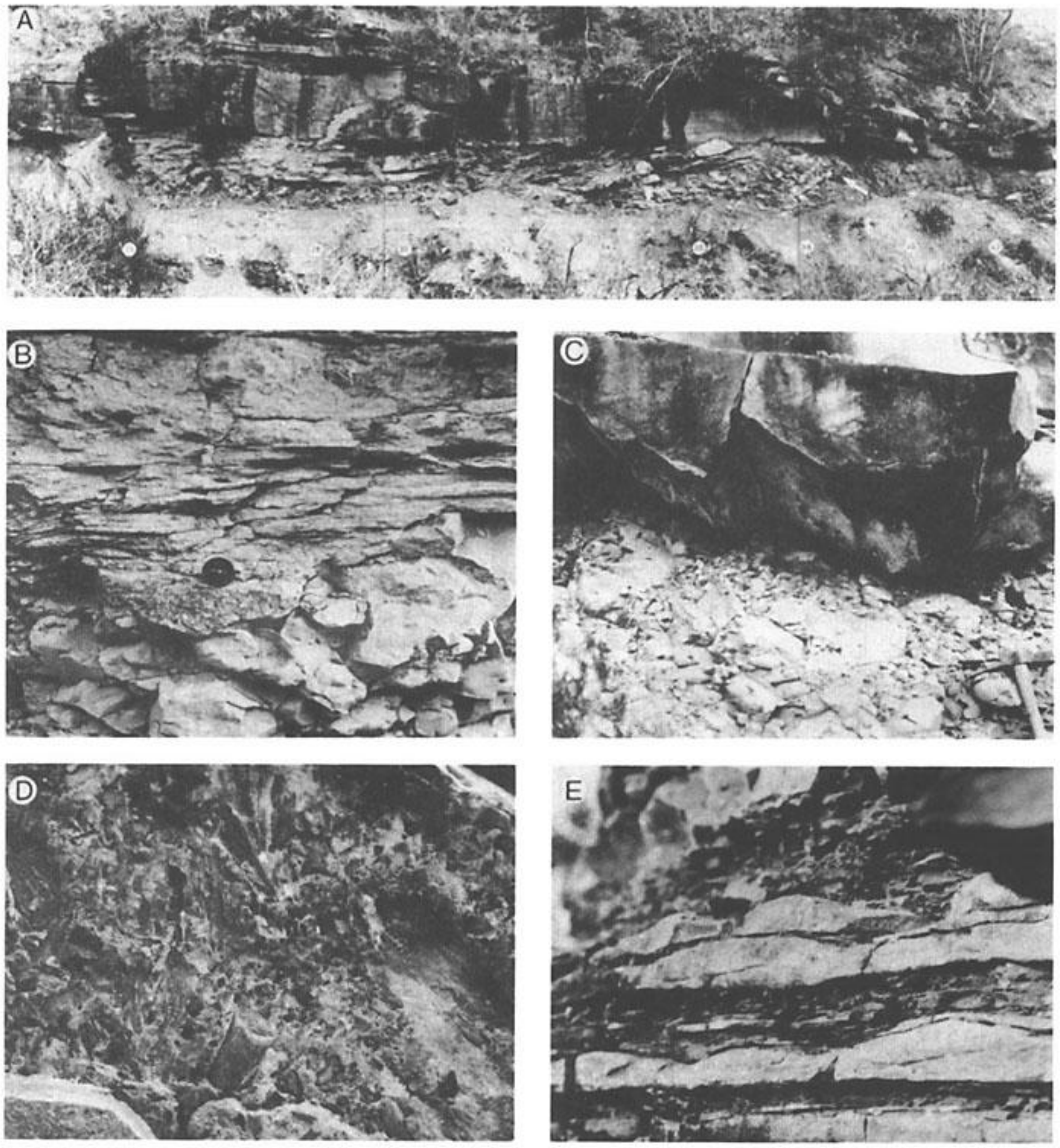
The Maastrichtian succession consists of 30 m of rhythmically bedded marls and limestones and occasional thin bentonite layers overlain by clastic deposit of variable thickness from 0.2–3 m, apparently representing channel-fill. The channel fill sediments consist of a basal unit characterised by spherules and relict impact glass overlain by a unit of laminated sandstone with mud clasts and plant debris at its base followed by series of cross-laminated sandstone, siltstone, and mudstone layers (Hough et al., 1997). The cross-laminated beds are overlain by a 4 cm thick silt layer, enriched in iridium. The iridium enriched layer is overlain by 7 cm of micritic limestone which again is overlain by up to 2.5 m of greyish shale (Smit et al., 1996). The channel fill sediments are designated as the K/T boundary sandstone and has been interpreted as deposited by large tsunami waves, caused by the Chicxulub impact (Smit et al., 1996). Although the impact itself did not occur in the deep ocean basin a large part of the ejecta curtain, presumably thousands of cubic kilometres, fell in the Gulf of Mexico, and slope failures along the Campeche escarpment may additionally have trigged tsunamis (Smit, 1999).

Fossil content

The site contains foraminifers and abundant trace fossils. Furthermore, the middle unit of the channel contains rare siliceous sponges and is rich in plant debris and pieces of wood.

Significance of the site

The Mimbral site is located very close to the Chicxulub impact area and the succession shows the result of the impact in deep water, not as the classical impact ejecta layer but as a presumed tsunami layer caused by the impact.



The K/T boundary at Mimbral. A) View of outcrop; circled numbers indicate 2 m horizontal intervals. B) Deep scour with spherules. C) Groove casts at the base of lowest laminated bed. D) Fossil plant material in lowest laminated bed. E) Rippled sandstone beds separated by clay layers (From Smit et al., 1992).

4.12 Beloc, Haiti – Marine section near the impact area

Geographic description of the site

The Beloc site is located in the southern part of the Haitian peninsula along the road from Port au Prince to Beloc and Jacmel (Leroux et al., 1995; Stinnesbeck et al., 1999). A complete K/T interval is preserved in a graben about 1 km north of Beloc on a steep slope and 30−40 m below the road.

All other road cut sites are intensely faulted, folded and sheared and in particular the K/T boundary clay is generally sheared and highly condensed (Stinnesbeck et al., 1999).

Lithology and palaeoenvironment

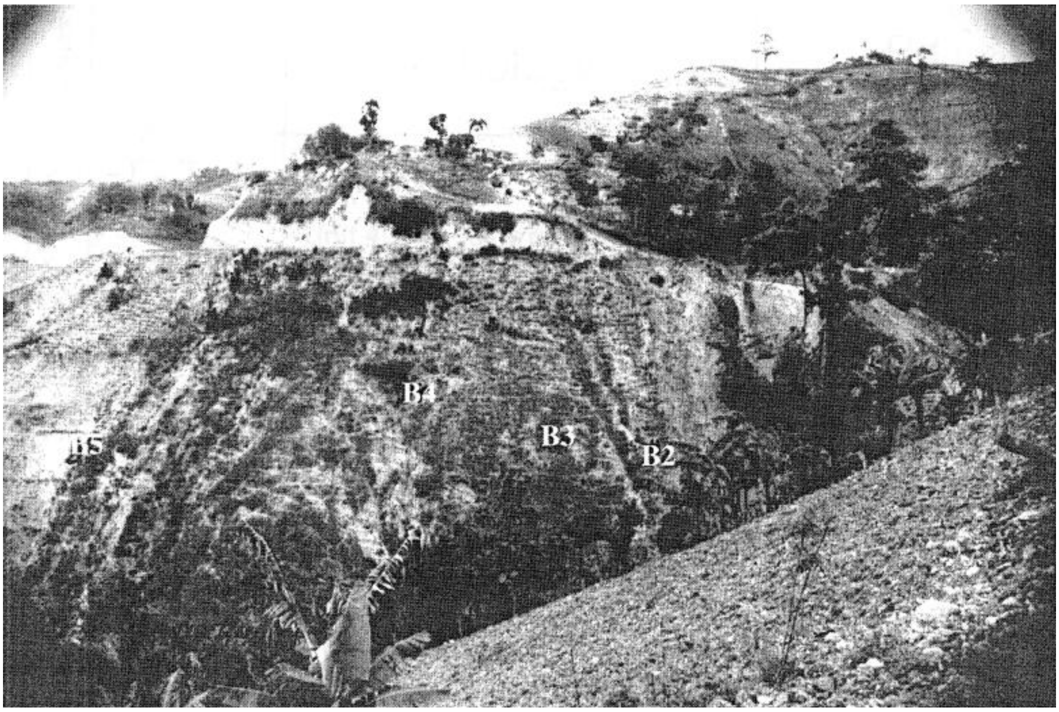
The Beloc site consists of more than 100 m of Upper Cretaceous and 30 m of horisontal Danian which are exposed along the hillslope. The Maastrichtian succession consists of pelagic marly limestone with an undulating erosional upper surface (Stinnesbeck et al., 1999). The K/T boundary is marked by a 30 cm thick layer of spherules possibly representing impact ejecta (Leroux et al., 1995). The K/T boundary layer is 10−30 cm thick in road outcrops and reaches a maximum thickness of 70 cm along the slope. The upper 5-15 cm are characterised by the presence of abundant black glass spherules, abundant spherule debris and rounded limestone clasts. The K/T boundary layer is overlain by 6 cm of Cretaceous bioclastic limestone and on top of this is a 2 cm thick grey-green shale layer with a thin, rust-coloured layer containing maximum concentrations of iridium, Ni-rich spinels and shocked minerals (Leroux et al., 1995; Stinnesbeck et al., 1999). The iridium-rich layer is overlain by a 50 cm thick limestone layer, which is overlain by a 0.5 cm thick and rust-coloured clay layer characterised by a palladium enrichment and low iridium values. The clay is overlain by a 1 cm thick volcanic tuff layer and a 10 cm thick volcanic-rich marl layer. The Danian succession consist of marly limestone (Stinnesbeck et al., 1999).

Fossil content

The site contains a rich and varied microbiota of foraminifers, radiolarians, calcispheres, sponge spicules, and ostracods (Stinnesbeck et al., 1999).

Significance of the site

The Beloc site is famous for the content of vesicular glass cores inside spherule droplets and 1−2 cm-sized blebs with rims of smectite (Smit, 1999). The site probably suffered from a major extraterrestrial impact at or before the K/T boundary as suggested by the spherule-rich layer, possibly a second impact event suggested by the iridium anomaly, and a major volcanic event suggested by the palladium-dominated anomaly (Stinnesbeck et al., 1999).



The K/T boundary at Beloc. B2 − B5 represents K/T interval sections (From Stinnesbeck et al., 1999)

4.13 Brazos River, USA – Marine section

Geographic description of the site

The Brazos River site is exposed in the low banks and on the floor of the Brazos River, near the town of Rosebud in Falls County, central Texas. The site is exposed for a few hundred metres to the north and 1−2 km to the south of the roadbridge where Route 413 crosses the Brazos River (Gale, 2006).

Lithology and palaeoenvironment

The Brazos River site consists of the Maastrichtian Corsicana Formation below the K/T boundary layer and the Kincaid Formation above it. At one place the site comprises about 1 m of Cretaceous clay with dark grey clay clasts which show evidence of physical disturbance quite unlike the underlying undisturbed, massive, grey claystone. The disturbed clay is overlain by a sandstone complex known as the "event deposit" interpreted by some as a tsunami deposit. The event deposit consists of 10 cm laminated skeletal sandstone with phosphate and glauconite grains, impact spherules, and shells in horizontal, current-stable orientations. This is overlain by a 10 cm thick calcareous, organic-rich, silty, fine-grained quartz sandstone with well developed hummocky cross-stratification which is capped by a 1−2 cm thick sandy claystone with minor iridium concentrations.

The event deposit is overlain by a 5 cm thick silty limestone and a 10 cm thick massive grey claystone both with minor iridium concentrations. The grey claystone contains no macrofossils except for a few contained in burrow fills descending from the overlying unit which consists of a 3.5 cm thick claystone with sandy laminae. This unit is overlain by a 2.5 m thick silty claystone with sparse fossils and maximum values of iridium. The event deposit is highly variably laterally and in thickness throughout the Brazos area (Hansen et al., 1987; Keller et al., 2007).

Fossil content

The site contains a rich and varied microbiota of foraminifers, calcareous nannofossils, ostracods, and palynomophs. Furthermore, it is one of the few K/T boundary sites where the macrofossils are well preserved and includes ammonites, bivalves, gastropods, scaphopods, solitary corals, and trace fossils (Hansen et al., 1987; Gale, 2006; Keller et al., 2007).

Significance of the site

The Brazos River site is famous for the macrofossil content and for the controversy about the placement of the K/T boundary. The palaeontologically defined K/T boundary, including the mass-extinction of foraminifers, first appearance of Danian species, iridium anomaly, and the $\delta^{13}O$ shift occurs significantly above the event deposit which contain impact spherules near the base and small iridium concentration within the laminated sandstone (Keller et al., 2007).

The (K/T boundary at Brazos River, Falls County, Texas (pick and shovel for scale). The pick rests on a rippled sandstone bed immediately below the paleontological K-T boundary at this locality. The overlying dark, calcareous mudstone containing the iridium anomaly (Photo Alan Hildebrand).

4.14 Raton Basin, USA – Terrestrial section

Geographic description of the site

The Raton Basin site is located at the top of a saddle about 1.5 km west of Raton on Southwell Mountain Road, the old Raton Pass Road, in New Mexico, USA. The roadcut exposes the first outcrop discovery of the iridium anomaly in the Raton basin. Several K/T boundary sites are preserved in the east-central part of the basin.

Lithology and palaeoenvironment

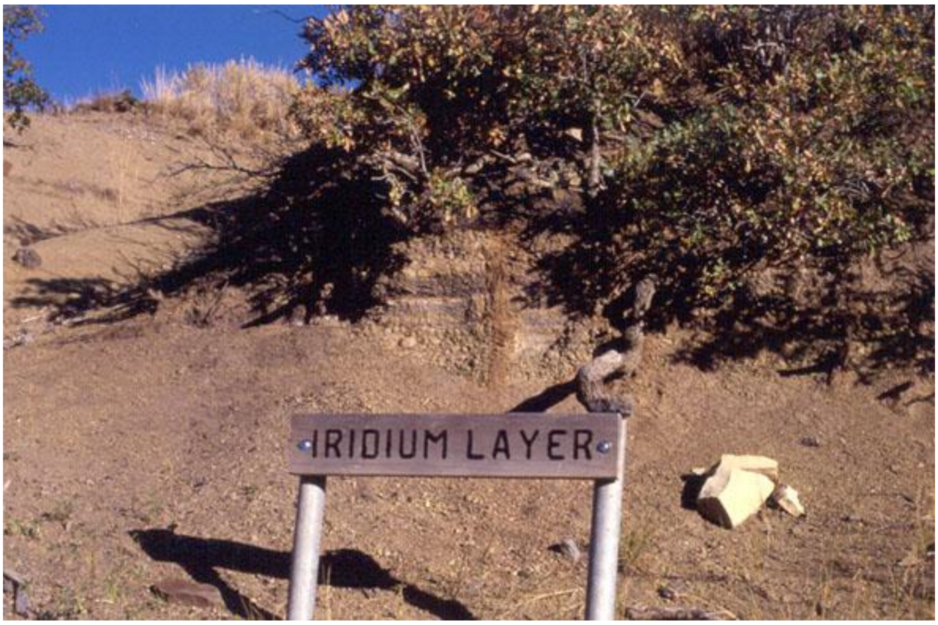
The K/T boundary is preserved in a succession of coal-bearing, fluvial deposits in the lower part of the Upper Cretaceous − Danian Raton Formation, which is up to 640 m thick. The boundary occurs at the base of a 2.5 cm thick layer of rusty-weathering kaolinitic claystone, the boundary clay layer, in an interval of coal and carbonaceous shale. The boundary is defined by the disappearance of certain pollen taxa and the presence of shocked quartz grains and anomalies of iridium, chromium, and other elements (Gardner and Gilmour, 2002; Keller et al., 1995; Nichols, 2007; Pillmore et al., 1999).

Fossil content

The site contains palynoflora, leaf megafossils, and in many areas the boundary is associated with Maastrichtian dinosaurs below and Paleocene mammals above (Nichols, 2007).

Significance of the site

Palaeomagnetic studies have demonstrated that the K/T boundary in terrestrial rocks is within subchron C29r, as it is worldwide in marine rocks.



The K-T boundary exposed at the Raton Pass site. The boundary claystone layer is visible about midway between the top of the sign and the shrubs on the bank behind the sign (From http://esp.cr.usgs.gov/info/kt/).

Closer view of the Raton Pass site. The knife blade is at the boundary claystone layer (From http://esp.cr.usgs.gov/info/kt/).

4.15 Hell Creek, USA – Terrestrial section

Geographic description of the site

The Hell Creek Formation extends nearly 700 km from east to west and is exposed in Montana, North Dakota and South Dakota with the type area located on the south bank of the Fort Peck Reservoir in Glendive, Montana. The thickness of the formation varies from a maximum of 170 m in Garfield County, Montana to a minimum of 41 m in McCone County, Montana (Johnson et al., 2002). The K/T boundary layer is surprisingly thin and unremarkable and can be difficult to recognise it in the field (Bigelow, 2009).

*Lithology and palaeoenvironment*3

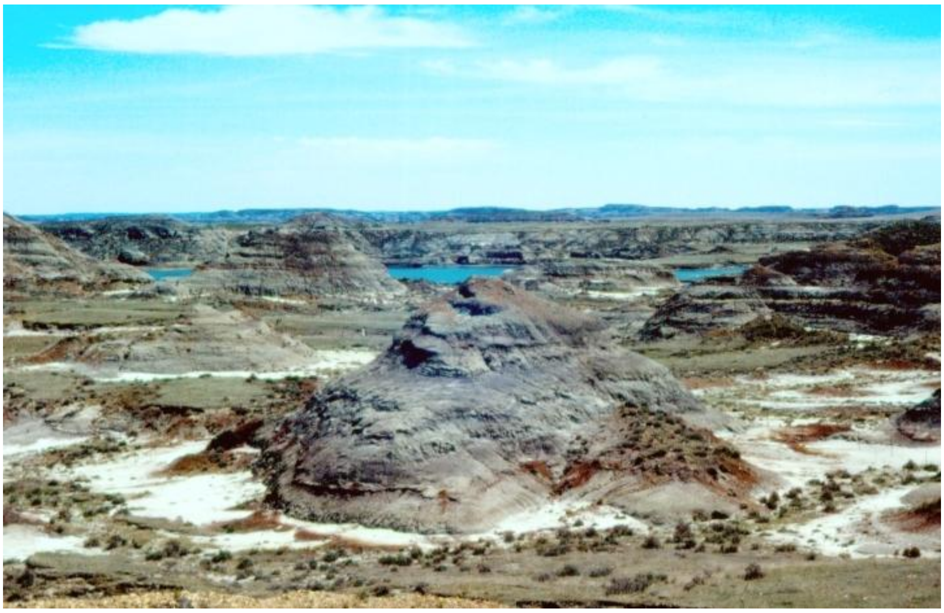
The K/T boundary site of Hell Creek is contained within the Hell Creek Formation. The 3 cm thick K/T boundary clay is enriched in iridium and shocked quartz grains and is preserved at the base of a 145 cm thick lignite layer. The lignite contains several ash layers and contains typical Cretaceous pollen taxa at its base. Compared to the lower parts of the Hell Creek Formation the 10 cm of lignite that overlie the boundary clay contain an unusually large amount of fossil fern spores. The Hell Creek Formation comprises; cross-stratified and ripple-laminated sandstone, siltstone, carbonaceous mudstone, and lignite. Siltstone dominates the Upper Hell Creek Fm whereas the iridium-bearing K/T boundary clay is preserved only in the lignite. The site also contains volcanic ash layers which provide radiometric control on the timing and duration of the carbon isotope excursion (Arens and Jahren, 2000; Bigelow, 2009)

Fossil content

The site contains pollen and wood fragments from a diverse flora and root traces are common. Furthermore, it contains all common taxa of Late Cretaceous dinosaurs and a diverse insect fauna.

Significance of the site

The Hell Creek site covers a huge area and is one of the few complete terrestrial K/T boundary sites. It contains all common taxa of Late Cretaceous dinosaurs which are found at all known localities (Johnson et al., 2002).



The Hell Creek Formation is well exposed in the badlands in the vicinity of Ft. Peck Reservoir (http://en.wikipedia.org/wiki/Hell_Creek_Formation).

4.16 Seymour Island, Antarctica – Marine section

Geographic description of the site

The Seymour Island site is located on the northeastern tip of the Antarctic Peninsula along the southwestern and central parts of the island (Brizuela et al. 2007).

Lithology and palaeoenvironment

The K/T boundary site of Seymour Island is contained within the marine Lopéz de Bertodano Formation which reaches a thickness of about 1,190 m. The formation consists of shallow marine muddy sandy siltstones, muddy sandstones and occasional glauconitic sandstones. The K/T boundary is found within a widespread glauconitic interval which crops out along strike for about 5.5 km (Elliot et al., 1994); Brizuela et al. 2007). The beds are bioturbated but lack other sedimentary structures (Elliot et al., 1994).

Fossil content

The site contains a rich and varied microbiota, including dinoflagellates, diatoms, silicoflagellates, pollen, and foraminifers bivalves, ammonites, gastropods, polychaetes, echinoderms, solitary corals, wood, plesiosaurs, and trace fossils (Macellari, 1986; (Kiessling and Claeys, 2001)

Significance of the site

The Seymour Island site is one of only few sites at high southern latitudes that provide important information on the K/T boundary event.

The K/T boundary at Seymour Island (Photo by Andrew George Netting from http://www.travelblog.org/Photos/2441989.html#)

4.17 Hokkaido, Japan – Marine section

Geographic description of the site

The K/T boundary is exposed in the bed of a shallow stream of the Mokawaruppu River about 4 km upstream of the Kawaruppu Township on the island Hokkaido in Japan.

Lithology and palaeoenvironment

The succession consists predominantly of a massive, dark grey siltstone with occasionally calcareous concretions. A distinct, 6–10 cm thick greyish black claystone is the only lithological break in the otherwise monotonous sedimentary succession and represents the K/T boundary.

Fossil content

The site contains a rich and varied foraminifer fauna.

5. Comparison and evaluation of the K/T boundary sites (Comparative study)

The 17 described sites, which all meet the general criteria, are compared in details in order to evaluate their potential as a World Heritage Site. Seven specific criteria are identified and used for the comparative analysis. The first criterion belongs to category 1 of Falcon-Lang (2002, page 6 this document), criteria 2 and 3 belong to category 2 and criteria 4 − 7 to category 3:

Criterion 1: *The fossil diversity*
Criterion 2: *The appearance of the boundary layer*
Criterion 3: *The lateral extent of the boundary layer*
Criterion 4: *The degree of exposure and permanency of the site*
Criterion 5: *The accessibility of the site*
Criterion 6: *Degree of research on the site*
Criterion 7: *Probability of continued discoveries*

These criteria are chosen since the K/T boundary represents a stratigraphic event and not a palaeontological site. The species diversity, the fossil density, and their state of preservation is thus not as important as the location and accessibility of the site, and the appearance of the boundary layer.

5.1 Comparative analysis

The seven criteria are quantified by giving each K/T boundary site points for issues that make the site a better World Heritage Site. Criteria 3 and 5 are given fewer points than the other criteria as the lateral extent of the boundary layer and the accessibility of site are less important for a WHS.

Table 3: *Fossil diversity*

In this criterion the diversity of the major biota groups present in each site is calculated. The site is given 1 point for each group present at the site except for the macrofaunal group. At some sites the presence of macrofauna is described but in such insignificant numbers that it is impossible to study the evolution and faunal turnover for this group. Sites with an insignificant presence of macrofauna are given 1 point, whereas sites with macrofauna present which can be used for research is given 2 points. The site with the greatest number of groups and thereby the highest number of points is ranked first.

Site	Microfauna	Microflora	Macrofauna	Macroflora	Trace fossils	Points
Seymour Island	Present	Present	Present	Present	Present	6
Stevns Klint	Present	Present	Present		Present	5
Hell Creek		Present	Present	Present	Present	5
Nye Kløv	Present	Present	Present		Present	5
Brazos River	Present	Present	Present		Present	5
El Kef	Present	Present	insignificant		Present	4
Agost	Present	Present	insignificant		Present	4
Caravaca	Present	Present	insignificant		Present	4
Aïn Settara	Present	Present	Present			4
Raton Basin		Present	Present	Present		4
Mimbral	Present			Present	Present	3
Elles	Present	Present			Present	3
Woodside Creek	Present	Present				2
Flaxbourne River	Present	Present				2
Gubbio	Present	Present				2
Beloc	Present	Present				2
Hokkaido	Present					1

The fossil diversity tells the evolutionary story of the biota across the K/T boundary. The more groups present the more studies can be made on the timing of extinction, the degree of extinction, survivorship of some groups, recovery after extinction, and selective extinction. Sites with a high number of groups can thus tell a more complete story of the extinction event.

Even though the macrofauna is less abundant it is ecologically more diverse than microfaunas in both habits and feeding types and may reflect regional patterns of stress and extinction better than the more dispersed microbiotas (Hansen et al., 1987). All kinds of fossil are therefore included in this criterion.

The Seymour Island site ranks highest with all major groups present. The Stevns Klint site ranks secondly, together with three other sites, due to the absence of macroflora. All of the sites which scores five points include macrofauna which has been used for research of extinction patterns.

Table 4: *Appearance of the boundary layer*

This criterion evaluates the visibility of the boundary layer. Sites are given two points if the boundary layer is easily recognised and zero point if a guide is required to find it. Sites with an easily recognised boundary layer are ranked first.

Site	Cannot be found without guide	Not easily recognised	Easily recognised
Stevns Klint			6
Caravaca			6
Agost			6
Woodside Creek			6
Gubbio			6
Aïn Settara			6
Elles		3	
Mimbral		3	
Beloc		3	
Brazos River		3	
Raton Basin		3	
Nye Kløv		3	
Seymour Island		3	
Hell Creek		3	
Hokkaido		3	
El Kef	0		
Flaxbourne River	0		

The boundary layer, and thereby the event layer should be easily recognised to tell the story of the K/T boundary event when visiting and looking at the site. The Stevns Klint site, together with five other sites, contains an easily recognised boundary layer. At two sites, El Kef and Flaxbourne River, the boundary cannot be found without a guide

Table 5: *Lateral extent of the boundary layer*

This criterion calculate the lateral extent of the boundary layer. The longer the boundary layer extends horizontally the more points. Sites with the longest horizontal extend are ranked first.

Site	Less than a few metres	Few metres – 100 m	100 m – 1 km	More than 1 km
Stevns Klint				3
Hell Creek				3
Seymour Island				3
Brazos River				3
El Kef			2	
Elles			2	
Mimbral			2	
Beloc			2	
Aïn Settara			2	
Caravaca		1		
Woodside Creek		1		
Flaxbourne River		1		
Raton Basin		1		
Nye Kløv		1		
Agost	0			
Gubbio	0			
Hokkaido	0			

The longer the boundary layer extends the more study material, such as fossils and impact material is accessible for research and the better is the opportunity for permanency of the site. The Stevns Klint site, together with Hell Creek, ranks highest with a lateral extent of more than 10 km. Eleven sites have a lateral extent of less than 1 km.

Table 6: *The degree of exposure and permanency of the site*

The 17 sites are located in four different settings each representing different degrees of erosion and permanency. The setting which is ranked the lowest is quarries since the erosion degree is low and many quarries are filled with tailings and refuse after quarrying have ended so the degree of permanency is low. Roadcuts, valleys, and creeks normally are overgrown by vegetation and the erosion rate is low so both the degree of exposure and permanency is relatively low. Along streams, rivers, and channels erosion is continuous and thereby keep the site clean, but these waters may stop to flow which makes the degree of exposure relative high but the permanency relative low. Coastal cliffs are subject to natural continuous erosion which will keep a high exposure of the sites and the permanency high, since there is no risk of oversampling or overgrowth. Sites with highest degree of exposure and permanency are ranked first.

Site	Quarries	Road cuts Valleys Creeks	Along streams, rivers, and channels	Coastal cliffs
Stevns Klint				5
Seymour Island				5
Brazos River			3	
Mimbral			3	
Hokkaido			3	
Aïn Settara			3	
Agost		2		
Gubbio		2		
Beloc		2		
Caravaca		2		
Woodside Creek		2		
Raton Basin		2		
Hell Creek		2		
El Kef		2		
Elles		2		
Flaxbourne River	1			
Nye Kløv	1			

The third category of Falcon-Lang (2000) bring together the World Heritage Site criteria that states that geological sites continuously subject to natural erosion such as sea-cliffs, are to be preferred over artificial excavations, because they are of greater permanency and are most likely to continuously yield new fossils in the future (Falcon-Lang, 2002). Only two sites are coastal cliffs and are ranked highest, Stevns Klint and Seymour Island.

Table 7: *Accessibility of the site*

This criterion evaluates the accessibility of the site. Sites are given 1 point if access is easy by car. The criterion does not concern the access to the site after arriving by car or how far you have to drive from a town to get to the site. Sites with easy access are ranked first.

Site	Difficult access	Easy access
Stevns Klint		2
Agost		2
Gubbio		2
Beloc		2
Caravaca		2
Woodside Creek		2
Flaxbourne River		2
Brazos River		2
Raton Basin		2
Nye Kløv		2

Hell Creek		2
Aïn Settara		2
El Kef	0	
Elles	0	
Mimbral	0	
Seymour Island	0	
Hokkaido	?	

The access of the site is important to get as many people as possible to visit the site. Unfortunately informations about the access to the Hokkaido are not available. Twelve of the seventeen sites have an easy access.

Table 8: *Degree of research on site*

This criterion evaluates the scientific impact of the site in order to quantify the degree to which the site has been investigated. Data were collected from the online databases Web of Science and GeoRef (Table 2). Numbers in the columns indicate numbers of publications found in either of the databases searching on locality name and K-T, K-P or C-P. Sites with highest scientific impact are ranked first.

Site	10−20	21−40	41−60	61−100
El Kef				6
Stevns Klint			4	
Hell Creek			4	
Caravaca			4	
Raton Basin		2		
Brazos River		2		
Beloc		2		
Mimbral		2		
Agost		2		
Gubbio	0			
Hokkaido	0			
Nye Kløv	0			
Seymour Island	0			
Elles	0			
Flaxbourne River	0			
Aïn Settara	0			
Woodside Creek	0			

The scientific impact may give an estimate on the amount of studies which have been carried out on the sites and to which degree the site has been investigated through time. This criterion is doubtful since for example the El Kef site, which is the stratotype for the K/T boundary, is cited in many publications without any research actually going on at this site. The El Kef site is therefore also the most cited site. Stevns Klint is ranked second together with two other sites.

Table 9: *Probability of continued discoveries*

The last criterion attempts to access the likelihood of continued significant discoveries in the future. This criterion is reached by adding the lateral extent of the boundary layer and the degree of erosion for each site. A large area with an exposed boundary layer together with continuous erosion may yield more fossils and not yet discovered features of the K/T boundary event compared to less exposed areas with less erosion. Sites with the highest potential of continued discoveries are ranked first.

Site	Lateral extent	Erosion	Total
Stevns Klint	3	5	8
Seymour Island	3	5	8
Brazos River	3	3	6
Hell Creek	3	2	5
Mimbral	2	3	5
Aïn Settara	2	3	5
Beloc	2	2	4
El Kef	2	2	4
Elles	2	2	4
Hokkaido	0	3	3
Caravaca	1	2	3
Woodside Creek	1	2	3
Raton Basin	1	2	3
Nye Kløv	1	0	1
Flaxbourne River	1	0	1
Agost	0	2	2
Gubbio	0	2	2

This criterion is speculative but a requirement from the World Heritage Site criteria and is of importance for future investigation at the site. The Stevns Klint site is ranked highest due to its coastal location, which is preferable for permanency and erosion of the site, and due to its long lateral extent.

Table 10: *Cumulative table of the scores*

Scores for each of the seven criteria as well as the total scores for each K/T boundary site are summarized. Numbers in columns correspond to those of tables: (3) The fossil diversity; (4) The appearance of the boundary layer; (5) The horizontal extent of the boundary layer; (6) The degree of exposure and permanency of the site; (7) The accessibility of the site; (8) Degree of research on the site; (9) Probability of continued discoveries. The highest cumulative score is used as selection criterion for a K/T boundary site.

Site	3	4	5	6	7	8	9	Total
Stevns Klint	5	6	3	5	2	4	8	33
Seymour Island	6	3	3	5	0	0	8	25
Hell Creek	5	3	3	2	2	4	5	24
Brazos River	5	3	3	3	2	2	6	24
Aïn Settara	4	6	2	3	2	0	5	22
Caravaca	4	6	1	2	2	4	3	22
El Kef	4	0	2	2	0	6	4	18
Mimbral	3	3	2	3	0	2	5	18
Agost	4	6	0	2	2	2	2	18
Raton Basin	4	3	1	2	2	2	3	17
Beloc	2	3	2	2	2	2	4	17
Woodside Creek	2	6	1	2	2	0	3	16
Elles	3	3	2	2	0	0	4	14
Gubbio	2	6	0	2	2	0	2	14
Nye Kløv	5	3	1	1	2	0	1	13
Hokkaido	1	3	0	3	?	0	3	10
Flaxbourne River	2	0	1	1	2	0	1	7

Informations about the Hokkaido section are scarce primarily because the literature about this section was not available. The Hokkaido section may therefore appear lower ranked than it should be.

6. Summary and conclusion

A comparative analysis of K/T (Cretaceous/Tertiary) boundaries around the world have been undertaken in order to evaluate their potential as a World Heritage Site (WHS). More than 500 K/T boundary sites are recorded worldwide but only 17 of these meet the three main criteria of completeness of the succession across the boundary, scientific documentation, and the presence of a boundary layer which are enriched in iridium and other elements considered to be mainly or partly of meteoritic origin.

Seven specific criteria are identified for the comparative analysis of the 17 sites meeting the main criteria. The specific criteria primarily concern appearance, extent, exposure, and accessibility of the sites. The criteria are selected in order to choose the site that presents this unique geological event in an easy way for all humanities as all the 17 compared K/T boundary sites illustrate the impact event, mass extinction and the faunal turnover across the boundary.

The Stevns Klint site ranks first in five of the seven criteria: the appearance of the boundary layer; the lateral extent of the boundary layer; the degree of exposure and permanency of the site; the accessibility of the site; probability of continued discoveries, and ranks second in two criteria: the fossil diversity and degree of research on the site, resulting in a total score on 33 points. Second best is Seymour Island with a score on 25 points. The Seymour Island site comprises the most detailed fossil record of the major biota groups with the macroflora preserved but the boundary layer is not easily recognised and it is difficult to get to the site since it is located on Antarctica. The Seymour Island site is therefore not a suitable WHS. Hell Creek and Brazos River both scored 24 points. In Hell Creek the boundary layer is exposed in a valley and may therefore be covered by vegetation and scree and get even more difficult to find or disappear in the future. The Brazos River boundary layer is exposed along a river and has a higher potential of continuous erosion but at both sites the boundary layer is not easily recognised. The stratotype locality El Kef ranks low in almost all criteria and ends with a total score on 18 points. El Kef would not be suited as a WHS since the boundary layer is difficult to find, the access to the site is difficult, and the site is endangered by oversampling and agricultural encroachment, and will probably not remain for future generations of humanity.

The classical Stevns Klint K/T boundary site has not only the highest score in the comparative analysis but stands out from all other sites with its beautiful coastal position and the easily recognised K/T boundary layer, immediately beneath the topographic overhang that separates the lowerlying, soft Cretaceous chalk from the harder Tertiary limestone above. Stevns Klint is arguably the most famous, scenic and best exposed K/T boundary locality in the world. Together with the nearby Faxe quarry it constitutes the type locality of the Danian Stage and, furthermore, it is one of the discovery localities of the famous iridium anomaly, which formed the basis for the asteroid impact hypothesis of Alvarez et al. (1980) proposed to explain the mass extinction at the end of the Cretaceous. Stevns Klint is therefore a key locality in the ongoing debate about the K/T boundary and international researchers have flocked to Stevns Klint to sample the famous iridium-rich boundary layer and collect macro- and microfauna and nannoflora across the boundary.

The faunal assemblage is unique at the Stevns Klint site since it includes a diverse macro invertebrate fauna which expands the understanding of invertebrate recovery and evolution after the K/T mass extinction event. The invertebrate fauna is rarely found at other marine sites and has only been studied at Stevns Klint, Brazos River, Nye Kløv, and Seymour Island.

The geological story of the K/T boundary event, the lithology across the boundary, and many of macrofossils found at Stevns Klint are exhibited at Stevns Museum located at the village of Højerup. The museum is situated at the top of a stairway leading to the base of the coastal cliff at one of the best places to observe the K/T boundary layer. The easy access to the cliff and the story told by the museum makes it possible for tourists to go and study one of the major events in Earth's history, including the evolution of life across the boundary. Besides the numerous tourists and researchers visiting the Stevns Klint site every year it is also visited by student excursions and school classes. The Stevns Klint site is easily reached only about one hour drive from the Copenhagen airport and access to the coastal cliff is possible from several places along the main road 261 running from Strøby Egede to Rødvig.

The Stevns Klint site will remain for future generations of humanity due to the coastal cliff nature of the locality with ongoing erosion which maintain the quality of the site, exposes new fossils, and ensuring that the site is accessible for research. The site is not endangered by oversampling or by agricultural encroachment due to its coastal location.

This comparative analysis illustrates that Stevns Klint K/T boundary site in Denmark is the site most representative as a World Heritage Site. The Stevns Klint K/T boundary site stands out from all other sites in terms of exposure, permanency, and very easy accessibility and it has the longest, continuous boundary clay layer which is easily recognised due to the lithology and the overhanging character of the cliff face. The Stevns Klint K/T boundary site provide is a superb record of geological features which represent an important event in the past development of the planet with the interpreted extraterrestrial impact, the associated mass extinction and the recovery of the global fauna across the boundary. The nominated site thus presents a unique record of a geological significant time in the Earth's history that is exceptional and of outstanding universal value.

References

Abdelkader, O.B., Salem, H.B., Donze, P., Maamouri, A., Méon, H., Robin, È., Rocchia, R., Froget, L., 1997. The K/T Stratotype section of El Kef (Tunesia): Events and biotic turnovers. Geobios 235−245.

Adatte, T., Keller, G., Stinnesbeck, W., 2002. Late Cretaceous to early Paleocene climate and sea-level fluctuations: the Tunisian record. Palaeogeography Palaeoclimatology Palaeoecology 178, 165−196.

Alvarez, L.W., Alvarez, W., Asaro, F., Michel, H.V., 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science 208, 1095−1108.

Arenillas, I., Arz, J.A., Molina, E., Dupuis, C., 2000. An independent test of planktic foraminiferal turnover across the Cretaceous/Paleogene (K/P) boundary at El Kef, Tunisia: Catastrophic mass extinction and possible survivorship. Micropaleontology 46, 31−49.

Arens, N.C., Jahren, A.H., 2000. Carbon isotope excursion in atmospheric CO2 at the Cretaceous-Tertiary boundary: Evidence from terrestrial sediments. Palaios 15, 314−322.

Arinobu, T., Ishiwatari, R., Kaiho, K., Lamolda, M.A., 1999. Spike of pyrosynthetic polycyclic aromatic hydrocarbons associated with an abrupt decrease in delta C-13 of a terrestrial biomarker at the Cretaceous-Tertiary boundary at Caravaca, Spain. Geology 27, 723−726.

Arthur, M.A., Fisher, A.G., 1977. Upper Cretaceous-Paleocene magnetic stratigraphy at Gubbio, Italiy I. Lithostratigraphy and sedimentology. Geological Society of America Bulletin 88, 367−371.

Bigelow, P., 2009. The K-T boundary in the Hell Creek Formation. http://www.scn.org/~bh162/k-t_boundary.html.

Brizuela, R.R., Marenssi, S., Barreda, V., Santillana, S., 2007. Palynofacial approach across the Cretaceous-Paleogene boundary in Marambio (Seymour) Island, Antarctic Peninsula. Revista de la Asociación Geológica Argentina 62, 236−241.

Canudo, J.I., Keller, G., Molina, E., 1991. Cretaceous Tertiary Boundary Extinction Pattern and Faunal Turnover at Agost and Caravaca, Se Spain. Marine Micropaleontology 17, 319−341.

Cloutier, R., Leliévre, H., 1998. Comparative study of the fossiliferous sites of the Devonian. Government of Quebec report 86 pp.

Cronholm, A., Schmitz, B., 2007. Extraterrestrial chromite in latest Maastrichtian and Paleocene pelagic limestone at Gubbio, Italy: The flux of unmelted ordinary chondrites. Meteoritics & Planetary Science 42, 2099−2109.

Dorset County Council, 2000. Nomination of the Dorset and East Devon Coast for inclusion in the World Heritage List 100 p.

Dingus, L., 1984. Effects of stratigraphic completeness in interpretations of extinction rates across the Cretaceous-Tertiary boundary. Paleobiology 10, 420−438.

Dingwall, P., Weighell, T., Badman, T., 2005. Geological world heritage: a global framework: IUCN, Gland, Switzerland.

Dupuis, C., Steurbaut, E., Molina, E., Rauscher, R., Tribovillard, N., Arenillas, I., Arz, J.A., Robaszynski, F., Caron, M., Robin, È., Rocchia, R., Lefevre, I., 2001. The Cretaceous-Palaeogene (K/T) boundary in the Aïn Settara section (Kalaat Senan, Central Tunesia): lithological, micropalaeontological and geochemical evidence. Bulletin de L'institut Royal des Sciences Naturelles de Belgique, Science de la Terre 71, 169−190.

Elliot, D.H., Askin, R.A., Kyte, F.T., Zinsmeister, W.J., 1994. Iridium and Dinocysts at the Cretaceous-Tertiary Boundary on Seymour-Island, Antarctica - Implications for the K-T Event. Geology 22, 675−678.

Falcon-Lang, H.J., 2002. Comparative analysis of Pennsylvanian fossil sites, 103 p.

Gale, A.S., 2006. The Cretaceous-Palaeogene boundary on the Brazos River, Falls County, Texas: is there evidence for impact-induced tsunami sedimentation?. Proceedings of the Geologists Association 117, 173−185.

Gallagher, W.B., 2002. Faunal changes across the Cretaceous-Tertiary (K-T) boundary in the Atlantic coastal plain of New Jersey: Restructuring the marine community after the K-T mass-extinction event. In: Koeberl, C., MacLeod, K.G., (ed.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, 291−301

Gardner, A.F., Gilmour, I., 2002. Organic geochemical investigation of terrestrial Cretaceous-Tertiary boundary successions from Brownie Butte, Montana, and the Raton Basin, New Mexico. In: Koeberl, C., MacLeod, K.G., (ed.), Catastrophic Events and Mass Extinctions: Impacts and Beyond, 351−362

Hansen, T., Farrand, R.B., Montgomery, H.A., Billman, H.G., Blechschmidt, G., 1987. Sedimentology and extinction pattern across the Cretaceous-Tertiary boundary interval in east Texas. Cretaceous Research 8, 229−252.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jacobsen, S.B., Boynton, W.V., 1991. Chicxulub Crater - a Possible Cretaceous Tertiary Boundary Impact Crater on the Yucatan Peninsula, Mexico. Geology 19, 867−871.

Hollis, C. J., 2003. The Cretaceous/Tertiary boundary event in New Zealand: profiling mass extinction. New Zealand Journal of Geology and Geophysics 46, 307−321.

Hollis, C.J., Strong, C.P., Rodgers, K.A., Rogers, K.M., 2003. Paleoenvironmental changes across the Cretaceous/Tertiary boundary at Flaxbourne River and Woodside Creek, eastern Marlborough, New Zealand. New Zealand Journal of Geology and Geophysics 46, 177−197.

Hough, R.M., Gilmour, I., Pillinger, C.T., Langenhorst, F., Montanari, A., 1997. Diamonds from the iridium-rich K-T boundary layer at Arroyo el Mimbral, Tamaulipas, Mexico. Geology 25, 1019−1022.

Håkansson, E., Hansen, J.M., 1979. Guide to Maastrichtian and Danian boundary strata in Jylland. In: Birkelund, T., Bromley, R., (ed.), Symposium on Cretaceous-Tertiary boundary events 1: Copenhagen, 78−91.

Håkansson, E., Thomsen, E., 1999. Benthic extinction and recovery patterns at the K/T boundary in shallow water carbonates, Denmark. Palaeogeography Palaeoclimatology Palaeoecology 154, 67−85.

IUCN, 1994. Recommendations concerning selection criteria of geological World Heritage Sites.

Johnson, K.R., Nichols, D.J., Hartman, J.H., 2002. Hell Creek Formation: A 2001 synthesis. Geological Society of America Special Paper 361, 503−510.

Johansen, M.B., 1987. Brachiopods from the Maastrichtian-Danian boundary sequence at Nye Kløv, Jylland, Denmark. Fossils and Strata 20, 99 p.

Karoui-Yaakoub, N., Zaghbib-Turki, D., Keller, G., 2002. The Cretaceous-Tertiary (K-T) mass extinction in planktic foraminifera at Elles I and El Melah, Tunisia. Palaeogeography Palaeoclimatology Palaeoecology 178, 233−255.

Keller, G., 1988a. Biotic Turnover in Benthic Foraminifera across the Cretaceous Tertiary Boundary at El-Kef, Tunisia. Palaeogeography Palaeoclimatology Palaeoecology 66, 153−171.

Keller, G., 1988b. Extinction, Survivorship and Evolution of Planktic Foraminifera across the Cretaceous Tertiary Boundary at El-Kef, Tunisia. Marine Micropaleontology 13, 239−263.

Keller, G., 1993. The Cretaceous-Tertiary boundary transition in the Antarctic Ocean and its global implications. Marine Micropaleontology 21, 1−45.

Keller, G., 2003. Biotic effects of impacts and volcanism. Earth and Planetary Science Letters 215, 249−264.

Keller, G., Barrera, E., Schmitz, B., Mattson, E., 1993. Gradual Mass Extinction, Species Survivorship, and Long-Term Environmental-Changes across the Cretaceous-Tertiary Boundary in High-Latitude. Geological Society of America Bulletin 105, 979−997.

Keller, G., Stinnesbeck, W., Lopez-Oliva, J. G., 1994. Age, deposition and biotic effects of the Cretaceous/Tertiary boundary event at Mimbral, NE Mexico. Palaios 9, 144−157.

Keller, G., Adatte, T., Berner, Z., Harting, M., Baum, G., Prauss, M., Tantawy, A., Stueben, D., 2007. Chicxulub impact predates K-T boundary: New evidence from Brazos, Texas. Earth and Planetary Science Letters 255, 339−356.

Keller, G., Li, L., MacLeod, N., 1995. The Cretaceous Tertiary boundary stratotype section at El Kef, Tunisia: How catastrophic was the mass extinction?. Palaeogeography Palaeoclimatology Palaeoecology 119, 221−254.

Kiessling, W., Baron-Szabo, R.C., 2004. Extinction and recovery patterns of scleractinian corals at the Cretaceous-Tertiary boundary. Palaeogeography Palaeoclimatology Palaeoecology 214, 195−223.

Kiessling, W., Claeys, P., 2001. A geographic database approach to the KT boundary. In: Buffetaut, E., Koeberl, C., (ed.), Geological and biological effects of impact events. Berlin, Springer, 83−140.

Leroux, H., Rocchia, R., Froget, L., Orueetxebarria, X., Doukhan, J.C., Robin, E., 1995. The K/T Boundary at Beloc (Haiti) - Compared Stratigraphic Distributions of the Boundary Markers. Earth and Planetary Science Letters 131, 255−268.

Luciani, V., 2002. High-resolution planktonic foraminiferal analysis from the Cretaceous-Tertiary boundary at Ain Settara (Tunisia): evidence of an extended mass extinction. Palaeogeography Palaeoclimatology Palaeoecology 178, 299−319.

Lykke-Andersen, H., Surlyk, F., 2004. The cretaceous-palaeogene boundary at Stevns Klint, Denmark: inversion tectonics or sea-floor topography?. Journal of the Geological Society 161, 343−352.

Macellari, C.E., 1986. Late Campanian-Maastrictian ammonite fauna from Seymour Island (Antarctic Peninsula). Journal of Paleontology 60, 55 p.

Molina, E., Alegret, L., Arenillas, I., Arz, J.A., 2005. The Cretaceous/Paleogene boundary at the Agost section revisited: paleoenvironmental reconstruction and mass extinction pattern. Journal of Iberian Geology 31, 135−148.

Nichols, D.J., 2007. Selected plant microfossil records of the terminal Cretaceous event in terrestrial rocks, western North America. Palaeogeography Palaeoclimatology Palaeoecology 255, 22−34.

Pillmore, C.L., Nichols, D.J., Fleming, R.S., 1999. Online guide to the continental Cretaceous-Tertiary boundary in the Raton basin, Colorado and New Mexico: Field guide to the continental Cretaceous-Tertiary boundary in the Raton basin, Colorado and New Mexico. Geological Society of America, Field Guide 1. http://esp.cr.usgs.gov/info/kt/.

Robin, E., Boclet, D., Bonte, P., Froget, L., Jehanno, C., Rocchia, R., 1991. The Stratigraphic Distribution of Ni-Rich Spinels in Cretaceous-Tertiary Boundary Rocks at El-Kef (Tunisia), Caravaca (Spain) and Hole-761C (Leg-122). Earth and Planetary Science Letters 107, 715−721.

Rodríguez-Tovar, F.J., Uchman, A., 2006. Ichnological analysis of the Cretaceous-Palaeogene boundary interval at the Caravaca section, SE Spain. Palaeogeography Palaeoclimatology Palaeoecology 242, 313−325.

Smit, J., 1999. The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta. Annual Review of Earth and Planetary Sciences 27, 75−113.

Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M., Bermudez, J., 1996. Coarse-grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact?. Geological Society of America Special Paper 307, 151−182.

Stinnesbeck, W., Keller, G., Adatte, T., Stuben, D., Kramar, U., Berner, Z., Desremeaux, C., Moliere, E., 1999. Beloc, Haiti, revisited: multiple events across the KT boundary in the Caribbean. Terra Nova 11, 303−310.

Strong, C.P., Hollis, C.J., 2009. Climatic and Biotic Events of the Paleogene Conference Field Trip Guides, 6-21 January 20092009, Te Papa, Wellington, New Zealand. GNS Science Miscellaneous Series 17, 145 p.

Surlyk, F., 1997. A cool-water carbonate ramp with bryozoan mounds: Late Cretaceous − Danian of the Danish Basin, *in* James, J.P., and Clarke, J.D.A., eds., Cool-water carbonates. SEPM Special Publication 56, 293−308.

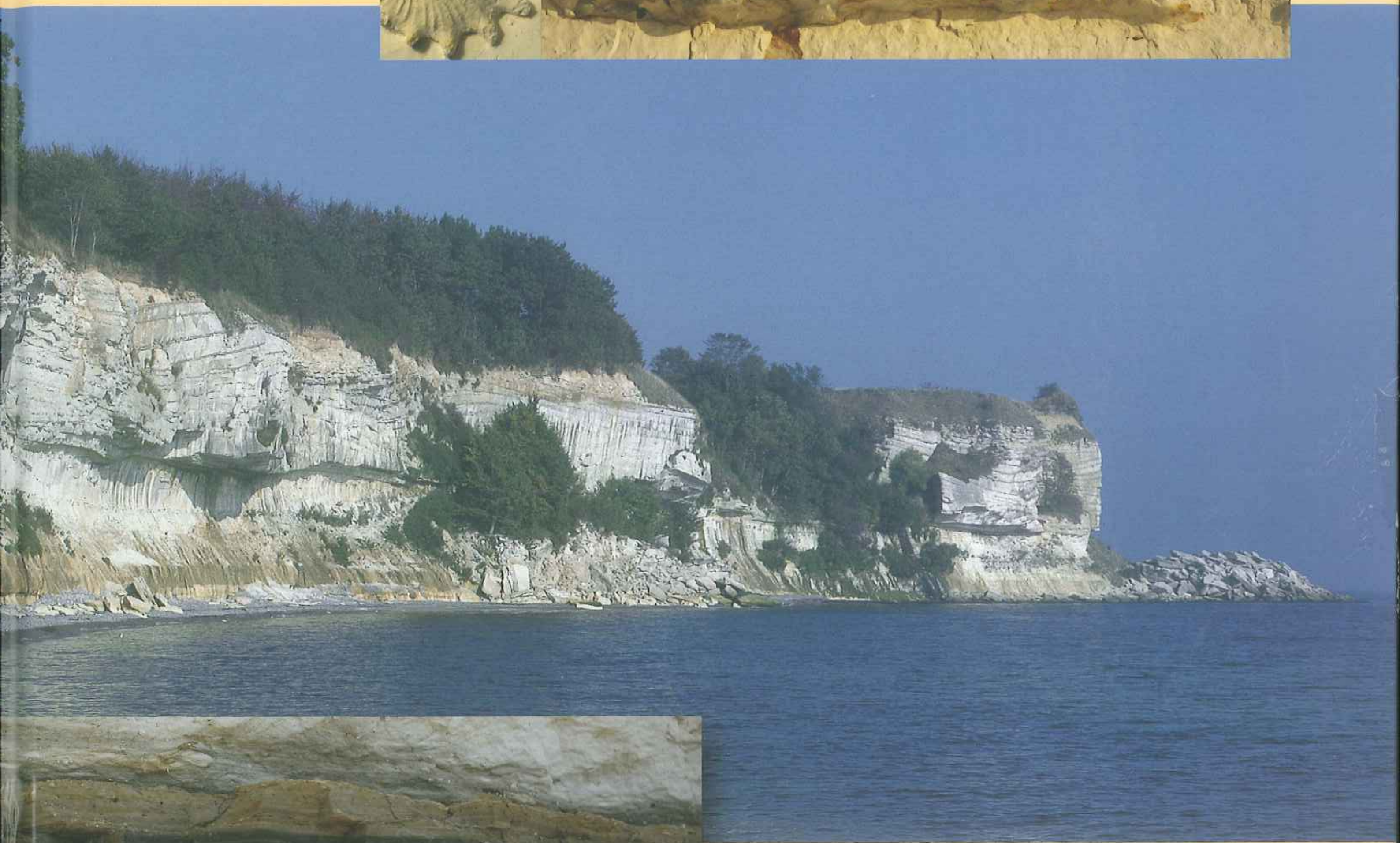
Surlyk, F., Johansen, M.B., 1984. End-Cretaceous Brachiopod Extinctions in the Chalk of Denmark. Science 223, 1174−1177.

Surlyk, F., Damholt, T., Bjerager, M., 2006. Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous-Tertiary boundary, and lower Danian bryozoan mound complex. Bulletin of the Geological Society of Denmark 54, 46 p.

Ward, P., Wiedmann, J., Mount, J.F., 1986. Maastrichtian Molluscan Biostratigraphy and Extinction Patterns in a Cretaceous Tertiary Boundary Section Exposed at Zumaya, Spain. Geology 14, 899−903.

Well, R.T., 1996. Earth's geological history: a contextual framework for assessment of World Heritage Fossil Site nominations. IUCN special paper, 43 p.

Zaghbib-Turki, D., Karoui-Yaakoub, N., Said-Benzarti, R., Rocchia, R., Robin, E., 2001. Review of the K/T boundary Elles section (Tunisia): Proposition of a new parastratotype. Geobios 34, 25−37.



Nomination of

STEVNS KLINT

for inclusion in the World Heritage List

Tove Damholt and Finn Surlyk

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Authors: Tove Damholt (Østsjællands Museum) and Finn Surlyk (Department of Geography and Geology, University of Copenhagen).
Background material: Anne Mehlin Sørensen, Thomas Hansen (Department of Geography and Geology, University of Copenhagen); Thomas Tram Pedersen, Helle Ålsbøl, Kirstine Østergaard (Østsjællands Museum); Niels Richardt (Ramboll Denmark A/S); Thomas W. Johansen (Senatur); Karsten Dahl (Section for Marine Ecology, Aarhus University); Stig A. Schack Pedersen (Geological Survey of Denmark and Greenland).
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Østsjællands Museum
Højerup Bygade 38
4660 St. Heddinge
Denmark

The scenic coastal cliff Stevns Klint comprises the most spectacular global mass extinction event in the history of the Earth: The Cretaceous—Tertiary boundary. The mass extinction that occurred 65 million years ago is particularly spectacular due to its association with an asteroid impact and because it marks the extinction of more than half of all species, including land-living dinosaurs and large marine reptiles.

At Stevns Klint the thin, black boundary clay found in the up to 40 m high, white cliff clearly marks the abrupt fall in primary production and makes the exceptional boundary visible even to the inexperienced eye. Stevns Klint is an outstanding locality representing a major stage in Earth's history and the record of life: The mass extinction at the Cretaceous—Tertiary boundary and is nominated for inclusion for the World Heritage List.

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3.5 Photographs of Stevns Klint

ID No. Caption	Format (slide/print/video)	Date of photograph	Photographer/ director of video	Copyright owner	Contact details of copyright owner	Non-exclusive cession of rights
Stevns Klint 1	jpg	07/2011	Peter Warna-Moors	Photographer	GEUS	Yes
Stevns Klint 2	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 3	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 4	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 5	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 6	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 7	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 8	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 9	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 10	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 11	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 12	jpg	06/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 13	jpg	07/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 14	jpg	07/2011	Jacob Lautrup	Photographer	GEUS	Yes
Stevns Klint 15	jpg	05/2011	Sten Lennart Jakobsen	Photographer	Natural History Museum of Denmark	Yes
Stevns Klint 16	jpg	03/2011	Jan Schulz Adolf-ssen	Photographer	Natural History Museum of Denmark	Yes

Contact details

GEUS, Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK 1350 Copenhagen, Denmark.
Tel: +45 38142000, E-mail: geus@geus. dk.

Natural History Museum of Denmark, Øster Voldgade 5-7, DK 1350 Copenhagen, Denmark.
Tel: +45 35322222, E-mail: rcp@snm.ku.dk

Appendix 4: Management Plan

Enclosed as a separate volume.

Appendix 5: Erosion Analysis

Enclosed as a separate volume.

Appendix 6: Comparative Analysis

Enclosed as a separate volume.