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Distribution of Chicxulub ejecta at the Cretaceous-Tertiary boundary

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ABSTRACT

The mineralogical, sedimentological, and geochemical information in a large database on the Cretaceous-Tertiary (K-T) boundary is used to document the distribution of impact debris derived from the Chicxulub crater. The database is coupled with a geographic information system (GIS) allowing the plotting of the information on a latest Cretaceous paleogeographic map. The database will be available in part on the internet in the near future, and contains data from 345 K-T boundary sites worldwide. However, relatively few sites are known in South America, Australia, Africa, and in the high latitudes. Major disturbances of sedimentation, such as massive debris flows, failure of platform margins, or significant erosion of Upper Cretaceous layers, occur throughout the Gulf of Mexico. Mass wasting of material also took place in the western and eastern parts of the Atlantic Ocean. Almost 100 K-T boundary sites analyzed for Ir recorded the positive anomaly; Ir is spread homogeneously throughout the world, but is diluted at proximal sites because of the high volume of sediment that was in suspension in the Gulf of Mexico after the impact. Shocked quartz is more common, and maybe larger in size west of the crater. The main advantage of the database is to provide a convenient method to manage the huge amount of data available in the literature, and to reveal patterns or characteristics of the data. The database can help refine the variables used in mathematical models and documents the origin, transport, and deposition of ejecta during a cratering event.

INTRODUCTION

The Cretaceous-Tertiary (K-T) boundary impact event produced a broad range of ejecta material. Impact debris can be easily located in many Late Cretaceous and early Tertiary sections, thanks to their close association with the K-T boundary mass extinction. It is difficult to argue against the fact that the ejecta debris and geochemical signal found in the K-T boundary layer resulted from a unique event, i.e., the formation of the Chicxulub crater in Yucatan. In the Gulf of Mexico region, millimeter-sized spherules, some with a preserved glass core, occur at the K-T boundary (Izett et al., 1990; Sigurdsson et al., 1991; Smit, 1999). The glass is linked to Chicxulub impactites by its major and trace element compositions, isotopic signa-

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tures, and radiometric age (Blum et al., 1993; Swisher et al., 1992). The crater impactites and several K-T layers contain shocked zircons dated as ca. 540 Ma by U-Pb methods (Kamo and Krogh, 1995; Krogh et al., 1993). This is the age of the Pan-African basement, which underlies the Yucatan carbonate platform (López Ramos, 1975). The study of Alvarez et al. (1990) in Italy and the results of the geochemical part of a K-T blind test carried out in 1994 clearly demonstrated that the K-T Ir anomaly is unique in the last 10 m.y. of the Cretaceous.

The Chicxulub crater is one of the few craters on Earth with a well-identified and complete ejecta sequence. Ejecta blanket material covers most of today's Yucatan, and proximal ejecta that is deposited within 3000 km from the impact site is found all over the Gulf of Mexico region, and in parts of North America. Distal ejecta occurs all over the world at the K-T boundary. It is possible to document variations in type, composition, and concentration of impact debris with distance from the source crater. Chicxulub is thus an ideal case study to understand the formation, transport, and distribution of various ejecta products during a large impact. Study of the ejecta material at different sites also provides information on the chemical and physical interactions between ejecta and the atmosphere during transport. Knowledge of the ejecta distribution pattern can be used to refine existing mathematical models for cratering and ejecta production on Earth and other rocky planets. Eventually, understanding the distribution of ejecta at the K-T boundary will help to identify ejecta debris from other craters and to link impact particles found in the sedimentary record with a specific source crater. Before these studies can be carried out, careful and extensive documentation of the Chicxulub ejecta is required. This can best be accomplished with the support of a database, coupled with a geographic information system tied to the Late Cretaceous geography. This chapter is largely a survey of K-T boundary ejecta distribution. The new database approach and the focus on geographic patterns rather than vertical successions make this chapter complementary to the extensive review of Smit (1999).

DATABASE

Computer databases offer the opportunity to organize, review, and evaluate large amounts of data easily and more objectively than other data collection means. Our database (named KTbase) is a relational database designed to combine geochemical, mineralogical, sedimentological, and paleontological information from all currently known K-T boundary sites. The development of KTbase started in May 1999, and is based on the information extracted from the literature. It is designed for Visual dBase 5.5, but is also available in Microsoft Access format. The main table in KTbase is a locality-based summary table mostly containing information on the kind of data available on each site. Basic lithological, chemical, and mineralogical data are also included in the main table. For each important entry a link to the reference table is available. The paleontological data require several additional tables that are also linked to the main table. KTbase currently summarizes data from 348 K-T boundary sites. A K-T boundary site is defined as an area where at least late Maastrichtian and/or Danian sediments are preserved. The paleontological part of the database has been described in Kiessling and Claeys (2001), and is not discussed here. Interested colleagues are invited to use additional parts of the database. However, the paleontological part of the database will not be available until it has been published.

The part of the database containing K-T boundary geochemical, sedimentological, and mineralogical information is based on the earlier unpublished database developed at the University of California, Berkeley, by Walter Alvarez and colleagues. It listed 113 localities with iridium anomalies, 28 localities with occurrences of shocked quartz, 54 localities with spherules, and 18 localities with Ni-rich spinel. Whereas the Berkeley database was largely text based, the KTbase contains numerous quantitative fields.

A major difference from the former database is the 20 km distance criterion for K-T sites to be included separately. In this chapter, a K-T site may thus be composed of several outcrops, separated by $<$20 km. The criterion was applied to obtain a more homogenous spatial distribution of sites in the database. This implies that data from an area of $\sim$315 km^2 are summarized for each site in KTbase. Consequently, the number of sites with a recorded Ir anomaly is reduced in Ktbase, because many well known but closely spaced sections in North America and the Italian Apennines are now combined. There are 85 sites known on a global scale to have a significant iridium anomaly; 49 sites yield shocked quartz, 54 sites contain spherules, and 21 sites with Ni-rich spinel are known. A total of 101 of 345 K-T boundary sites contain ejecta material.

A locality-based entry format was defined for the database main table in connection with a geographic information system (GIS). This main table presents an overview of the K-T sites studied and lists basic data and information, the details of which are contained in a set of related tables. The relevant fields for this study are (1) maximum iridium concentration reported from the boundary clay (in ppt); (2) integrated iridium concentration in the boundary clay when available (in ng/cm^2); (3) maximum diameter of shocked quartz grains in the boundary clay (in μm); (4) abundance of shocked quartz grains in the boundary clay (in grains/cm^2); (5) presence of suspect tsunami and mass-wasting deposits; (6) presence of Ni-rich magnesioferrite spinel; (7) maximum concentration of Ni-rich spinel; (8) presence of impact spherules; (9) maximum diameter of spherules; and (10) presence and abundance of soot.

KTbase is essentially a compilation of the data available in the literature, combined with the authors' experiences of the problem. To be complete, the database must be maintained and regularly updated. The aim of our database is first to gather and then to render the existing information more approachable, manageable, and objective. The database and the presentation of the data on a Late Cretaceous paleogeographic map (Scotese and Golonka, 1992) can also point out possible characteristics or ordering of the data, which then need to be further investigated in the field or in the laboratory.

In KTbase, quantitative information is provided wherever possible and as precisely as possible. Unfortunately, not all authors present their data in the same manner and/or with the same rigor. The database format reflects the average quality of published data extracted from the literature. This is clearly illustrated by the concentration of Ir. In the K-T layer Ir is ideally reported in flux per square centimeter of sediment (ng/cm). However, most commonly in the literature the Ir concentration is given in parts per billion or parts per trillion (ppb or ppt = ng/g or pg/g). Only 30 Ir flux values are stored in KTbase, whereas 67 precise Ir maximum concentration measurements are available. Thus our analysis focuses on the maximum Ir concentration in the boundary clay, although, when available, integrated values are also considered. This information (e.g., flux or concentration of other platinum group elements [PGE]) is stored in a memo field together with additional data and remarks concerning the site.

Despite these drawbacks, some patterns emerge. The main advantage of the database is to point out these possible patterns and allow scientists to test them in a more constrained manner. In a multidisciplinary field such as the K-T boundary, it also rapidly provides the specialist in one discipline with both a global perspective of the problem and with detailed information in an unfamiliar field. Another significant advantage of the database is to indicate clearly what needs to be done and where, in order to further develop the understanding of the ejecta distribution problem. As clearly shown in Figure 1, the worldwide distribution of studied K-T sequences is strongly biased toward Europe and North America. Africa, Australia, South America, and the high latitudes (>60°) appear as open fields of research on the K-T event, especially in term of impact tracers.

In this chapter we first focus our discussion on the sedimentology and the quality of K-T sites for ejecta studies, then examine the broad distribution of chaotic sedimentary units at the K-T boundary. We then present and discuss the distribution patterns of Ir and shocked quartz.

EVALUATION OF K-T BOUNDARY SECTIONS

Completeness criteria

In the database, a K-T boundary site is defined as a locality with at least the late Maastrichtian or the Danian preserved. So far, 345 K-T boundary sites are recorded in KTbase. The completeness of K-T sections is often debated (see discussion in Kiessling and Claeys, 2001). Biostratigraphic correlation and precision between marine and continental location can be problematic. In this case, we decided to rely on the presence of impact products to define precisely the K-T boundary, and to evaluate stratigraphic completeness. The timing of impact debris deposition ranges from about an hour for the proximal ejecta curtain material (Alvarez et al., 1995) to several years for the finest Ir-rich dust to settle from the upper atmosphere (Toon et al., 1982) and through the water column. In a section, the record of an event as geologically short as the deposition of ejecta debris is probably one of the best indications (if not the best) of stratigraphic completeness available. In addition, deposition of ejecta is more likely to be synchronous than the global first occurrence of a newly evolved species. In addition, the ejecta material criterion eliminates the possible problems of biostratigraphic correlation between marine and continental sections. Although strictly speaking the ejecta criterion only applies to the completeness of the K-T layer, nearly all of the reported sites containing impact debris are also biostratigraphically complete.

On the basis of this convention, nearly 30% of all localities in KTbase are stratigraphically complete; i.e., 101 K-T sites contain ejecta debris, and can thus be considered as true K-T boundaries for the purpose of this study (Fig. 1). Another 15% do not seem to contain the Chicxulub ejecta, but would be considered complete in terms of biostratigraphy, because they contain the latest Maastrichtian and earliest Danian zones. They are classified as fairly complete sections for the purpose of this study and are also shown in Figure 1. Most of them have never been checked for impact tracers. This gives a first hint of the research possibility opened by KTbase.

At almost 60% of the localities in KTbase the completeness is either unknown or a significant sedimentation break is evident. These so-called incomplete sites cannot be used to study ejecta distribution patterns, but they might be used to understand some aspects of the K-T extinction (Kiessling and Claeys, 2001).

Depositional environment

Sites from all paleoenvironments are considered in KTbase. The great majority of K-T boundary sites are located in the marine realm (84%); 33% are in deep water and 48% are in shallow-marine environments. The other 3% are labeled only as marine sites without any bathymetric information. The terrestrial environment represents 16% of the sites. Comparing Figures 1 and 2, it is obvious that the sites considered incomplete in term of ejecta distribution are mostly from shallow-water depositional environments.

K-T regression

Several authors advocate a significant regression at or just prior to the K-T boundary (Archibald, 1996a, 1996b; Keller and Stinnesbeck, 1996; Schmitz et al., 1992). Figure 3 indicates that this regression does not seem to be globally recorded. Looking at the sea-level curve, the K-T regression appears very minor compared to the one clearly marked ~7 m.y. later at the Selandian-Thanetian boundary (Haq et al., 1988; Hardenbol et al., 1998). In addition, a good part of the data for a pre-K-T

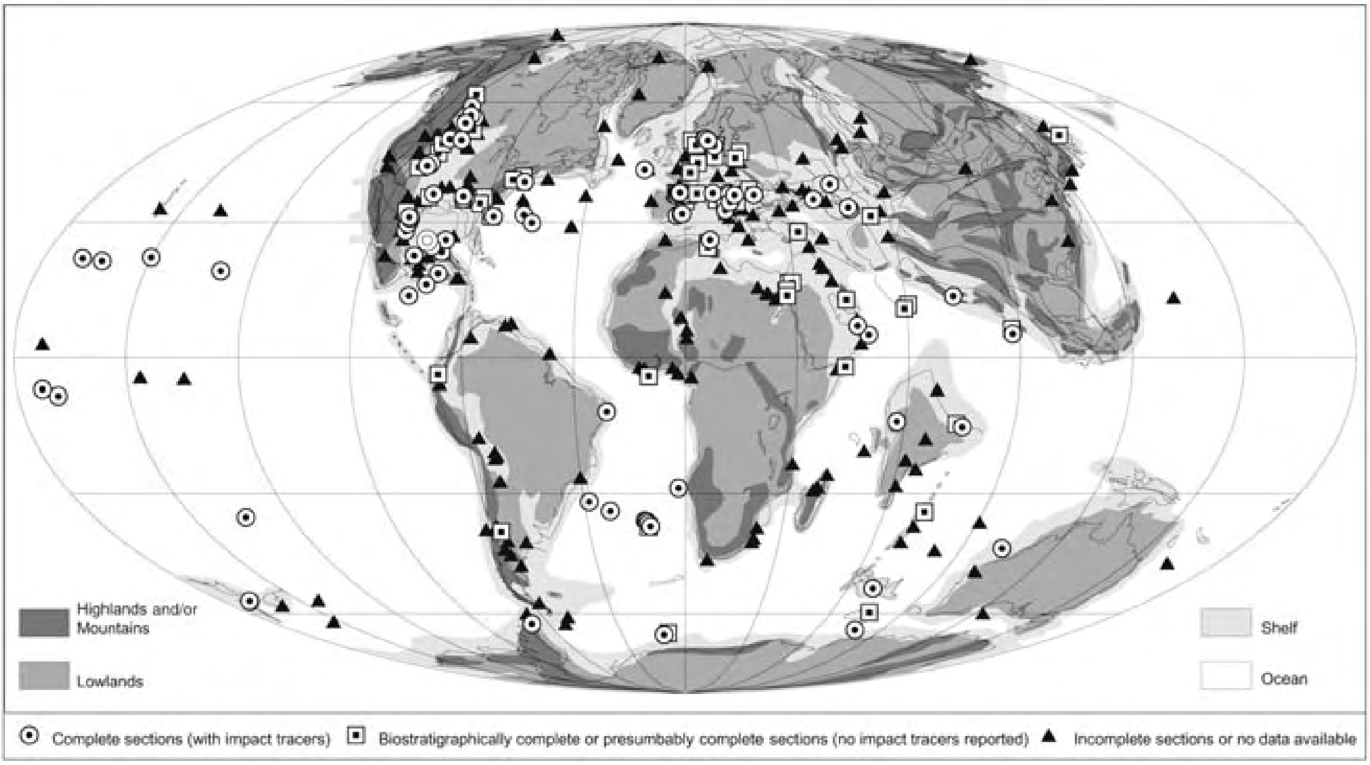

Figure 1. Completeness of Cretaceous-Tertiary (K-T) sections: 101 K-T sites that have recorded ejecta debris are globally distributed, clearly supporting worldwide deposition of Chicxulub ejecta. Paleogeographic reconstruction (J. Golonka, 1997, personal commun.) presented here is based on modified version of Late Cretaceous map of Scotese and Golonka (1992.)

boundary regression came from the Braggs section in Alabama (Baum and Vail, 1988; Donovan et al., 1988; Habib et al., 1992). This Gulf of Mexico locality is <1500 km from the Chicxulub crater, in a region where the K-T boundary is marked by a clastic sequence several meters thick that has proximal ejecta at its base (Smit, 1999). The displacement of material and large earthquakes involved in the formation of the 200-km-diameter Chicxulub crater must have severely affected the sedimentology of the Gulf of Mexico and triggered major sediment disturbances. Gravity flows and tsunami-related deposition are present throughout the Gulf of Mexico (Bourgeois et al., 1988; Bralower et al., 1998; Smit, 1999; Smit et al., 1992, 1996). Therefore, the sediments interpreted at Bragg as a transgressive sequence tract overlying a sequence boundary (Baum and Vail, 1988; Donovan et al., 1988) may instead reflect the deposition of debris flows triggered by tsunami waves related to the nearby Chicxulub impact, as suggested by Pitakpaivan et al. (1994) (Fig. 4). These coarse sediments thus have no relation to eustatic sea level. KTbase also supports the view of Speijer and van der Zwaan (1996) that the complex pattern of sea-level fluctuations for the late Maastrichtian evoked by some is based on unconstrained and contradictory data. It is thus more likely that the pattern observed in Figure 3 outside the Gulf of Mexico region reflects local regression (Keller et al., 1998) opposed by local transgressions (Pardo et al., 1999), even in tectonically stable areas.

TSUNAMI AND MASS-WASTING DEPOSITION

Effect on regional sedimentation

Paleogeographic reconstruction shows that, contrary to the tectonically active Caribbean region, the morphology of the Gulf of Mexico has not changed much since the Late Cretaceous (Acton et al., 2000; Pindell, 1994). The impact took place on the platform, displacing and/or pushing away huge volumes of sediments, leading to major wave disturbance in deeper water. Very large earthquakes were also generated for an extended period of time after the event (Covey et al., 1994; O'Keefe and Ahrens, 1991). Seismic shaking induced the fracturing and collapse of the unstable parts of the Yucatan platform margins even at a distance of several hundred kilometers from the crater (Grajales-Nishimura et al., 2000). As a result, huge tsunami waves and massive debris flows formed in the Gulf of Mexico, locally eroding the Upper Cretaceous strata, and reworking, transporting, and redepositing sediments. Bourgeois et al. (1988) estimated that at Brazos River (Texas) the waves were at least 50–100 m high. Crashing onshore, the huge tsunami

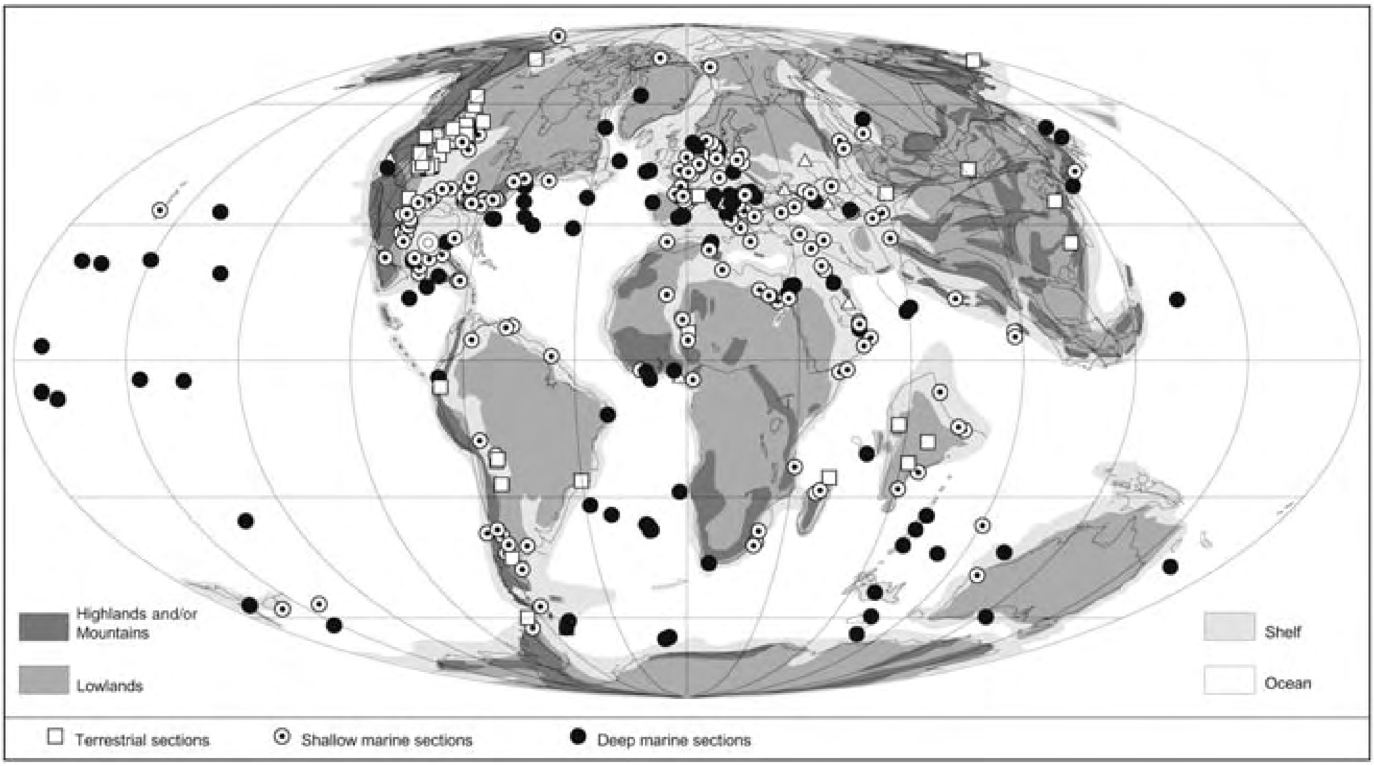

Figure 2. Depositional environment of Cretaceous-Tertiary boundary sites. Marine environments dominate by far; terrestrial sections are only conspicuous in North America.

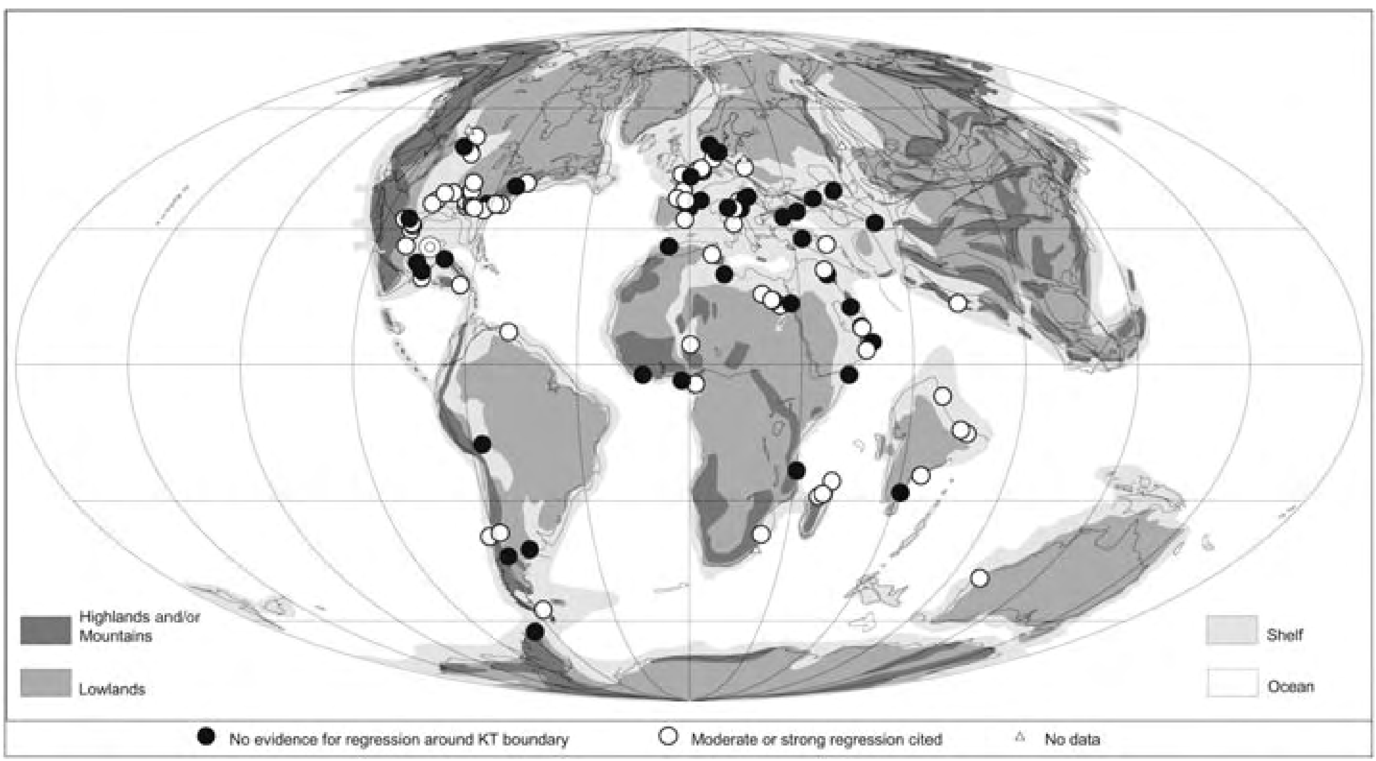

Figure 3. Distribution of Cretaceous-Tertiary (K-T) boundary sites marked by regression at boundary versus sites where no regression or even transgression is indicated. Only shallow-marine sites with sedimentological data are shown.

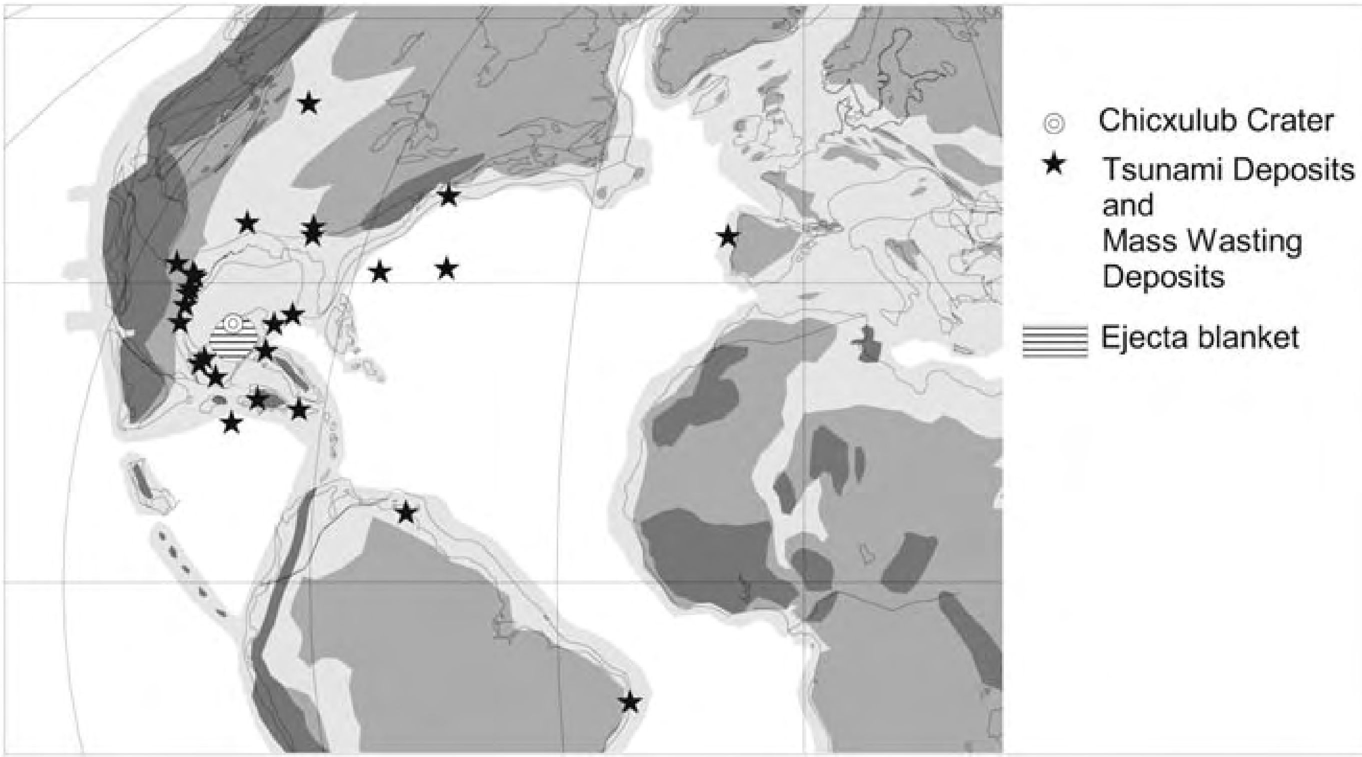

Figure 4. Major disturbance of sedimentation at Cretaceous-Tertiary boundary is recorded in Gulf of Mexico region and in Atlantic. Ejecta blanket surrounding crater, and first discovered in Belize to 350 km from crater (Ocampo et al., 1996), is shown by hachured pattern.

waves had a strong erosive power, and as they retreated they dragged back large amounts sediment to the deep water (Kruge et al., 1994). Figure 4 indicates the location of K-T boundary chaotic sediments, such as breccias, coarse clastic units, debris flows, and tsunamites related to the Chicxulub impact event. It seems that this catastrophic sedimentation also extended to parts of the Atlantic Ocean.

Proximal ejecta blanket

On the Yucatan platform, from the crater rim all the way to Belize, the K-T boundary is composed of breccias. At the crater rim, it is formed of suevite overlying a Bunte Breccia-like unit (Urrutia-Fucugauchi et al., 1996). This polymict breccia is composed essentially of blocks of carbonate and evaporites from the upper part of the Chicxulub target rock. Near the Mexican-Belize border the breccia is composed of a >20-m-thick diamictite formed essentially of dolomite blocks. This unit formed on the shallow-water carbonate platform and is recognized all over Yucatan, from Campeche to Valladolid, around Chetumal, and in northern Belize (hachured pattern in Fig. 4). The mode of formation of this unit is still unclear. It could have been formed as a ground-hugging flow, according to the Oberbeck (1975) model of ballistic ejection and secondary cratering. This model was successfully advocated by Hörz (1982; Hörz et al., 1983) for the Bunte Breccia around the Ries crater.

Failure of the Yucatan platform margins

The stratigraphy and distribution of the large sediment gravity flows resulting from the collapse of the continental margins around the Chicxulub crater were examined in detail by Bralower et al. (1998) and nicknamed the "K-T boundary cocK-Tail." Evidence for erosion caused by the passage of the flows, or deposition of K-T cocK-Tail material, are widespread from the margin of the Yucatan platform to the north, between Yucatan and Florida to the Nicaragua Rise and the Venezuela basin to the south. Farther west, offshore of the Cretaceous platform in the Mexican states of Tabasco and Chiapas, an ~40-m-thick breccia is below the ejecta-rich K-T boundary sequence (Grajales-Nishimura et al., 2000; Montanari et al., 1994). This breccia is 170 m thick in the oil-producing region of the Campeche bank (Grajales-Nishimura et al., 2000). Similar breccias are also reported from Guatemala and Cuba (Fourcade et al., 1997, 1998; Kiyokawa et al., 1999; Tada et al., 1999). In the entire region, the breccia is formed of decametric to millimetric blocks of limestone, and the fossil content indicates that they originated from an Upper Cretaceous shallow-water carbonate platform environment. Where found in deep-water settings, this chaotic deposit fines upward and resembles a major single-unit debris flow. The breccia is interpreted to be the result of fracturing and collapse of the Yucatan platform margin, caused by the Chicxulub-induced seismic shaking (Bralower et al., 1998; Grajales-Nishimura et al., 2000).

Tsunamites in the Gulf of Mexico

Material displaced by the crater formation, the failure of the margins, and huge earthquakes induced the formation of major tsunamis in the enclosed basin of the Gulf of Mexico. It is difficult to separate the effects of major mass flow and that of tsunamis on sedimentation across the K-T boundary. The breaking of the huge tsunamis (at least 100 m high, according to Bourgeois et al., 1988) on shore or in the shallow water eroded and dislocated large volumes of sediment, which then traveled as large masses or flows to the deeper water environment.

From Alabama to the northern part of the Mexican state of Vera Cruz, the K-T boundary is marked by a coarse clastic sequence interpreted as rapidly deposited by the combination of high-energy tsunamis and triggered gravity flows (Smit et al., 1996). However, this explanation is contested (for a complete discussion see Smit, 1999). A turbidite origin has also been proposed (Bohor, 1996). Others estimate that this unit resulted from channelized deposition taking place over several hundred thousand years due to rapid sea-level changes (Stinnesbeck et al., 1993). One of the characteristics of this sequence is its remarkable homogeneity over more than 2500 km, which clearly reflects unusual sedimentary processes. The sequence can be subdivided into four units (Smit, 1999).

The lower unit is a sandstone composed of ejecta material such as impact spherules, some with a preserved glass core, shocked grains, and limestone fragments. This unit also contains rip-up clasts of the underlying Upper Cretaceous Mendez marls. Unit two is a coarse carbonate-cemented sandstone with lithic clasts, quartz grains, foraminifera debris, and plant fragments. This unit is ejecta free, except for some reworked material at its base. Smit et al. (1996) reported repetitive changes of paleocurrent direction. Unit II fines upward and the transition to unit III is gradual and marked by the appearance of silt layers. The amount of sand diminishes upward. Unit IV is composed essentially of size-graded silt and appears often more lithified than the underlying units (Smit, 1999). It contains reworked fine ejecta, including shocked grains and Cretaceous fossils, and is enriched in Ir.

Debris flows and tsunamis outside the Gulf of Mexico

Sediment disturbances are also reported outside the Gulf of Mexico region. South and east of Yucatan the situation appears confused. In Cuba, Tada et al. (2000) interpreted the 180-m-thick Peñalver Formation as a K-T boundary deposit formed by debris flow and tsunamis. In Cuba, the 500-m-thick Cacarajicara Formation is viewed as related to giant mass-flow deposits triggered by the Chicxulub impact (Kiyokawa et al., 2000). The two units contain impact ejecta material such as shocked quartz and altered glass, and appear to be formed of an accumulation of chaotic clastic carbonate material from various sources. It is difficult to clearly differentiate the precise sedimentological processes taking place in this region. At K-T time, these Cuba sites must have been located very at close to the crater to explain such an input of material, capable of forming sections several hundred meters thick. Another possibility is that all the material originated from the collapse of the southern Yucatan platform margins, as observed to a lesser extent in the Campeche area (Grajales-Nishimura et al., 2000). In comparison, the K-T boundary debris-flow deposits found at nearby Beloc (Haiti) and at Ocean Drilling Program (ODP) site 1001 are <10 m thick (Maurasse and Sen, 1991; Bralower et al., 1998; Smit, 1999).

The Chicxulub impact also triggered large submarine slope failures in both the western and eastern North Atlantic. At ODP Site 171B on Blake Nose in the western Atlantic north of Florida, the K-T boundary is marked by an ~20-cm-thick clastic unit underlying the classic ejecta Ir succession (Smit et al., 1997). Seismic data in the area show sediment disturbance near the K-T boundary (Klaus et al., 1997).

At Bass River (New Jersey), more than 2500 km from Chicxulub, a biostratigraphically complete upper Maastrichtian—Paleocene sequence is interrupted by a 12-cm-thick spherule bed and reworked clay clasts of various sizes (Olsson et al., 1997). This sequence is equivalent but much thinner than that found throughout the Gulf of Mexico region. The basal contact of the spherule layer is nonerosional, indicating that the spherules settled quietly on a soft surface undergoing sedimentation (Olsson et al., 1997). This contrasts with the Gulf of Mexico sequence, where the presence of rip-up clasts of the underlying upper Maastrichtian marls reworked in the spherule bed indicate more energetic deposition and cutting of the underlying sediments. At Bass River, the upper contact of the spherule bed is sharp. The overlying 6-cm-thick clay-clast layer contains Cretaceous foraminifera and nannofossils indicating that they were eroded, transported, and redeposited on the spherule bed (Olsson et al., 1997). This unit was interpreted by Olsson et al. (1997) to have originated from erosive action of impact-triggered tsunami or megastorms affecting the North Atlantic. It appears to be a single event with waves strong enough to affect the Bass River middle shelf at a depth of ~100 m. Norris et al. (2000) identified K-T boundary age mass-flow deposits associated with ejecta in Deep Sea Drilling Project (DSDP) Sites 387 and 386 on the Bermuda Rise, ~2500-2800 km from Chicxulub. These deposits can be correlated with a distinctive acoustic reflector known across the North Atlantic, from Puerto Rico to the Grand Bank of Canada (Norris et al., 2000). In the eastern Atlantic, at DSDP Hole 398D on the abyssal plain offshore Portugal, an interval of 70 cm below the K-T boundary is slumped (Norris et al., 2000). These authors interpreted it as possibly reflecting a single mass-failure event predating the arrival of the overlying ejecta material, caused by slope failure along the Portuguese coast by direct effect of ground motion or tsunamites across the Atlantic. In the western Atlantic the mass-wasting material originated in shallow-water environments and was transported over a significant distance; in the eastern Atlantic the slump is locally derived and reworked (Norris et al., 2000), which might perhaps be viewed as reflecting the variation in the intensity of the ground motion disturbance with distance from the crater.

It appears that sediment disturbance across the boundary is also present in the Poty quarry of northern Brazil (Albertão et al., 1994), and probably in Venezuela. Coarse- to medium-grained sandstones overlying silty shales mark the K-T boundary interval in eastern Venezuela (Helenes and Somoza, 1999). Although detailed sedimentological data are lacking, the overall stratigraphic context is similar to that reported at Gulf of Mexico tsunamite sites. The Pernambuco region of northeastern Brazil seems to mark the southern extension of Chicxulub-induced disturbance of K-T sedimentation. The tsunamis, slope failure, or major earthquakes do not seem to have extended south of the equator. At ODP and DSDP sites in the southern Atlantic, the K-T boundary appears to be marked only by the classic thin Ir-rich clay layer.

EJECTA MATERIAL

Iridium distribution

The first reported and probably most characteristic feature of the K-T boundary is an enrichment in Ir. Several studies have demonstrated that the K-T boundary clay also contains high concentrations in the other PGE (Pt, Pd, Os, Ru, Re), Ni, Cr, Co, and gold (Evans et al., 1993a, 1993b; Kyte et al., 1980). However, KTbase contains essentially Ir data; most authors have reported the K-T boundary geochemical anomaly mainly in terms of Ir concentration (Fig. 5).

The database shows that the Ir anomaly was detected in 85 K-T boundary sites worldwide, in a broad range of depositional environments from deep marine to continental settings. KTbase allows the comparison of Ir data determined at different laboratories, using different methods. We discussed, in the presentation of the database, the problem of reporting Ir data in flux versus maximum concentration. Despite this difficulty and the various analytical techniques utilized, the reported Ir data are generally in good agreement. The maximum concentration ranges from 0.1 to $>$87 ppb.

Outside the Gulf of Mexico, there is no correlation between Ir concentration and distance from the impact site. Local conditions, such as sedimentation rate, lateral sediment redistribution, bioturbation, and diagenesis, can probably account for the difference in Ir concentration reported, even between geographically close sites. In some K-T sites, for example in the U.S. Western Interior, the Ir anomaly is concentrated in a thin ($<$1 cm) interval. At other locations, bioturbation, reworking, diagenesis, and chemical diffusion can cause the remobilization of Ir and its spread over as much as several meters of section. Small Ir peaks recorded in the early Paleocene can also be attributed to redeposition of eroded Ir-rich K-T boundary material. In that case, the Ir is likely to be associated with reworked Cretaceous microfossils (Pospichal, 1996). Robin et al. (1991) discussed the diffusion of Ir compared to other denser and thus less mobile ejecta components such as the Ni-rich magnesioferrite spinels. Meteorite-rich dust and vapor from the impacting bolide and target rock were transported to the upper atmosphere by the fireball rising from the crater. It thus appears that, after the impact, the Earth was engulfed in a homogeneous cloud of vapor and dust particles. The database does not support the idea that some areas of the Earth, e.g., the high latitudes, were less affected by this dust cloud than tropical regions. Several southern high-latitude sites (i.e., Seymour Island or Kerguelen Plateau) display fairly high Ir concentrations. KTbase thus confirms that the Ir anomaly is global and homogeneous (Fig. 5). It is detected in all known parts of the Late Cretaceous world, including in high latitudes.

The only region to show a particular Ir pattern is the proximal Gulf of Mexico. At nine sites around the Gulf of Mexico, the concentration of Ir determined in the upper part (units III and IV of Smit, 1999) of the K-T sequence ranges between 0.25 and 1 ng/g. These concentrations are clearly lower than those determined at more distal sites (Fig. 5). This is a direct reflection of the highly unusual sedimentation taking place close to the Chicxulub crater. At the base, in the ejecta-rich unit I, the Ir concentration varies extensively between samples, reaching 0.2 ng/g. This is probably due to the presence of some minor meteoritic components included in the ejecta. No anomalous Ir concentration is detected in unit II, which is mainly formed of local coarse sand material eroded and transported by the combined effect of tsunami waves and debris flows. The silt layers at the base of unit III contain more Ir than the underlying sands (Fig. 6). In the fining-upward successions of units III and IV the finer layers are systematically enriched in Ir. The highest Ir concentration occurs in the size-graded fine silts of unit four (Fig. 6).

At the time of deposition of units III and IV, weeks to months after the K-T impact (Smit, 1999), Ir-rich material was raining down from the atmosphere and slowly settling through the water column. Although the carrier is still unknown (Schmitz, 1988; Schmitz et al., 1990), it appears that Ir is associated with the very fine fraction of the sediment and thus settled slowly. The sand interlayered with silt in unit III represents the last pulses of coarse material being deposited. Their rapid deposition had a diluting effect on the Ir sedimentation. The fining-upward sequence reflects the progressive decrease in frequency and magnitude of the tsunamis and debris-flow deposition (Smit, 1999). However, at that time, the waters of the Gulf of Mexico probably still contained much fine material in suspension, stirred up by the sedimentological disturbances induced directly or indirectly by the impact. The finer silts in unit III and especially in unit IV represent periods of less active sedimentation. During this time, finer sediments settled slowly,

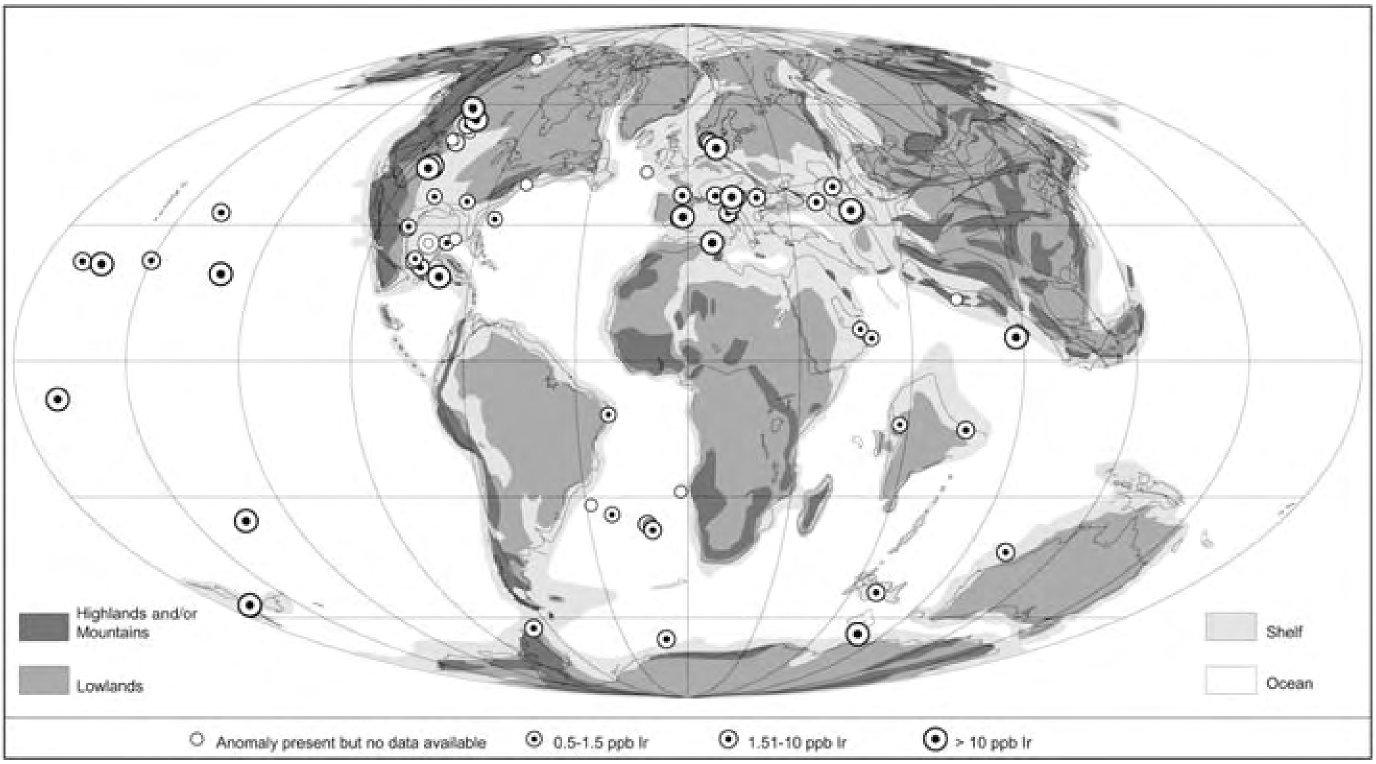

Figure 5. Location of Cretaceous-Tertiary boundary sites marked by positive Ir anomaly. Size of dot is proportional to maximum concentration of Ir (in ppb; or ng/g). Analyzed sites located around Gulf of Mexico contain <1.5 ppb Ir because of Ir dilution effect by high volume of disturbed sediment in suspension in Gulf of Mexico. Outside this region there is no correlation between concentration and distance from impact site.

incorporating the Ir. In the upper part of the K-T sequence, the Ir enrichment is thus diluted over almost 30 cm, rather than concentrated in a thin 1 cm layer as at more distal sites. This dilution effect is responsible for the lower Ir concentrations determined when single silt layers are analyzed. However, if the Ir data are integrated over the entire thickness of units III and IV, the Ir flux is comparable to the highest value detected outside the Gulf of Mexico region.

Shocked mineral distribution

The high-pressure shock wave generated by a meteorite impact produces deformations in minerals. In quartz, at dynamic pressures above 5 Gpa, several sets of very fine glassy silicate lamellae known as planar deformation features are created. Such shocked quartz grains were discovered in the K-T boundary sediments by Bohor et al. (1984). Shocked quartz distribution appears to be widespread (Bohor et al., 1987) (Fig. 7). Detailed studies at K-T sites in the U.S Western Interior yielded abundant quartz grains, commonly >300 µm (Bohor, 1990; Izett, 1990; Pillmore and Flores, 1987). These U.S. Western Interior sites were 2200–4200 km from the Chicxulub crater. ODP or DSDP cores recovered at distances as far as 10 000 km from Chicxulub crater (e.g., ODP Site 596) in the southwest Pacific, west of the crater, also yielded numerous shocked quartz grains (Bostwick and Kyte, 1996; Kyte et al., 1996). Abundance of shocked quartz in the K-T unit reaches >1000 grains per cm^2 (Bostwick and Kyte, 1996).

The largest shocked quartz grains are found in the U.S. Western Interior, where they reach sizes >500 µm. The only location outside the Western Interior where large shocked quartz grains are reported is in the Poty quarry in northern Brazil (Albertão et al., 1994). However, no precise statistics are given for this site. In the Pacific, a few grains are as large as 150 µm, but the majority are below 100 µm, the average being ~30 µm (Bostwick and Kyte, 1996). It is difficult to compare the searches for shocked material made at different sites, by different authors, using different techniques. The size difference could be an effect of the amount of sample available for study, and/or the amount of time invested in the search. Much larger volumes of sediments can be processed from the Western Interior outcrops than from deep-sea cores. Shocked quartz is also reported in the K-T clay layer in Italy, Spain, France, and Denmark (Bohor et al., 1987). However, at these outcrops, shocked quartz concentrations appear lower and their size smaller than reported at equivalent distances (~6000–8000 km) to the west in the Pacific Ocean (Bohor and Izett, 1986; Montanari, 1991). Outcrops in Europe also provide ample material for shocked

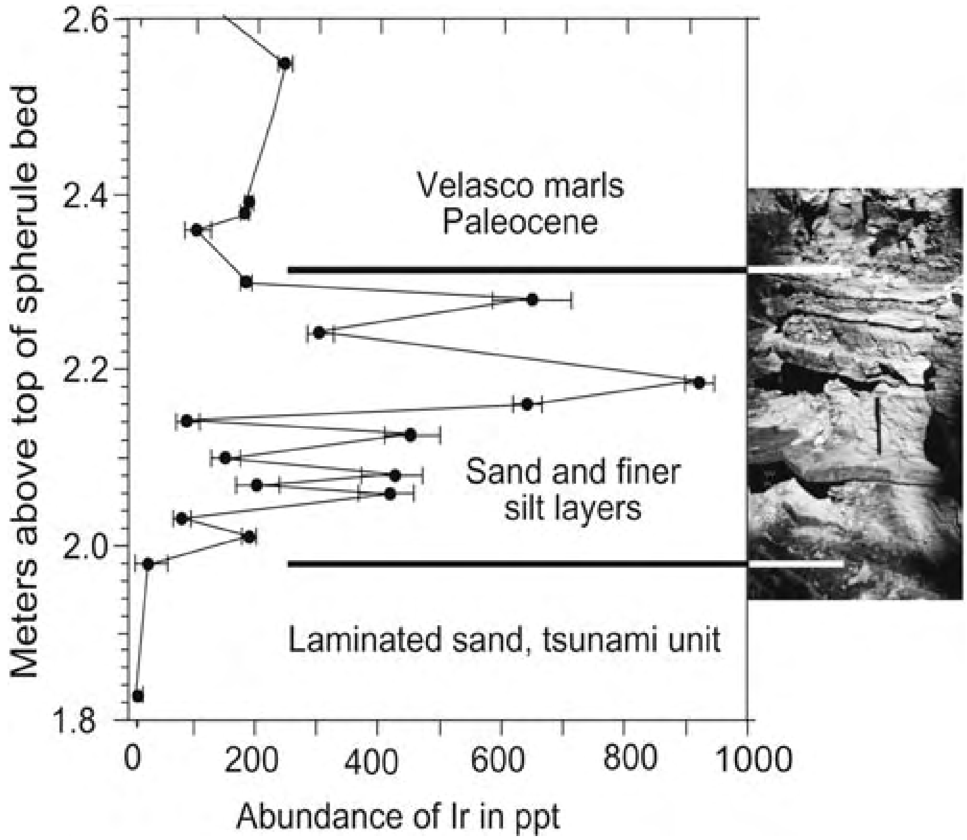

Figure 6. Ir profile across alternating sand and silt layers forming fining-upward sequence of units III and IV at Cretaceous-Tertiary boundary in arroyo El Mimbral (northeastern Mexico) illustrating progressive enrichment in Ir as sediment fines upward from sand to finer silt. Lower Ir content systematically characterizes coarser material of sequence.

mineral searches: no grains >300 µm have been reported there.

Unfortunately, many reports of shocked quartz failed to mention clearly the range and average sizes as well as precise concentration. This information is only available for K-T boundary sites on the Pacific plate, and for some in the U.S. Western Interior. More rigor in the way shocked minerals are characterized is required to extract quantitative meaningful information about the global distribution of this type of ejecta. On the basis of the available data, we suggest that there is a pattern of higher abundance, and possible larger sizes west of the Chicxulub crater, as first pointed out by Alvarez et al. (1995). Alvarez et al. attributed this asymmetric distribution of the shocked quartz to the rotation of the Earth, which affected differently the ballistic trajectory and orbit of the eastbound and westbound particles (see Fig. 1 in Alvarez, 1996; Alvarez et al., 1995). The shocked grain pattern agrees with the oblique impact hypothesis of Schultz and D'Hondt (1996). The impact structure asymmetries suggest a trajectory from the southeast to the northwest at an angle <30° from the horizontal (Schultz and D'Hondt, 1996). This predicts that most of the shocked material was ejected preferentially toward the northwest. The large shocked quartz found in the Brazilian Poty quarry is problematic for both hypotheses. Unfortunately, there is too little information on how common or rare such grains are in this section, which is the only shocked mineral-bearing K-T outcrop reported in South America.

In the Gulf of Mexico region, distribution of shocked quartz is complex. In northeastern Mexico sites, shocked grains are associated with the basal ejecta-rich unit of the K-T sequence (Smit et al., 1992). Shocked quartz grains are rare in this unit, compared to impact glass spherules and limestone fragments. The uppermost fine-grained unit IV, the K-T cocK-Tail of Bralower et al. (1998), also contains shocked grains. There are no reports of quartz with planar deformation features in the coarser clastic units II and III of the sequence. In Beloc, Haiti, shocked quartz occurs in the spherule layer and associated with Ir in the upper part of the sequence (Leroux et al., 1995). Leroux et al. reported shocked quartz abundance of 104 grains/cm^2 in the spherule layer, much higher than that found in the same level in northeastern Mexico. Shocked quartz grains are also found in southern Mexico, in the ejecta-rich layers above the breccia in Bochil and El Guayal, and in the bentonite layer sealing the oil-producing breccia on the Campeche bank (Claeys et al., 1996; Grajales-Nishimura et al., 2000; Montanari et al., 1994).

Rare shocked quartz is present in the diamictite-like dolomite ejecta breccia that forms the distal part of the ejecta blanket in Yucatan (Pope et al., 1999). The ejecta blanket also contains small, highly altered basement fragments, similar to those found in the Chicxulub suevite inside the crater. In this unit, crater products appear to be greatly diluted by the local dolomitic material. However, shocked grains are more common

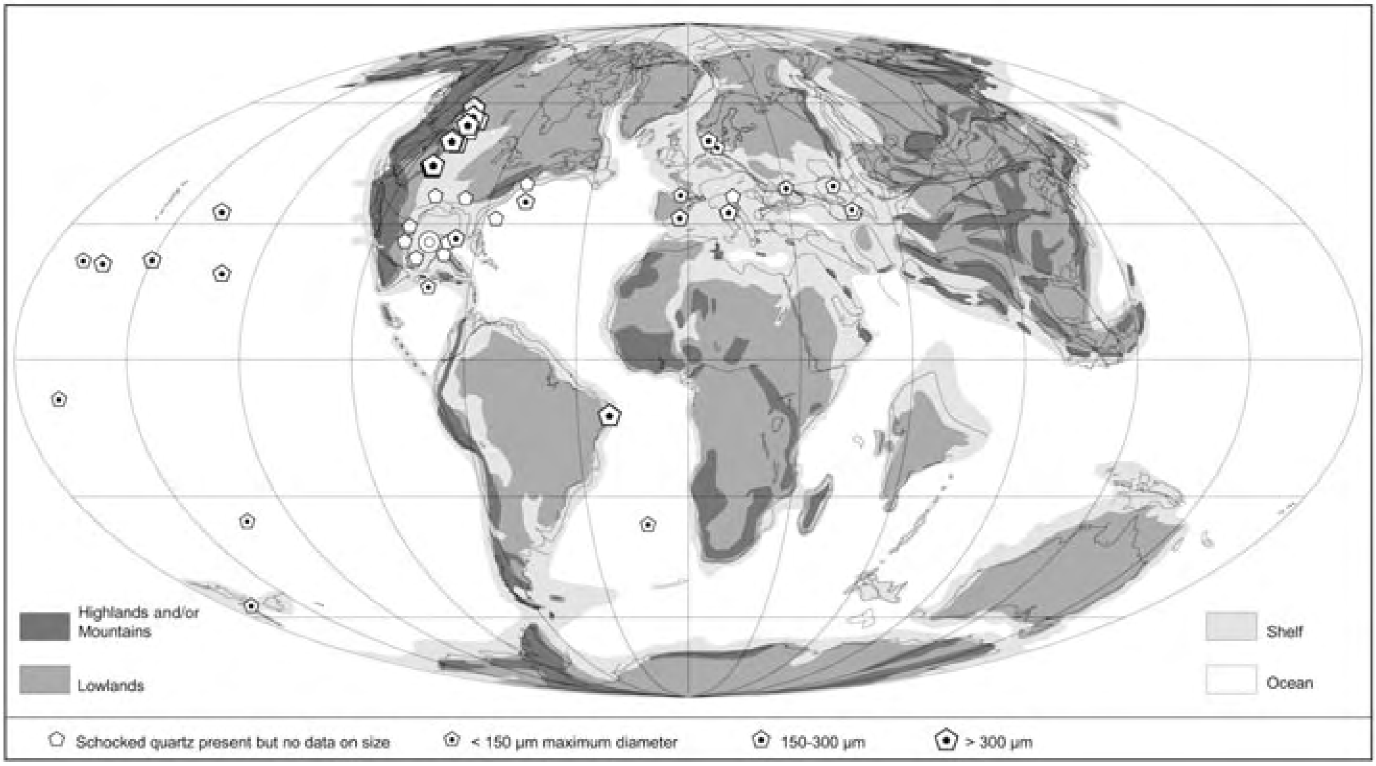

Figure 7. Grain-size distribution of shocked quartz grains at Cretaceous-Tertiary (K-T) boundary. K-T layer in U.S. Western Interior contains largest quartz with planar deformation features (PDF) reported so far. Only maximum size is represented; figure does not show abundance of shocked quartz grains. Data suggest that at equivalent distance, quartz with PDFs are more common to west of crater.

in the suevite and polymict breccia of wells UNAM 5 and UNAM 6, drilled at the crater rim (Claeys et al., 2000).

CONCLUSIONS

1. There are 101 K-T boundary sites (some representing multiple outcrops), all over the world, that contain ejecta debris. This represents nearly 30% of all the sites entered in KTbase. Of the sites that contain latest Maastrichtian and earliest Danian biozones, 15% (i.e., more than 50 sites) have not been investigated for ejecta material.

2. K-T sites formed in shallow-water depositional environments are more commonly considered incomplete in terms of ejecta debris than deeper marine ones.

3. KTbase does not support a global regression at the K-T boundary. The hypothesis of a K-T regression stems in parts from the misinterpretation of impact-related coarse clastic or debris-flow units deposited in the Gulf of Mexico region. These coarse sandy units do not represent a transgressive sequence tract overlying a sequence boundary and are not related to a K-T boundary sea-level change.

4. The Chicxulub impact affected sedimentation within the Gulf of Mexico region and the Atlantic, probably all the way to offshore Portugal. This effect is reflected by the presence of coarse clastic units and/or breccia in deep-water settings and/or by the erosion of Upper Cretaceous sediments from depositional settings usually not prone to unconformities. The precise sedimentological mechanisms are not fully understood: for example, it is not clear if debris flows are created by the seismic wave or ground shaking or by the tsunami waves generated by the impact. It is also possible that in some places, massive debris flows generated tsunami waves. Most likely all these processes acted together, leading to the chaotic sedimentation and erosion occurring at or near the K-T boundary in the Gulf of Mexico and the North Atlantic.

5. The positive Ir anomaly has been recorded at 85 sites and appears to have been spread homogeneously all around the globe. Concentration does not vary systematically with distance from the crater. At proximal sites, the Ir concentration is diluted by the high amount of sediment put in suspension in the Gulf of Mexico's water after the impact.

6. Shocked quartz grains appear more abundant and larger west of the Chicxulub crater, although the absolute size factor may strongly depend on the amount of material available for study. Nevertheless, as proposed by Alvarez et al. (1995) and Bostwick and Kyte (1996), the maximum grain size of quartz

grains with planar deformation features seems larger in the Pacific than at sites located at equivalent distances from the crater in Europe.

7. KTbase demonstrates that a significant effort is needed to improve our knowledge of K-T boundary sites in South America, Africa, Australia, and the high latitudes (>60°).

Preliminary examination of the K-T database in terms of the ejecta debris distribution and K-T boundary sedimentation shows that it is probably the most convenient and user-friendly method to compile and sort the huge amount of literature on the subject. Plotting the current data on paleogeographic maps indicates zones where further studies are required. The occurrence of impact debris must also be reported in a clear and quantitative manner (e.g., abundance per cm^2 of sediments) before the distribution pattern of impact products can be understood.

The main advantage of the database is to point toward potential trends or characteristics in the data, which can then be investigated further. The information extracted from the database coupled with mathematical models will permit the documentation of the origin, transport, and deposition of ejecta material during cratering events. It is our goal to have the ejecta debris part of the database available through the internet in the near future.

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