Comparison of the Cretaceous-Tertiary Boundary Impact Events and the 0.77-Ma Australasian Tektite Event: Relevance to Mass Extinction

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Comparison of the Cretaceous-Tertiary Boundary Impact Events and the 0.77-Ma Australasian Tektite Event: Relevance to Mass Extinction

By E.C.T. CHAO

Reinterpretation of iridium anomalies, shocked quartz, and microtektites attributed to cratering events in Cretaceous-Tertiary boundary sections. Evidence from the Ries crater of Germany and Australasian tektites is essential to understanding giant craters and mass extinction

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Comparison of the Cretaceous-Tertiary Boundary Impact Events and the 0.77-Ma Australasian Tektite Event: Relevance to Mass Extinction

By E.C.T. Chao

Abstract

Cretaceous-Tertiary (K-T) boundary sections provide records of events of the K-T transition: retreat of the Cretaceous marine sea that left continents dotted with peat swamps, and impacts that left craters on exposed land and the ocean floor. Interpretation of the occurrence of iridium anomalies, layers containing weakly shocked quartz, laminae of coaly materials, and the clay layer that separates a gorceixite-goyazite layer from the layers above in representative K-T boundary sections can put constraints on and raise key questions regarding the types of events that occurred and their effects.

Data are presented to support the premise that the principal source for the iridium anomalies along major stratigraphic hiatuses, including the K-T boundary, may be ablation products of stony meteorites instead of being from dispersed, probably highly diluted, vaporized asteroids of impact events. In order to best understand the K-T boundary record, geologic, geochemical, and petrographic data obtained from the study of tektites and three impact craters are reviewed and compared in this study. The three craters are the 14.8-million-year-old, 25-kilometer-diameter crater of Ries, Germany, and two candidate K-T boundary craters, the 35-kilometer-diameter Manson crater of Iowa and the 180-kilometer-diameter Chicxulub crater of Yucatan, Mexico. Data from the well-studied Ries crater are also recommended as constraints for proposed models of giant impacts.

The Haitian microtektites, possibly from the Chicxulub crater event, are compared to the tektites and microtektites associated with the larger Australasian event. Those who favor the terrestrial origin of all tektites and microtektites must explain how there could have been mass extinction caused by the Chicxulub cratering event if there was no mass extinction associated with the 0.77-million-year-old Australasian tektite event.

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This bulletin is based on the address presented by the author on the occasion of his receipt of the Barringer Medal of the Meteoritical Society, July 27, 1992, Copenhagen, Denmark.

INTRODUCTION

I fondly remember first becoming acquainted with the Barringer Meteor Crater of Arizona in June 1960, when Dr. John O'Keefe (NASA, Greenbelt, Md.) brought me for study a small piece of shocked Coconino Sandstone from the U.S. National Museum, collected by George Merrill in 1911. It was from this sample that I first discovered the natural occurrence of coesite.

When I was first assigned a project to study tektites in the summer of 1960, I had no idea what a tektite looked like, so I learned from studying tektite collections in the British Museum, the private collection of von Konigswald in Holland, the collection of tektites from the Museum of Natural History in Paris, and other collections. Later, in September 1962, it was a rewarding coincidence that I visited various museums and field occurrences of tektites of Southeast Asia and Australia at the same time that Dean Chapman and Howard Larson of NASA's Ames Research Center near San Francisco planned a similar tour to Southeast Asia, the Philippines, Java, and Australia. Without knowing each other's schedules, we met in Bangkok, Manila, Sangiran in Java, and in Australia. Figure 1 is a photograph taken in Bangkok at the Thailand Museum, where Dean Chapman, Howard Larson, and I met to study the museum collection of Thailand tektites. Later I visited Professor Virgil Barnes of the University of Texas on my visits to the bediasites, I visited Dr. Vladimir Bouska in Prague regarding the sites of moldavites of Czechoslovakia, and I made field studies of tektites of the Ivory Coast in Africa. The discovery of Ni-Fe metallic spherules (some containing schreibersite; Chao and others, 1964) in some of the Australasian tektites and the distinctions that can be made between tektites and terrestrial impactites may help us to better interpret the place of origin of tektites (Chao and others, 1961; Chao 1963a, 1963b, 1964a, 1964b; Chao and others, 1964; Chao and Xie, 1990).

Observations accumulated from study of the 25-km Ries meteorite crater of Germany (fig. 2), the focus of my terrestrial crater study from about 1964 to 1977, may be

Figure 1. Dean R. Chapman, Howard K. Larson, and E.C.T. Chao (left to right) inspecting tektites from various localities in Thailand. (Thailand Museum, 1962.)

helpful in understanding the Chicxulub crater of the Cretaceous-Tertiary (K-T) boundary period. The major features of the Ries as a model shallow-basin-type meteorite crater include (1) evidence of the mechanics of ejecta transport; (2) the distribution and superposition of an unshocked sedimentary ejecta blanket and strongly shocked glass-bearing suevite; and (3) the location of the metallic component of the impacting body in the shatter-coned amphibolite of the crystalline bottom of the crater.

Izett (1990, 1991a) provided detailed and accurate descriptions and key identifications of shock products in K-T boundary sections from the Western United States and from the Haiti section near Beloc. Examination of data from these sections, and comparison of data from the Chicxulub K-T boundary crater (Hilderbrand and others, 1991) and the Ries crater, provides critical geologic and petrographic constraints regarding models of terrestrial impacts from giant asteroids. My background as a coal petrologist from 1977 to 1986 is helpful in the interpretation of the K-T boundary sections involving coaly materials and clays.

This paper discusses the interpretation of impact-shock evidence found in the K-T boundary sections and discusses the constraints imposed by the Australasian tektites and microtektites on the role of the 180-km Chicxulub crater in mass extinction.

REPRESENTATIVE CRETACEOUS-TERTIARY BOUNDARY SECTIONS OF WESTERN U.S. INTERIOR BASINS AND HAITI: INDICATION OF SEPARATE EVENTS

The K-T boundary sections represent the records of an exposed land surface on a continent such as North America during the end of a time period when the marine sea withdrew and left a continental landscape dotted with peat swamps. The change from a marine to a continental ecology and climate was environmentally drastic in itself and may have been a significant contributor to the K-T extinction event.

Some K-T boundary sections that have been studied occur at Clear Creek North, Colo., Dogie Creek, Wyo., Teapot Dome, Wyo., and Brownie Butte, Mont. In all, about 20 sites occur in the Raton basin of Colorado and New Mexico, and at least 10 sites occur in Wyoming, Montana, and western Canada (Izett, 1990). The two types of K-T boundary sections are (1) sections that contain evidence of only one cratering event, such as one of the sections from Clear Creek North in Colorado (such sections are less common and may not be typical), and (2) sections that contain evidence of two impact events, such as Dogie Creek of Wyoming and most K-T boundary sections in the Raton basin.

The importance of the detailed record of the K-T boundary sections cannot be overemphasized, because the sections (1) record events across the K-T boundary transition, including the retreat of the Cretaceous sea and transition to a continental environment, and (2) record cratering impact events. What is present in and what is absent from this record are equally important. If we can identify, read, and interpret this K-T boundary record correctly, we can put constraints on the types of events responsible for the transition or mass extinction of fauna and flora at this time.

Figure 3*A* is a photograph of the K-T boundary section from Clear Creek North, Colo., taken from Izett (1990). Figure 3*B* is a photomicrograph of a doubly polished ultrathin thin section (about 10 μm thick) made from a sample provided by Izett that covers most of a K-T boundary section from the same location. A doubly polished ultrathin thin section is necessary for optical study of the clay minerals and coaly materials.

As shown in figure 3*B*, this K-T boundary section can be divided into 9 units that are based on mineral contents. Ir anomalies, which usually occur above the shocked quartz, extend through units 1–5. The top layer, unit 1, is a finely laminated band consisting of scattered detrital clastic grains separated by thin, discontinuous laminae of coaly vitrinitic materials, and some jarosite (ferrous Fe sulfate). The clastic grains consist mostly of quartz in an illite matrix. Weakly shocked quartz grains with closely spaced microfractures are present. Most of the grains are larger than 100 μm in size. Nearly all the illite grains in the matrix are larger than 10 μm, and none are less than 1 μm.

Unit 2 consists of a nearly solid band of yellow jarosite with a few grains of quartz, and rare minute pyrite grains. Units 5 and 6 are jarosite bands similar to unit 2. The presence of jarosite bands is atypical in K-T boundary sections of the Raton basin (Glen Izett, written commun., 1992).

Unit 3 is similar to unit 1, with scattered detrital grains in a laminated layer consisting of alternating laminae of discontinuous coaly materials and illite. Detrital clastic grains are more abundant in unit 3 than in unit 1. They consist dominantly of quartz and of spindle-shaped graupen (aggregates of kaolinite). Small amounts of lithic quartzite fragments and chert are also present, as are coarsely crystallized kaolinite grains. Many of the spindle-shaped grains have a brownish iron-stained coating. Weakly shocked quartz grains with closely spaced microfractures are also present in this unit.

Unit 4 is a dominantly kaolinitic layer with scattered quartz and lithic fragments. One of the quartzite fragments shows weakly shocked parallel microfractures. This unit contains many discontinuous laminae of coaly materials.

Unit 7 consists mostly of smectitic clays that have grain sizes a few micrometers across. Spherulitic textures in the smectitic clays are often present. Unit 8 underlies unit 7 and consists mostly of kaolinitic clays generally without spherulitic textures. Some of the kaolinitic clays on the left of figure 3*B* show signs of reworking. The kaolinitic layer lies directly above unit 9. Clastic grains are generally absent in both units 7 and 8. Unit 9 consists of Cretaceous well-layered illite-dominated carbonaceous shale with very fine grained quartz. Gorceixite-goyazite spherules are not observed in this K-T section.

Most of the material above the smectitic and kaolinitic clays consists of layers containing detrital clastic grains in a clayey matrix that alternate with laminae of coaly materials and bands or lenses of jarosite. I concur with Izett (1990) that the dominant clays (units 7 and 8) are neither ejecta material nor volcanic ash. They resemble the underclay of peaty materials of a poorly drained swamp. This clay layer was deposited probably from stagnant water, which may have taken years to accumulate and provided a substrate for plant precursors of peat to grow. This clay also underwent leaching under low pH and reducing anaerobic conditions.

Figure 4 shows two polished slabs of a K-T boundary section from Dogie Creek, Wyo. Shocked quartz and anomalous Ir occur above the underclay. Gorceixite-goyazite (Ba- and Sr-Al phosphate) spherules occur under the smectite-kaolinite underclay. Recently, Izett (1991a) has shown evidence of teardrop and dumbbell morphology and surface sculptures on gorceixite-goyazite spherules that resemble microtektites, although the assumed previous glassy cores or hollow spheres had been completely replaced by gorceixite-goyazite. Some of the teardrop- and dumbbell-shaped and spherical particles may be pseudomorphs of microtektites. However, many of the hollow particles without such teardrop and dumbbell shape and sculptures may not be pseudomorphs, because hollow microtektites are very rare. They are spherules of unknown origin that have been replaced by aluminum phosphate. The Teapot Dome, Wyo., K-T boundary sections also contain gorceixite-goyazite spherules below the claystone or underclay layer.

Because the gorceixite-goyazite spherule-bearing layer is generally separated from the shocked-quartz-bearing layer above the underclay, I agree with Izett (1991b) and Shoemaker and Izett (1992) that this layer below the underclay probably represents products from another event. However, the gorceixite-goyazite spherule-bearing layer or horizon is unique. So far, the principal Ir anomaly is associated solely with the shocked-quartz-bearing layer above the underclay. The spherule layer below the underclay does not contain shocked quartz and other impact ejecta materials (Glen Izett, oral commun., 1992). If the gorceixite-goyazite spherule layer were the product of Chicxulub, then it would be reasonable to expect the presence of a strong Ir anomaly severalfold that of the Ir anomaly produced by the Manson crater of Iowa, and more shocked ejecta as well. As will be shown, an Ir anomaly is not necessarily attributable to an impact event.

Vickery and others (1992) suggested that the layer containing shocked quartz and the gorceixite-goyazite layer could have been produced by a single event. These authors are probably not aware of (1) the nature of the separating underclay and (2) the fact that, if they were from the same event, the layer of shocked quartz representing materials of low shock should underlie and not overlie the gorceixite-goyazite layer, which represents materials of high shock.

Figure 5 is a photograph of a polished slab of the lower part of a K-T boundary section from Haiti. This slab was described by Izett (1991a) particularly with reference to the finding of smectite-coated microtektites with glassy cores. The 0.5-m K-T boundary section is described as a turbidite with shocked quartz mixed in. According to Izett (1991a, fig. 3) there are similarities in the size distributions of shocked quartz grains from Clear Creek North, Colo., and from near Beloc, Haiti. Izett showed photographs of teardrop- and dumbbell-shaped smectite particles (Izett, 1991a, fig. 4) and flow structures on smectite pseudomorphs and on glass cores (Izett, 1991a, figs. 8 and 18, respectively). These are convincing evidence of microtektites. The $^{40}Ar/^{39}Ar$ ages of these microtektites are 64.5±0.1 Ma (Izett and others, 1991) or 65.01±0.08 Ma (Swisher and others, 1992). The numbers differ due only to methods of data reduction, so the age is the same in both cases. The Haitian microtektites are probably the oldest tektites known, although glassy particles yet to be firmly identified as microtektites have been reported from Devonian sections recently by Wang (1992) and Claeys and others (1992). Izett interprets the Haitian microtektites as having been derived from the Chicxulub impact structure of the Yucatan.

On the basis of comparisons with studies to determine the place of origin of the Australasian land tektites and

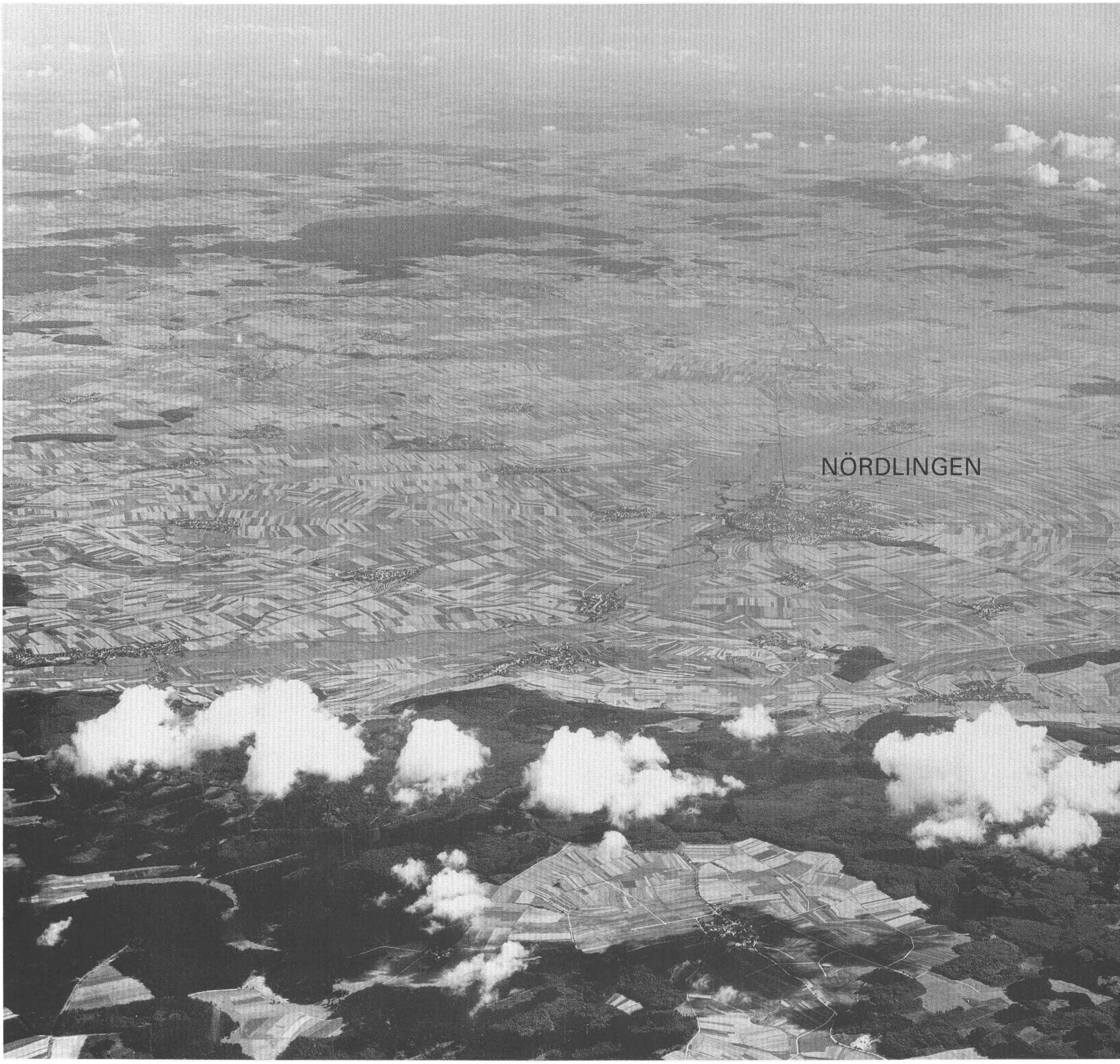


Figure 2. Aerial photograph showing the landscape of the Ries meteorite crater of Germany. The clusters of cumulus clouds and forests (dark areas) in the foreground mark the rim of the crater. The interior of the crater is covered by

microtektites, in my view the Haitian microtektites, which should be compared with the nature and age of the Chicxulub impactites, may not be related to Chicxulub and may have a much wider distribution than the impactites from Chicxulub.

Before trying to further understand and interpret the K-T boundary sections, it is important that we examine the sources of the Ir anomalies, the possible places of origin of weakly shocked quartz grains and the method of their transport, and the possible places of origin of microtektites

cultivated fields and scattered towns, such as Nördlingen, and villages. The photograph is a gift to the author from Professor Ekkehard Preuss of München, Germany. Reprinted with permission from Mayor Paul Kling of Nördlingen.

and pseudomorphs of microtektites. In order to evaluate what is present in the K-T boundary sections, we need to know more about events such as that which produced the Australasian tektites and microtektites, and we need to know more about the Chicxulub crater.

SOURCES OF Ir ANOMALIES

Most K-T boundary investigators have attributed the source of the Ir anomalies to cratering events, in spite of the fact that cosmic spherules and other sources equally will

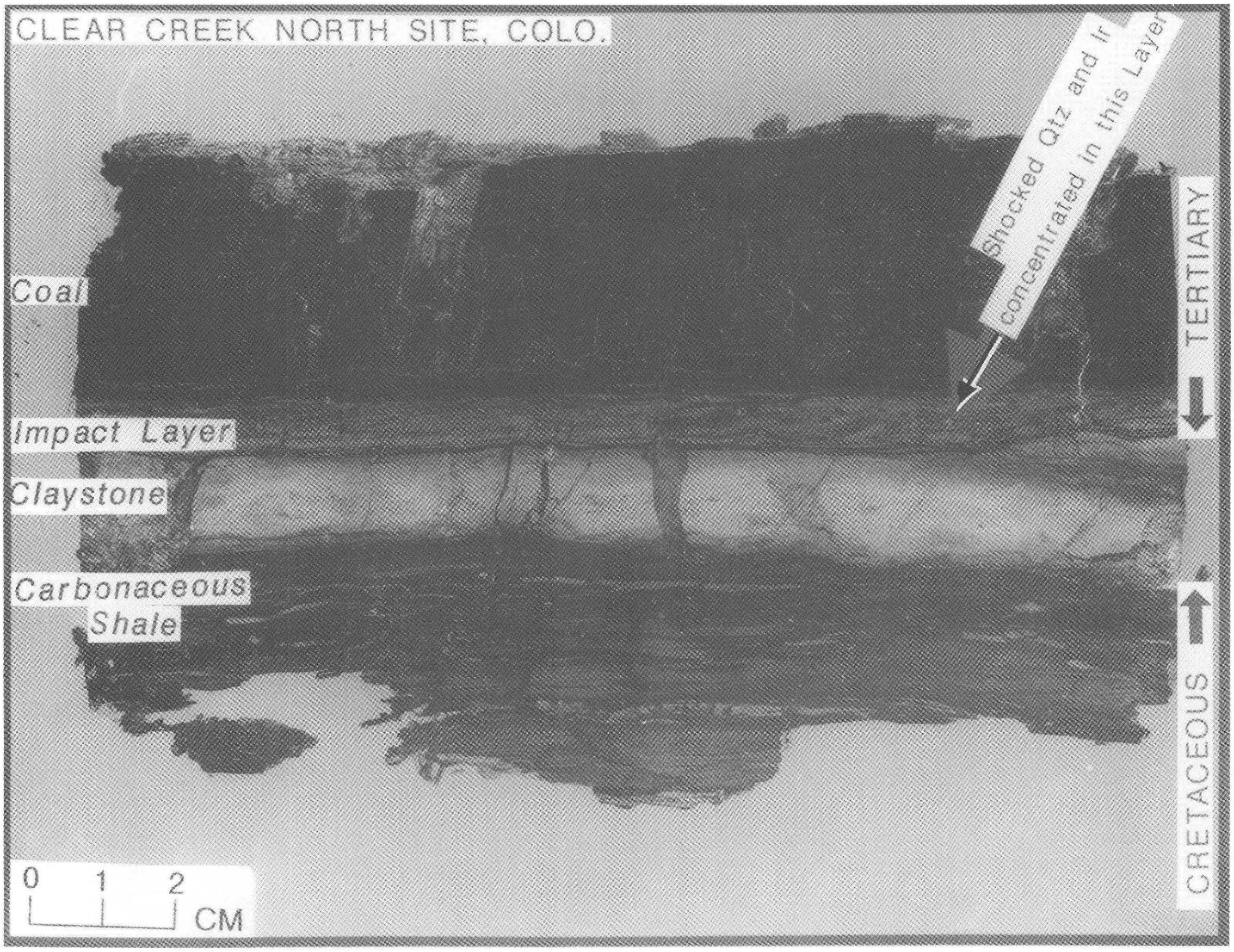


Figure 3*A*. Mounted Cretaceous-Tertiary boundary section from Clear Creek North, Colo. (From Izett, 1990.)

have produced the Ir anomalies. They assumed that there is a constant rate of sedimentation in which the cosmic contribution has been included. Hence, the K-T boundary Ir anomalies are caused by the addition from the K-T boundary cratering event contributed by the impact fusion-vaporization of the impacting body. This interpretation, in my view, is probably incorrect, because the K-T boundary is a stratigraphic hiatus, meaning that there is a break in the normal terrestrial sedimentation cycle. During this break, an erosional surface existed with a time interval of tens of thousands of years, where there was no normal terrestrial sedimentation but only deposition and accumulation of extraterrestrial materials such as ablated meteorite spherules and other cosmic particles. I favor this latter interpretation because it is a normal geological phenomenon. Hence, it is possible that the most important source of the Ir anomalies is ablation products from chondritic stony meteorites. In order to demonstrate the importance of this source, the fusion crusts of the Pultusk chondrite from Poland and the Nuevo Mercurio chondrite from Mexico were analyzed by Hugh Millard (this study) using the INAA (instrumental neutron activation analysis) method. Table 1 lists the findings of Ir concentrations from three sources: impactites of meteorite crater ejecta, cosmic particles, and fusion crusts of stony meteorites.

Glassy impactites from small craters produced by iron meteorites such as Barringer (Meteor) Crater of Arizona and the Wabar Crater from Saudi Arabia contain 350–500 and 87–740 ppb Ir, respectively (table 1). However, the average from 8 of 23 impactite samples enriched in Ir from the Ries crater of Germany contain only 0.015 ppb Ir. Impactite glass samples from other craters such as Lake Mistastin, Canada; Lonar Lake, India; and Strangways crater, Australia, are not particularly high in Ir either. Substantial metallic components of cratering events such as the Ries crater are actually found in the bottom of the crater (El Goresy and Chao, 1976; Chao and El Goresy, 1977). Hence, metal concentrations, including Ir, are enriched in the bottom of terrestrial craters and not necessarily in their ejected impactites.

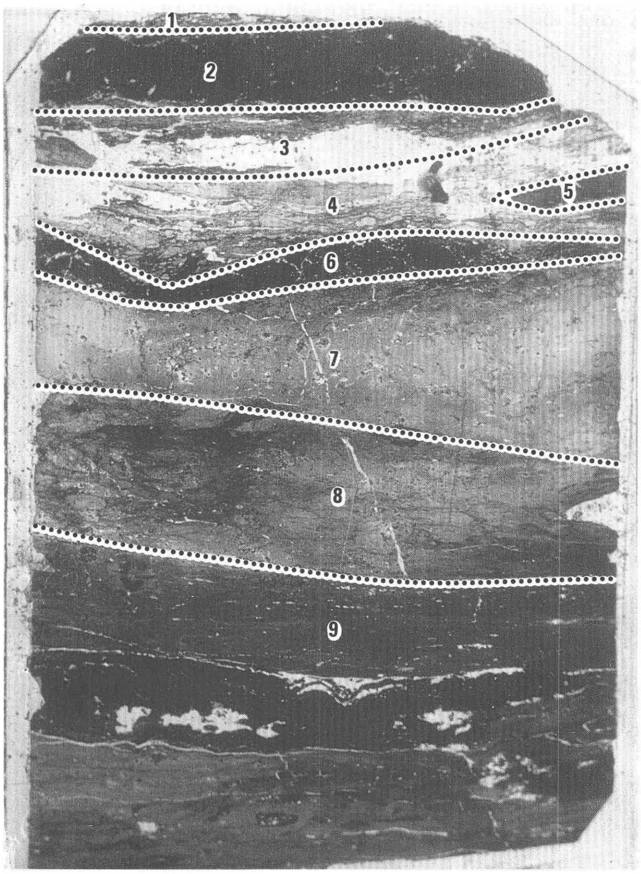


Figure 3*B*. A whole, doubly polished ultrathin thin section of a sample from a portion of the Cretaceous-Tertiary boundary section from Clear Creek North, Colo. The sample is from Glen Izett. The units, which are based on variation of mineral components, are described in the text. Size of section is 2 × 3 cm.

The Ir concentrations from cosmic particles are generally much higher, ranging from less than 5 to more than 2,000 ppb (table 1). The magnetic fusion crusts of stony meteorites, about 100–300 μm thick, are typical ablation products of chondrites such as those of the Pultusk and the Nuevo Mercurio. They contain 860±15 ppb Ir. The fusion crusts of these two chondrites also contain 177±9 and 166±5 ppb Au, respectively. The ablation products of shooting stars and stony meteorites are extremely high in Ir, and these events occur frequently! When stony meteorites enter the Earth's atmosphere at high velocities, they often break up into small pieces, scatter, and ablate. The ablated Ir-rich particles are decelerated and further spread by wind drifts over land surfaces and oceans. Hence, Ir anomalies in the K-T boundary sections, which are geologic hiatuses, have little value as a definitive indicator of an impact cratering event. Ir anomalies should be widespread and can be found on any land surface that represents a hiatus where the normal terrestrial sedimentation cycle was interrupted and ceased. They certainly should be more widespread in occurrence than shocked quartz, for example.

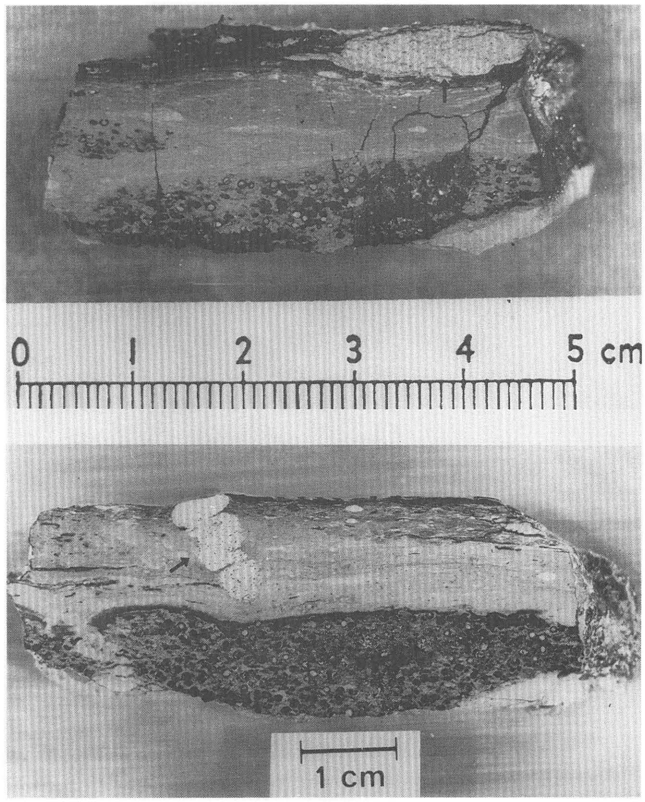


Figure 4. Two Cretaceous-Tertiary boundary sections from Dogie Creek, Wyo. Note the gorceixite-goyazite spherule layer below the underclay. Arrows point to fine-grained sand filling burrows. (From Izett, 1990.)

An independent observation also supports the presence of ablation products found in the K-T boundary clay. Magnesioferrite spinels, which have never been reported from impact ejecta, were found in K-T boundary sections from Caravaca, Spain, and sites in Italy (Izett, 1991a). Recently, Robin and others (1992) showed that such spinels are ablation products from cosmic objects, probably stony meteorites, entering the Earth's atmosphere.

Far too few large terrestrial craters (35 km in diameter or larger) have been identified to have produced the many Ir anomalies that occur in association with widespread stratigraphic hiatuses. Similarly, microtektites have been found in different stratigraphic horizons, but not enough large terrestrial craters have been identified that could have produced them.

LAYER WITH SHOCKED QUARTZ ATTRIBUTED TO THE MANSON CRATER

The origin of weakly shocked quartz and lithic fragments in the illitic clay layer of K-T boundary samples (see fig. 3*B*) just below the Ir anomalies was attributed by Izett (1990, 1991b) and Hartung and others (1990) as being the Manson crater in Iowa. As described in the doubly polished

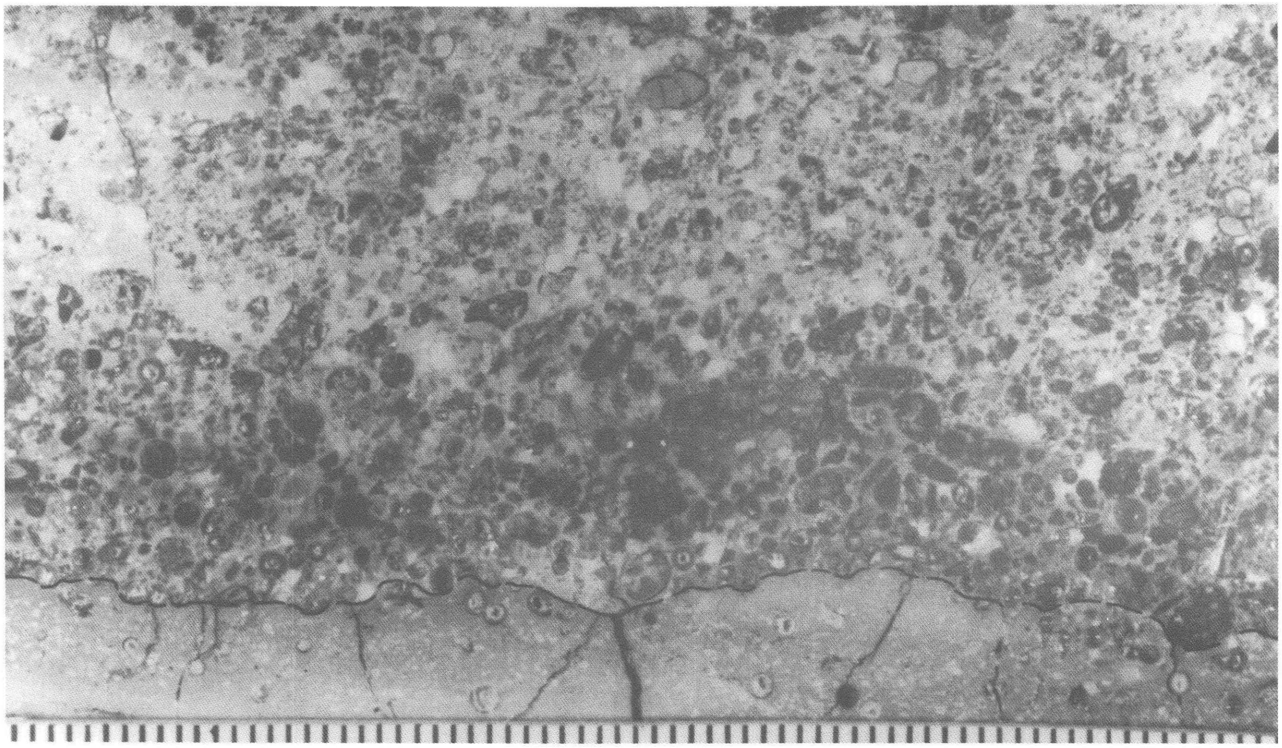


Figure 5. The lower portion of the Cretaceous-Tertiary boundary section near Beloc, Haiti. Smectite pseudomorphs with glassy cores were identified by Izett as microtektites, concentrated in the lower centimeter of the section. Dashed line marks the contact between the Cretaceous-Tertiary marker bed (above) and the Cretaceous marl (below). (See Izett, 1991a.) Scale is in millimeters.

Table 1. Sources of iridium concentrations
[ppb, parts per billion]

Sample	Ir (ppb)	Reference
Impactites of Meteorite Crater Ejecta		
8 of 23 Ries, Germany, crater ejecta, enriched in Ir	0.015	Morgan and others (1979).
1 of 5 impact melts from Lake Mistastin, Canada	0.055	Morgan and others (1979).
6 Aouelloul glasses, Africa	0.115	Morgan and others (1979).
Lonar Lake, India, vesicular glass	0.004–0.026	Morgan (1978).
Strangways crater, Australia:		
6 granite melts	0.059–2.86	Morgan and Wandless (1983).
1 shale melt	0.025	Morgan and Wandless (1983).
Meteor Crater, Arizona, Fe-meteorite impactite glass	350–500	Morgan and others (1979).
Wabar crater, Saudi Arabia, Fe-meteorite impactite glass	87–740	Morgan and others (1979).
Cosmic Particles		
Type A shiny spherules from marine sediment	300–1,500	Millard and Finkelman (1970).
8 stony spherules from marine sediment	<5–2,900	Millard and others (1985).
Fusion Crusts of Stony Meteorites		
Pultusk, Poland, USNM 3003 fusion crust	860	Millard, this study.
Nuevo Mercurio, Mexico, USNM 6091 fusion crust	860	Millard, this study.
Nuevo Mercurio, Mexico, USNM 6091 metal conc	2,160	Millard, this study.

ultrathin thin section of Clear Creek North (fig. 3*B*), weakly shocked quartz and shocked lithic fragments occur in the K-T boundary sections in more than one layer alternating with laminae of vitrinitic coaly materials and jarosite, above the underclay. Regardless of the number of parallel sets of closely spaced microfractures in the shocked quartz, there is so far no evidence of vitrification along the microfractures. There is also a lack of strongly shocked, completely vitrified thetomorphic quartz and feldspars (solid-state vitrification, Chao, 1968) and an absence of impactite glass laden with shocked mineral and lithic inclusions in the layer containing weakly shocked quartz.

The 35-km-diameter, 65.7±1-Ma Manson crater (Kunk and others, 1989) of Iowa is similar to the 25-km-diameter, 14.8-Ma Ries crater of Germany with respect to the target rock formations in which they are located. The Manson crater is excavated in a sequence of Middle Proterozoic, Paleozoic, and Cretaceous sedimentary rocks (including marine carbonate rocks) that overlie a basement of Proterozoic metamorphic gneisses intruded by granitic rocks and diabase dikes (Hartung and others, 1990). The Ries crater, which will be described in more detail in comparison with the Chicxulub crater, is also excavated in a sequence of Mesozoic rocks that overlies pre-Hercynian basement crystalline gneisses and amphibolite rocks intruded by granitic rocks.

According to Hörz (1982), quoting Cohen's (1963) suggestion that moldavites in Czechoslovakia were derived from the Ries when the impacting body first contacted the Earth's surface, a Miocene surface soil upon impact was fused by a fireball into melt and was ejected while molten and cooling, 300 to 400 km from the Ries, to form the moldavite strewnfield in Czechoslovakia.

The major obstacle for deriving moldavites, including an aerodynamically spalled teardrop (Chao, 1964), from the Ries crater is the effect of aerodynamic drag. The Ries crater is on land, is only 25 km in diameter, and its ballistically transported ejecta must go through the atmosphere. According to figure 6, moldavites, several grams in weight and up to several centimeters in size, could not have traveled more than a few kilometers from the Ries. In order to overcome this aerodynamic obstacle, Lin (1966) outlined two mechanisms by which he suggested that it is dynamically possible for Australasian tektites to have originated from a gigantic comet impact on Earth. He calculated that, in order to remove the Earth's atmosphere, the impact would have to excavate a crater over 300 km in diameter. Chapman and Gault (1967), in rejecting Lin's suggestion, commented that the energies involved in the Ries, as well as the Bosumtwi, Africa, event, were entirely inadequate, less than about 10^{-3} and 10^{-4}, respectively, of the required energy for atmospheric blowoff. The Ries and Bosumtwi events cannot be regarded as dynamically plausible sources of the moldavites or Ivory Coast tektites.

In addition, recently, Blum and Chamberlain (1992) showed that the moldavite tektites have a $\delta^{18}O$ value 4.5 per mil lower than values for the Miocene surficial soil from the Ries. This discrepancy in $\delta^{18}O$ is difficult to explain if moldavites originated from surface soil of the Ries. The moldavite tektites must have formed under reducing conditions with extremely low ferric Fe and volatiles.

Clearly, there is no evidence that tektites similar to moldavites were produced from the Manson crater. Otherwise, such tektites or their pseudomorphs with or without glass cores would have been found in the layer containing weakly shocked quartz in the K-T boundary section of, for example, Clear Creek North.

If both Ir and shocked quartz of the K-T boundary section of Clear Creek North came from the Manson crater, and if the source of Ir was from the vaporized impacting body upon contact with the surface soil, then the Ir anomaly layer should underlie instead of overlie the layer with shocked quartz, which presumably originated from the crystalline basement rocks of the Manson structure. The absence of strongly shocked impactite-bearing ejecta above the layer bearing shocked quartz at Clear Creek North suggests that the source of the Ir anomaly layer at Clear Creek North may not have come from the Manson structure.

Geologic evidence from the Manson crater and the Ries crater suggests to me that, upon contact with the Earth's surface in a 1-km-sized meteorite or asteroid impact event, the moment of penetration through the soil was perhaps of less than microsecond or nanosecond in duration (that is, instantaneous), so that the surface material was displaced rather than strongly shocked or fused. This scenario is perhaps realistic because the not-yet-vaporized impacting body continued to penetrate the sedimentary sequence without producing highly shocked ejecta. The strongly shocked ejecta we observed both at Manson and the Ries were produced when the impacting body hit the resisting bottom. The impact caused a sudden increase in pressure and heating such that the major fraction of the strongly shocked ejecta is glassy impactites laden with debris of shocked basement crystalline rocks. These geologic and petrographic observations are of critical importance and have the following implication: regardless of the nature of the overlying formations, be they limestones or evaporite, if they were penetrated by the impacting body before the crater bottom was reached, in less than a fraction of a microsecond, they probably would not have been strongly shocked or fused.

PSEUDOMORPH-MICROTEKTITES AND MICROTEKTITES

Assuming that some of the teardrop-, dumbbell-, and spherical-shaped gorceixite-goyazite particles with flow structures are microtektite pseudomorphs, then we are faced with the controversial consideration of the source crater of microtektites. There is consensus and good evidence that microtektites are of impact origin (Chao and others, 1961, 1964). The controversy, if tektites are of terrestrial origin, lies in correlating microtektites of a certain age with particular giant cratering events of the same age. Izett (1991a) linked the Haitian microtektites to the Chicxulub crater of Yucatan Peninsula, Mexico. Proving this linkage will be very difficult even if both show similar ages. Where

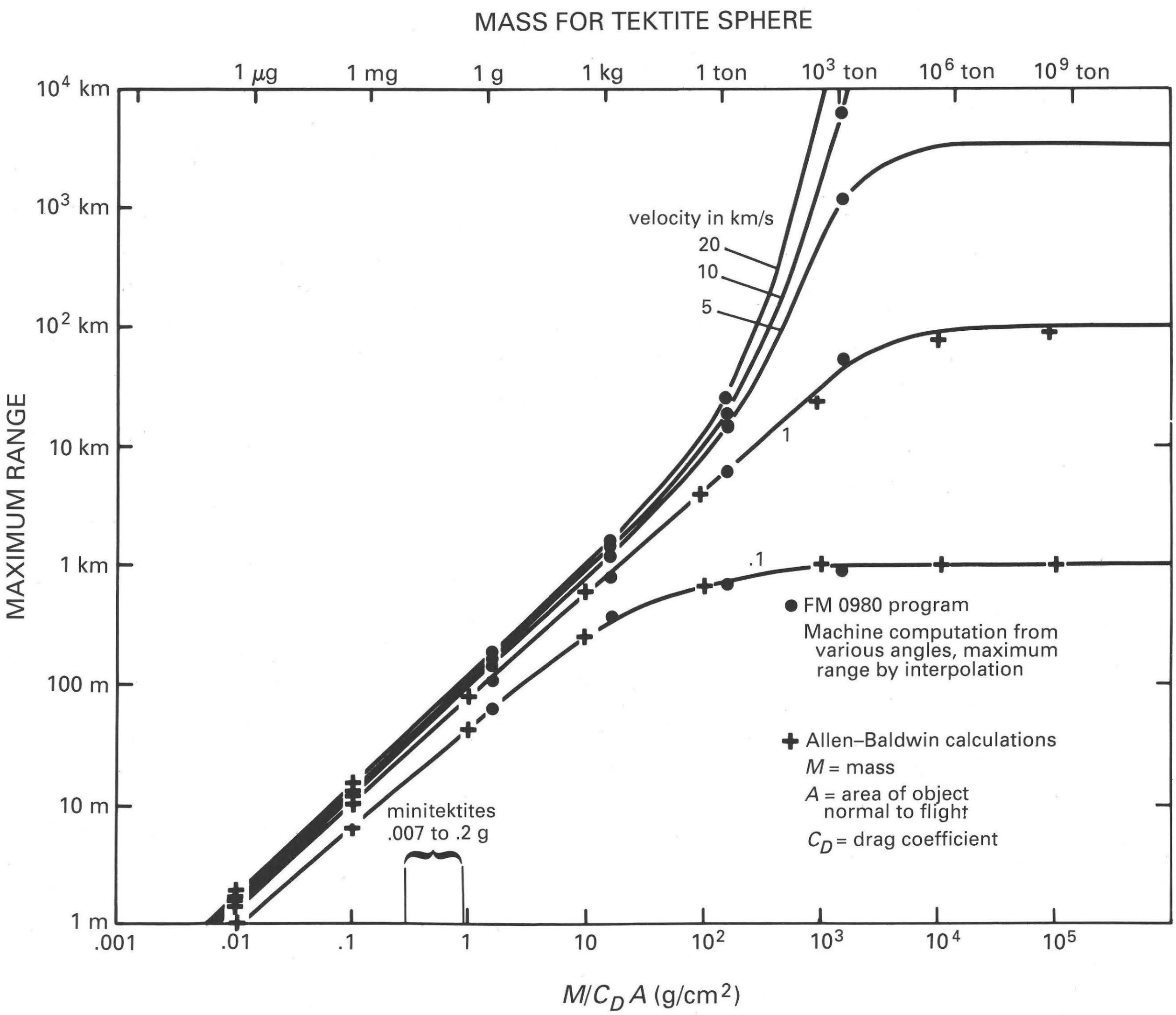


Figure 6. Diagram of maximum launched range of projectile versus optimum angle of launch at various velocities through stationary atmosphere. Note the limited distance, less than 100 m, of travel for minitektites, which is due to aerodynamic drag. (Courtesy of Dean R. Chapman.)

is the giant crater that should have been the source of the North American microtektites of late Eocene age (35.9± 0.4 Ma, time scale of Montanari and others, 1985) found in deep-sea sediments of the west equatorial Pacific and offshore of New Jersey (Keller and others, 1987)? I suggest that, in order to understand the place of origin of any microtektites, we must first understand the place of origin of the largest and most important Australasian land tektite and microtektite strewnfield.

ABUNDANCE, GRAIN SIZE, AND EJECTA TRANSPORT

Typical K-T boundary sections of the interior basins of the Western United States are less than 3 cm in total thickness. More than two-thirds of this thickness is accounted for by the underclay. Hence, the total thickness of ejecta from the two candidate crater events (Manson and Chicxulub) was about 1 cm. This amount of ejecta is too little to be dispersed in the atmosphere to obliterate sunlight. Furthermore, a substantial source of <1 μm crater ejecta particles is needed so that such particles may reside in the atmosphere for weeks before settling, in order to block out the sun and change the climatic conditions to cause mass extinction.

According to Toon and others (1982), in order to obtain worldwide distribution of ejecta, without removal of the atmosphere, the residence time in the atmosphere has to be greater than several weeks. This restricts ejecta particle size to 1 μm or less. As described from the doubly polished ultrathin thin section of the Clear Creek K-T section and the grain size histogram of shocked quartz from the Clear Creek North locality (Izett, 1991a), none of the shocked quartz grains are less than 10 μm in size, and no particles identifiable as ejecta are 1 μm or less. Hence, there is no evidence at all of ejecta of such small particle size. The author's study of suevite (strongly shocked glass-bearing ejecta) from the Ries also found no trapped ejecta particle less than 1 μm. Could it be that regardless of crater size, the impact process is not an efficient process of producing extremely fine particulate materials?

Unless the impact crater is about 300 km in diameter (Lin, 1966), large enough to remove the atmosphere, all impact ejecta transported ballistically must encounter aerodynamic drag. Figure 6 shows the limited launch range of particulate ejecta, and it shows that most ejecta of any terrestrial meteorite or asteroid impact are deposited within a distance of a few diameters of the crater. Those that were transported farther than several diameters of the crater size must rely on ejection to heights of several kilometers into the stratosphere and rely on atmospheric movements or wind drifts in order to achieve distribution throughout part of the world or worldwide.

THE RIES AND THE CHICXULUB CRATERS

The 25-km-diameter, 14.8-Ma Ries meteorite crater in Germany is well preserved and exposed. It is one of the best studied craters, although because of its unusually shallow basin geometry (Chao, 1977; Pohl and others, 1977), some crater investigators either did not accept its shallow depth geometry or, accepting the shallow depth, considered the crater atypical. The 180-km-diameter Chicxulub crater on the Yucatan Peninsula, Mexico, is apparently also a shallow-basin-type crater (Hilderbrand and Boynton, 1990; Hilderbrand and others, 1991; Smit and others, 1992). In addition to the general geometry of the crater, the stratigraphic section of the Ries is also similar to that of the Chicxulub. The Ries crater was excavated in a series of some 500 to 650 m of gently dipping sedimentary Triassic sandstones and shales and Jurassic limestones, sandstones, and shales that unconformably overlie a basement of pre-Hercynian metamorphic crystalline rocks that are intruded by Hercynian granitic rocks. On the basis of preliminary data, the Chicxulub crater was excavated in nearly horizontal Cretaceous limestone, marl, shale, bentonite, and evaporite that overlie a poorly known crystalline basement of probable Paleozoic age (Hilderbrand and others, 1991). Igneous clasts in breccias, and andesitic rocks (380 m thick) occur in drill cores (Hilderbrand and others, 1991). It is probable that the Chicxulub crater reached bottom in the poorly known Paleozoic crystalline basement rocks, since the most strongly shocked fragments are crystalline rocks or are of crystalline rock composition. Because of their similarities, comparison between the Ries and Chicxulub craters may provide interesting and useful information.

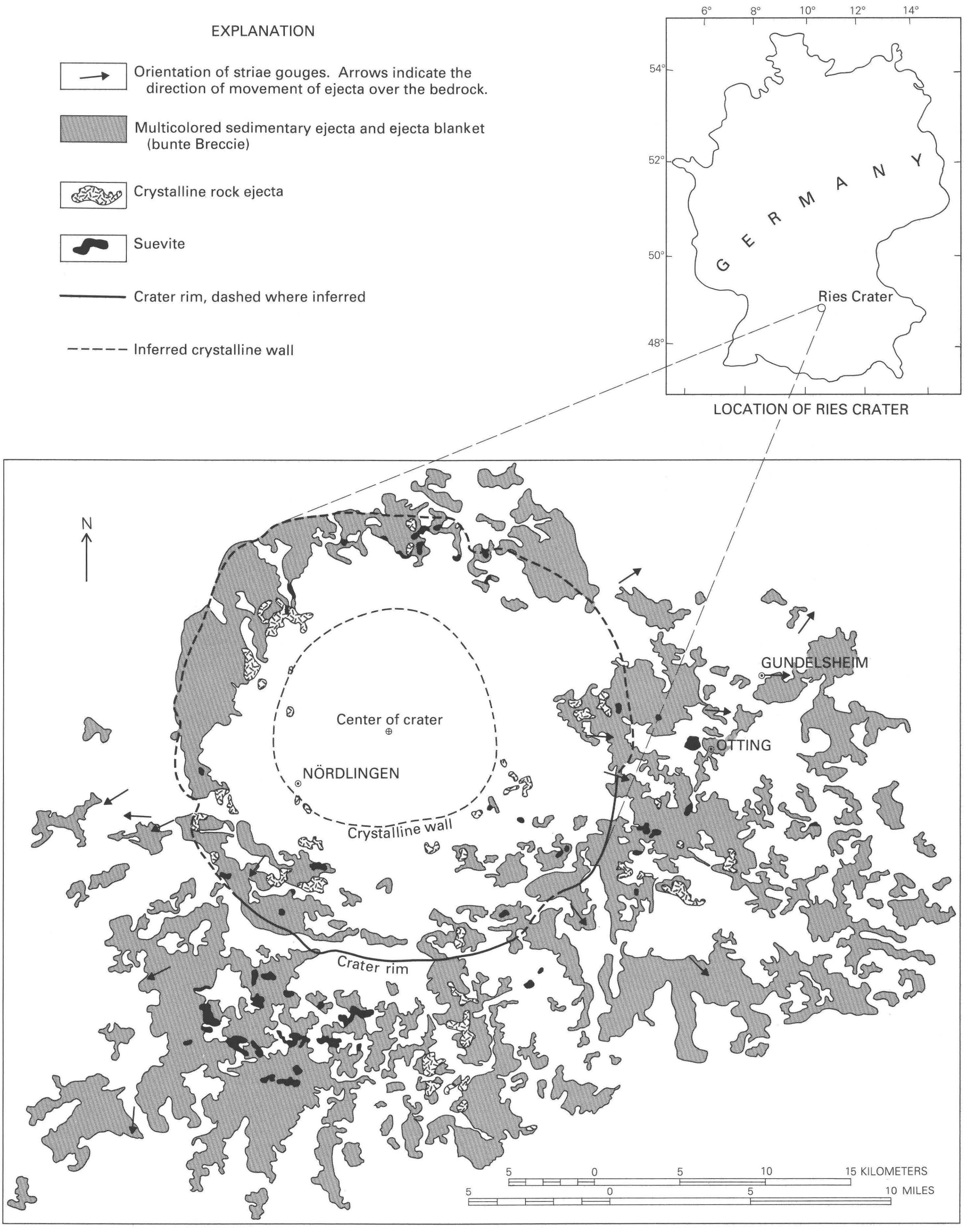
The Ries Crater of Germany

The Ries crater of Germany was a subject of my research between 1964 and 1977 (Chao and Minkin, 1977; Chao, 1977; Chao and others, 1978; Chao and Xie, 1990). The major mappable ejecta units of the Ries, based on complete geologic map coverage at the scale of 1:25,000 (fig. 7), are:

1. The essentially unshocked multicolored sedimentary breccias (bunte Breccie), which contain huge blocks of limestones, shales, and sandstones, some more than 100 m across. The matrix consists of fragments that range from fine to tens of centimeters in size and also consists of sedimentary rocks of the overlying formation. Some of the limestone blocks are finely crushed into small chips that are referred to as "Gries." Some investigators referred to those ejecta containing many huge blocks, such as those at Harburg, as megabreccias.
2. Weakly shocked to unshocked crystalline rock ejecta consisting mostly of basement crystalline rocks.
3. Suevite, a fallout and fallback unsorted finer grained type of ejecta containing numerous weakly to strongly shocked crystalline basement rocks, small amounts of unshocked to weakly shocked sedimentary rocks, and scattered glassy impactites in the form of pancakes (fläddler) and highly deformed and irregular-shaped glassy fragments, a few millimeters to several centimeters in size, laden with shocked and unshocked mineral and lithic fragments. The glassy inclusion-laden impactites contain numerous flattened vesicles coated with montmorillonite clays. Glassy impactite or melt rock within the suevite, larger than 50 cm across, is extremely rare.

Most of the crystalline rock and suevite ejecta lie within the crater rim. The crystalline rock breccias occur as displaced and uplifted ejecta blocks forming a concentric ring of about 12 km in diameter. Only small patches of suevite and crystalline rock ejecta occur outside of the crater, usually within one crater radius from the rim. Generally, the strongly shocked suevite ejecta overlie the essentially unshocked, multicolored sedimentary ejecta. The sedimentary ejecta blanket extends beyond a crater diameter and is the most abundant and extensive ejecta of the Ries.

Evidence for nonballistic transport of ejecta blanket of sedimentary breccias with huge blocks under confining pressure is as follows: radially distributed striations, grooves, and gouges (striated surface, or schlifffläche) occur on the limestone bedrock surfaces outside the crater below the ejecta blanket in the eastern, southern, and southwestern parts of the crater (fig. 7; Chao, 1977). Such



EXPLANATION
Orientation of striae gouges. Arrows indicate the direction of movement of ejecta over the bedrock.
Multicolored sedimentary ejecta and ejecta blanket (bunte Breccie)
Crystalline rock ejecta
Suevite
Crater rim, dashed where inferred
Inferred crystalline wall
6°
8°
10°
12°
14°
54°
52°
50°
48°
GERMANY
Ries Crater
LOCATION OF RIES CRATER
N
GUNDELSHEIM
OTTING
Center of crater
NÖRDLINGEN
Crystalline wall
Crater rim
5
0
5
10
15 KILOMETERS
5
0
5
10 MILES

◀ **Figure 7.** The orientation of striae and gouges on bedrock and the distribution of ejecta types, Ries crater, Germany. In some cases, the direction of the striations (arrows) does not appear to be exactly radiating from the center of the crater. Those striations were probably influenced by the preexisting valleys along which the ejecta were diverted.

striations are absent or have not been preserved on sandstone and shale bedrock surfaces forming the crater rim to the north and northwest of the crater. Abundant cobbles and boulders within the sedimentary breccia blanket containing huge blocks show gouges and striations. More specifically, freshly broken angular limestone fragments within the clayey matrix of the sedimentary breccia show either deeply incised mineral-produced striae or a high degree of clay polish (Chao, 1976). Limestone concretions within the clayey matrix are sheared and ruptured with offset fractures. These observations are used to conclude that the multicolored sedimentary breccias with huge crushed but not-disrupted blocks were nonballistically transported out of the crater under confining pressure as required by the production of mineral striae on angular limestone fragments, by radially rolling and gliding over the limestone bedrock surface, to distances more than 14 km away from the crater rim. The sedimentary breccias form the basal portion of the ejecta blanket. At least one-half of the total ejecta, consisting of those outside of the 12-km central crystalline wall, was estimated to have been nonballistically displaced out of the crater.

Figure 8 is a photograph of the striated limestone bedrock surface under the sedimentary ejecta blanket containing huge limestone blocks, at Gundelsheim quarry, 7 km east-northeast beyond the crater rim. Figure 9, also from the Gundelsheim quarry, is a photograph of an exposure from July 1992 showing the extensive striated bedrock surface without a trace of secondary craters. Note the huge block of limestone in the unshocked sedimentary ejecta blanket that sits above the bedrocks surface and is separated from it by about 0.3 m of fine-grained clayey ejecta matrix. Such huge limestone blocks would have definitely produced secondary craters if they had been ballistically ejected and transported. In reality, they are completely embedded in a clayey matrix containing centimeter-sized angular limestone fragments with clay

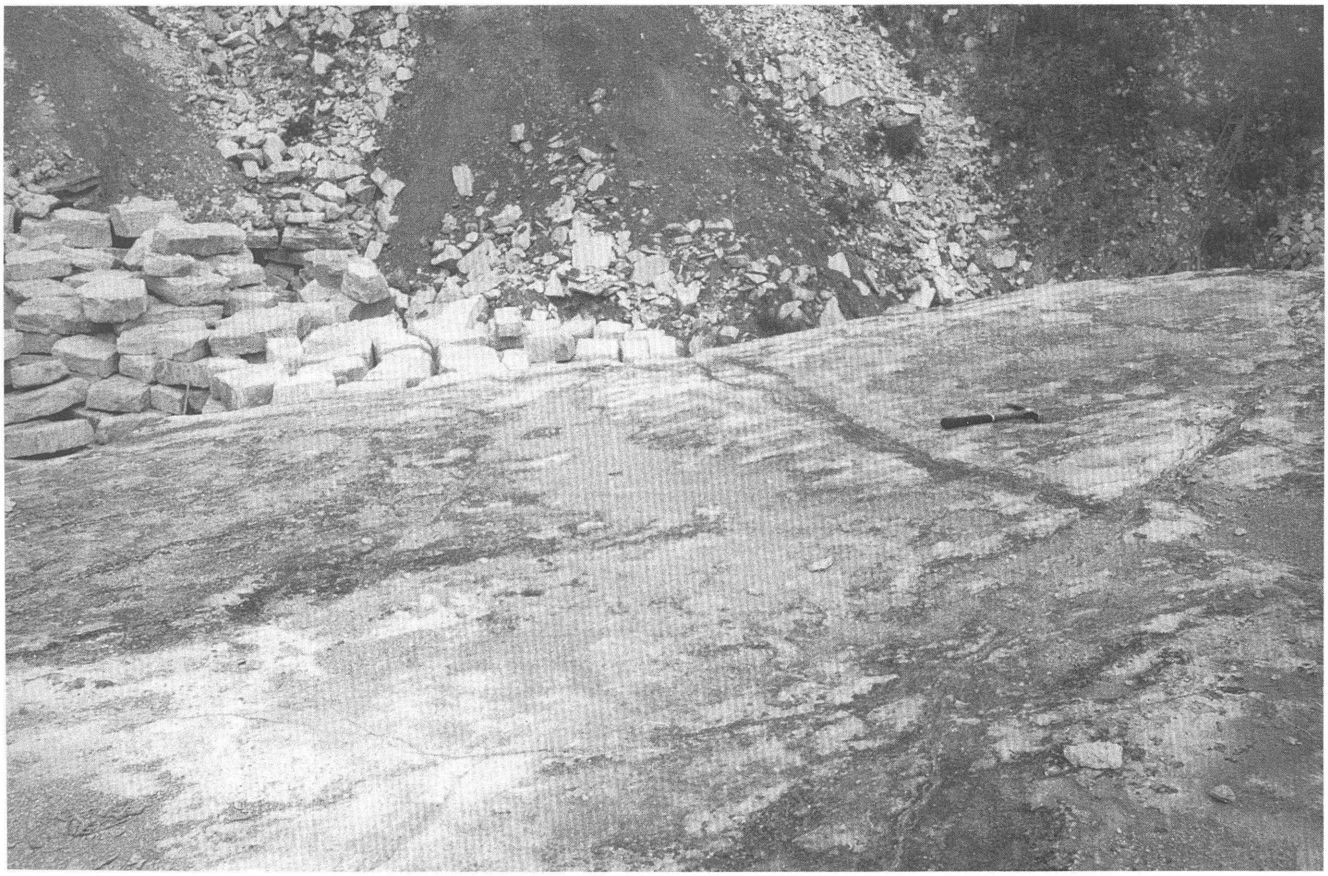


Figure 8. The limestone bedrock surface with parallel striae and gouges that were produced by unshocked sedimentary ejecta containing huge blocks that moved over the bedrock during the impact event. Hammer indicates direction of the striae. Location of photograph is Gundelsheim quarry, 7 km east-northeast from the Ries crater rim.

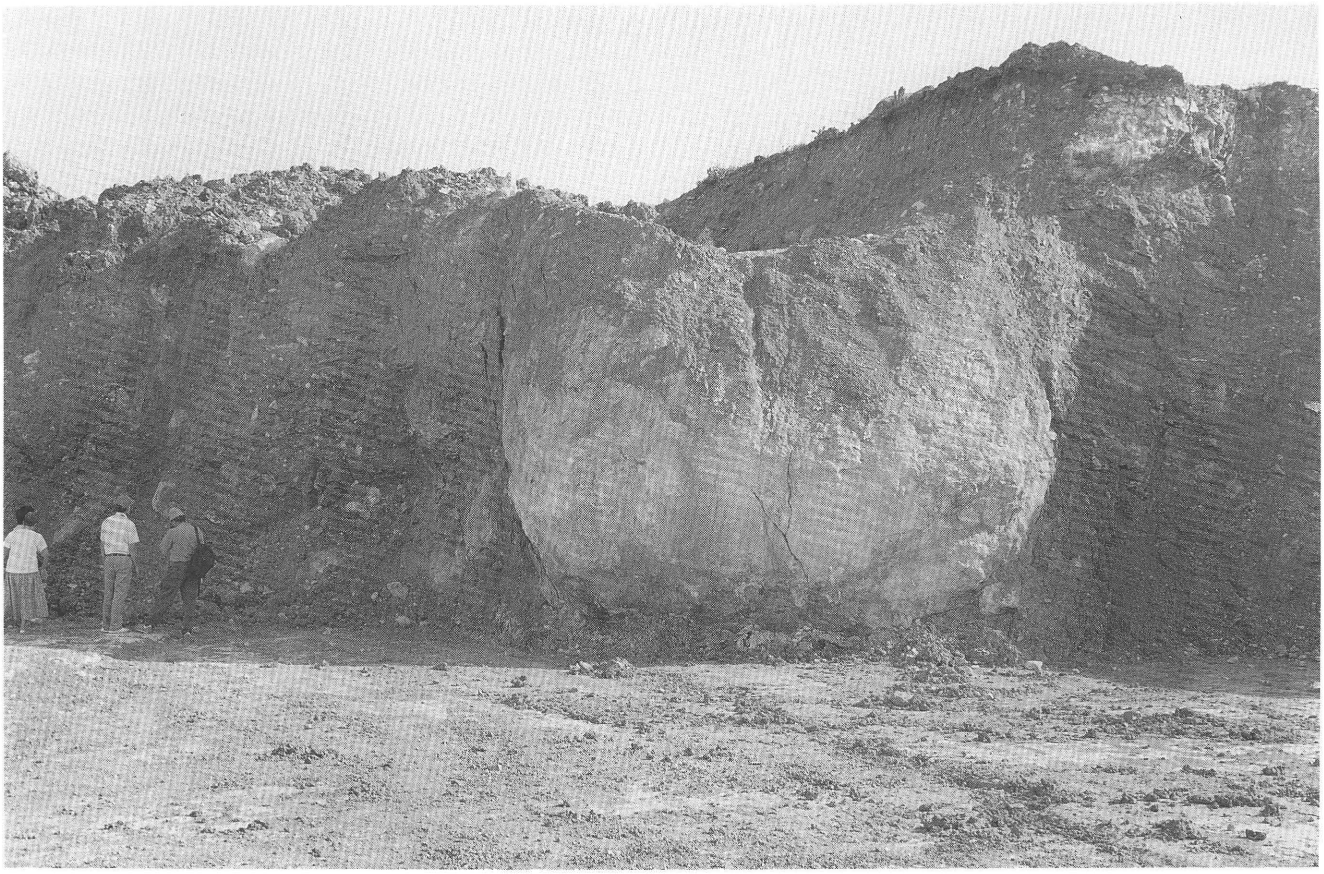


Figure 9. The limestone bedrock with parallel striae, grooves, and gouges (not resolved in this photo) in the foreground, overlain by an ejecta blanket of sedimentary rocks. Note the large limestone block surrounded by a fine-grained sedimentary debris consisting of angular centimeter-sized limestone fragments embedded in a clayey shaly matrix. Note that the huge limestone block sits about 0.3 m above the striated bedrock surface. This exposure is an excellent example of an occurrence of huge limestone blocks in the sedimentary ejecta blanket transported nonballistically. If the huge limestone block were transported ballistically, then surely secondary craters would have occurred on the bedrock surface. Location of this photograph is also Gundelsheim quarry.

polish and (or) mineral striae produced under confining pressure.

The following observational data from the Ries are also included as reference for comparison with pending studies of impactites or fusion products from the Chicxulub crater. These data indicate features that are either not observed or play a limited role.

1. The general absence of ejecta 1 μm or less in grain size.
2. The general absence of strongly shocked limestone from the overlying sedimentary formations above the crystalline basement rocks and the absence of impact glasses in suevite that originated from limestone. This situation is similar to the one in Barringer Crater of Arizona, where strongly shocked and fused dolomite is absent from the Kaibab Formation's dolomite beds that overlie the strongly shocked Coconino Sandstone. The only glassy impactites produced in the Ries are from the basement crystalline rocks *from the bottom of the crater*.
3. The lack of evidence of extensive mixing by impact fusion, such as mixing of fused cover sedimentary rocks with fused basement crystalline rocks. Impact fusion and melting is an instant process, so the glassy impactite usually reflects the parent rocks fused in situ, such as fused amphibolite versus fused granite.
4. Very small amounts of glassy impactites (roughly estimated to be a small fraction of 1 percent of the total ejecta). It is suggested that meteorite impact is not a very efficient process for producing large amounts of glass or melt. The inefficiency lies in the short duration (in terms of seconds) of the high-temperature, high-pressure impact process.

The Chicxulub Crater of the Yucatan

Descriptions of ejecta from the Chicxulub crater in published reports are restricted to samples from drill cores and thus are very scarce. In order to account for negative anomalies, an estimated 200- to 450-m thickness of breccia inside the crater was assumed (Hilderbrand and others, 1991). These authors also described a 90-m thickness of breccia 50 km outside of the crater's edge that probably represents the crater's ejecta blanket, and they reported that wells penetrated coarse breccias at depth. There are, however, no details concerning the coarse breccias. Sedimentary limestone and bentonite breccias as well as glass-bearing breccias were also mentioned. It certainly is premature to draw conclusions from such preliminary descriptions except that there is some shock evidence in some of the breccias.

It is important to know what the coarse breccias are composed of. We need to know the rock types of the blocks, their size, and whether such blocks are unshocked or weakly shocked. Because the Chicxulub crater may be the largest or next to the largest terrestrial crater known so far, and is shallow, megabreccias may be present. On the basis of the fragmentary data on breccias described so far, the impression is that such a huge structure did not produce a very thick ejecta blanket. If megabreccias do exist, then such megabreccias probably would have been transported nonballistically rather than ballistically.

Because inclusion-laden impactite glass of andesitic composition and Haitian microtektites have been linked to the same structure, it may be the only case where microtektites can be shown to have a terrestrial source crater. However, even if the ages of the impactite and melt rocks of Chicxulub are the same (Swisher and others, 1992) and cannot be resolved from that of the Haitian microtektites, it remains possible that the Haitian microtektites described by Izett (1991a) and the impactite glass in the ejecta blanket of Chicxulub may not be products of the same event. The main reason for this seemingly outrageous suggestion is that tektites must have formed under reducing conditions, whereas impactites and impact melts are formed under high temperatures and pressures and dominantly highly oxidizing conditions. How these two environments can be combined into one event is the key question.

MODELS OF GIANT TERRESTRIAL IMPACT CRATERS AND GEOLOGIC AND PETROGRAPHIC CONSTRAINTS

To be realistic, any hypothetical model for terrestrial giant asteroid impact, whether on land, in a shallow sea, or in the ocean, should conform with existing geological observations of well-studied craters and with experimental data. Hence, data from the Chicxulub crater will be extremely important. It is unfortunate that all of the Chicxulub crater is buried and inaccessible to study except from drill cores. Understanding ejecta relationships through drill cores is difficult because of extreme limitations. Nevertheless, on the basis of the nature and relationship of the well-preserved ejecta deposits of the Ries crater and drill-core data from the Manson crater, we may derive the necessary geologic and petrographic constraints for giant terrestrial craters in excess of 100 km in diameter.

Previously published theoretical models for giant craters in excess of 100 km, either in the ocean or on land (O'Keefe and Ahrens, 1982; Melosh, 1982, 1989), that have not taken geological constraints into consideration may be seriously flawed. First, O'Keefe and Ahrens recognized that the atmosphere and ocean are not expected to significantly impede the penetration of a 10-km bolide. The hypothetical model, however, did not take into consideration the instantaneous penetration (in terms of nanoseconds) of a bolide 10 km in diameter and an entry velocity of greater than 15 km/s into a soft surface and cover sedimentary rocks. Because I have found no evidence of fused or strongly shocked surface rocks at Barringer Crater of Arizona, and at the Ries crater, I suggest that we examine more closely the displacement phenomenon of the cover beds during the penetration phase of the meteorite-asteroid bolide and perhaps pay less attention to the jetting of fused and vaporized target and bolide at the initial contact and compression stage (Melosh, 1989). I also suggest that, because of the instantaneous (submicrosecond) initial stage of penetration, the energy transfer was probably not very efficient from the impacting body to the target rock, so the target surface material was displaced without being fused or highly shocked. Studies of Barringer Crater and the Ries crater also indicate that the maximum peak pressures and temperatures were reached when the impacting body ceased penetrating as it reached the more resistant basement material. For a giant impact, the bolide very likely has excavated and bottomed in crystalline basaltic rocks in the ocean or in crystalline volcanic, metamorphic, or plutonic rocks on the continent under sedimentary beds before reaching peak temperature and pressures at the bottom of the crater. Much of the energy of the asteroid impact would be dissipated in excavating the crater and expended in the basement crystalline rocks. Because asteroids of stony meteorite composition have a density of about 2.93 to 3.5 g/cm^3, the resultant crater would very likely be of a shallow-basin type. Such may be the case with Chicxulub. Hence, nonballistic transport of the ejecta blanket should be considered as an important part of the impact cratering model.

Craters such as the Ries, Manson, and Chicxulub, as well as many other large craters (larger than 25 km in diameter), all bottomed in crystalline basement rocks. The high-temperature ejecta, suevite of the Ries and glassy impactites from Manson, do not contain strongly shocked limestone from the sedimentary cover beds. Preliminary data from the Chicxulub crater (Hilderbrand and others, 1991) indicated that the crater also bottomed in basement crystalline rocks because the 380 m of "melt rocks" penetrated by drill holes are siliceous, with about 62 percent silica. In addition, on the basis of oxygen isotopic data, Blum and Chamberlain (1992) excluded the evaporite as a possible source of the calcium-rich glassy impactite from Chicxulub. Therefore, target cover rocks such as limestone and evaporite do not contribute as agents of mass extinction. It is important to keep in mind that the strongly shocked target rocks of Chicxulub are primarily crystalline rocks of andesitic composition.

In addition, in applying the model proposed by O'Keefe and Ahrens (1982), it would be much more convincing if there were data to support the premise that approximately 0.1 percent of the bolide mass is ejecta 1 μm or less in size. Such fine ejecta must eventually be deposited on the land surface. The burden of proof in the K-T boundary section lies in verifying the existence of significant amounts of ejecta particles 1 μm or less in size.

I have singled out the importance of the need to understand the penetration phenomenon when an asteroid first contacts the ground surface. We also need to understand how giant terrestrial impacts produce microtektites and tektites. As will be described in the next section, there is a geochemical constraint that, unlike glassy impactites embedded within highly shocked crater ejecta produced from the basement of the crater, tektites are characteristically low in volatiles and, more importantly, are dominated by divalent instead of trivalent Fe. Shiny metallic Ni-Fe spherules have been found in many tektites (Chao and others, 1961, 1964). Their presence here means that tektites were formed in a high-temperature, reducing environment and not in a highly oxidizing environment, engulfed in hot gas or steam. It is difficult to understand how hot jets of steam or heated air, an incompatible environment for tektites, could help to propel molten tektite glass particles to great distances, but such would be required in order to overcome in some way the obstacle of aerodynamic drag.

Shoemaker suggested that terrestrial craters larger than 50 km are more likely to show evidence of impacts by comets (Shoemaker, 1991). There are very few observed geologic data for use as a guide to hypothesizing the specifics of low-density (1–1.3 g/cm^3) and very low strength or cohesion cometary impact. Comets without asteroid nuclei would perhaps have difficulties penetrating the atmosphere and the solid earth without breaking up, scattering, and dispersing. The only data available are with regard to the Tunguska comet encounter on June 30, 1908 (Krinov, 1963; Rocchia and others, 1990). The Tunguska event had thunder upon atmospheric entry and travel and a spectacular fireball, but it only felled trees in an area 35 km in diameter and charred and seared trees in an area 15 to 18 km across on the ground. Nothing, except for some spherules, was recovered that could be attributed to the comet. If the Tunguska event were a meteoroid (Melosh, 1989), some evidence of its remains should be found. Because no crater was excavated by this low-density cometary body on contact with the ground surface, the Tunguska event was not even included in Grieve's (1991) list of terrestrial craters.

Because both Ir anomalies (result of vaporization of the impacting body) and microtektites have been linked to giant terrestrial craters such as the Chicxulub, any hypothetical giant terrestrial cratering model should explain why Ir anomalies and microtektites and tektites do not seem to coexist.

THE PLACE OF ORIGIN OF THE AUSTRALASIAN TEKTITES AND MICROTEKTITES

We have already mentioned moldavite tektites, pseudomorphs of microtektites, and microtektites. The most abundant and best preserved tektites are the 0.77-Ma (Izett and Obradovich, 1992) Australasian tektites and microtektites. In contrast to ferric-iron-rich, debris-laden glassy impactites from highly shocked ejecta, tektites are, in general, microlite free, water free (very low volatile), ferrous iron dominated, and well represented in primary forms (or forms of revolution) such as spheres, oblate spheroids, ellipsoids, discoids, teardrops, rods, and dumbbells. Of great importance is the fact that numerous Australasian tektites show well-preserved, ablated flanged buttons and features of spalling. The chemical compositions of tektites vary widely. They are usually high in silica, but different chemical groups are represented, such as the high-magnesian group and the high-calcium group (Chapman and Scheiber, 1969). Most tektites are also high in U and Th, similar to granophyres and some stony meteorites (Morgan, 1969, 1970). Other investigators who favor a terrestrial origin for tektites are convinced that they resemble sedimentary rocks because of the high silica content. Hence, trying to reach a conclusion on tektites on compositional grounds seems futile.

Figure 10 shows the strewnfield distribution of the Australasian land tektites (Chapman, 1964). If the land tektite strewnfield and the Australasian microtektites from ocean floors are combined, the Australasian tektites and microtektites represent the areally largest tektite event on Earth. In terms of strewnfield size, recovered weight, and the sizes of tektites produced, the event responsible for producing the Australasian tektites and microtektites is also the largest (Chapman, 1971; Glass and others, 1979). Events producing the North American tektites, the late Eocene microtektites, and the Haitian microtektites are apparently smaller.

Two places of origin of the Australasian tektites and microtektites have been proposed. The majority of investigators, who have a geological background, are in favor of a terrestrial origin, on the basis of geochemical

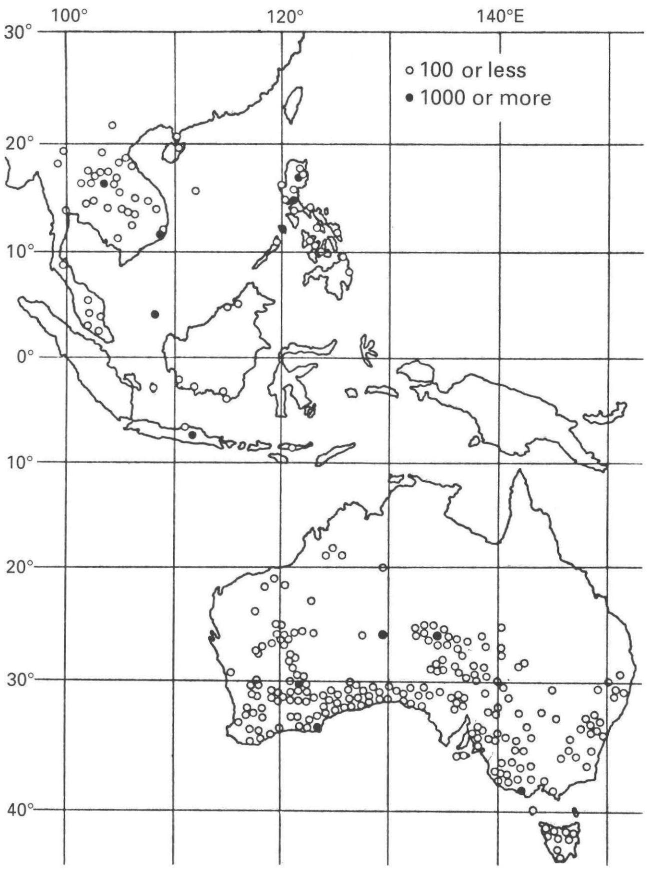


Figure 10. The huge strewnfield of land Australasian tektites. (From Chapman, 1964, 1971.)

data. A minority of investigators, represented by Chapman and his colleagues, who utilized extensive aerodynamical and chemical compositional evidence, favor a lunar origin. I consider the experimental and observational aerodynamic evidence more specific and precise than the geochemical evidence.

For those who favor a terrestrial origin for tektites and microtektites, a critical reading and review of the contributions of Chapman and his colleagues (Chapman and Larson, 1963; Chapman, 1964; Chapman and others, 1964; Chapman and Scheiber, 1969; Chapman, 1971) might make the importance and difficulty of resolving the question concerning the place of origin of tektites clearer.

According to Chapman and Larson (1963), aerodynamic drag is the major obstacle to the acceptance of a terrestrial origin for tektites. Figure 6 includes a plot of the launch range, or distance ejected, through a stationary atmosphere, with respect to the ratio of mass over the drag coefficient (which equals 1 for a sphere) times the cross-sectional area normal to flight. Figure 11 shows photographs of ablated minitektites from Serpentine Lake in central Australia. In an atmospheric condition, the minitektites that range in weight from 0.007 to 0.2 g cannot have traveled more than 100 m (fig. 6) through the Earth's atmosphere because aerodynamic drag prevents travel over longer distances. Also, according to Chapman (oral commun., 1992), if the ablated 2- to 3-mm-sized flanged australite buttons from Serpentine Lake had been produced by terrestrial impact, then more than 99.9 percent of the atmosphere must have been removed so that such small glass particles could overcome aerodynamic drag and escape through the atmosphere. This scenario would require a crater several hundred kilometers in diameter.

To account for the amount of ablation and the flattening of the flanges of ablated buttons, Chapman (oral commun., 1992) is absolutely certain of the following, based on aerodynamic experiments performed in the laboratory.

1. In order to account for the observed ring waves and the degree of flange flattening, the entry angle of australites and javanites into the atmosphere could not have been grazing or shallow but was relatively steep.
2. In order to account for the spalled ablated anterior shells of Australasian tektite cores of 4- to 6-cm size from Australia, Indonesia, and northern Luzon, these relatively large tektites must have been cooled well below the glass strain temperature (650°C), thus becoming rigid before entry into the atmosphere. Hence, smaller tektites (for example, 2 cm in size) were certainly rigid and relatively cool prior to entry.
3. In order to account for the observed amount of ablation, the entry velocity of australites and javanites must have been considerably greater than 5 km/s, the limit of velocity below which ablation of rigid tektite glass would not occur.

A second problem, in addition to the obstacle of aerodynamic drag, is the identification of a 0.77-Ma terrestrial crater perhaps 300 km in diameter that should be somewhere in Scandinavia, on the basis of the observed partial strewnfield distribution. A terrestrial crater of this size and age cannot be hidden easily or obliterated by subduction in this time span.

A third problem is explaining the absence of more than 95 percent of the huge amounts of nontektite ejecta from this same source crater. Some of the Australasian tektites were found embedded in unconsolidated sediments or cemented in laterite in Thailand (Chao, unpub. data, 1964). There were no nontektite ejecta present in the same site.

The general objection to the lunar origin of the Australasian tektites and microtektites is that none of the returned lunar samples (except perhaps sample no. 12013) resembles tektites in composition. Samples from the Apollo 15 and 16 geochemical data-collecting orbiter along the lunar equator also did not reveal high-silica tektite composition. Nevertheless, Chapman (1971) proposed that

Australasian tektites were ejected specifically from Tycho, along the Rosse ray from that crater. Until areas such as the Rosse ray have been sampled, a lunar origin should not be dismissed for the Australasian tektites and microtektites.

COMPARISON OF THE MANSON AND CHICXULUB CRATERS OF THE CRETACEOUS-TERTIARY BOUNDARY EVENTS WITH THE AUSTRALASIAN TEKTITE EVENT

Most investigators would agree that the 35-km-diameter Manson crater of Iowa, a possible source of shocked quartz in the K-T boundary sections, was too small and insignificant to have caused mass extinction.

If the coarse breccias that were present from the drill holes from the 180-km-diameter Chicxulub crater turn out to be significant, then by analogy with that of the Ries, many of these coarse breccias may not have been airborne.

The extent of the Chicxulub crater and its ejecta (beyond Haiti) fits nicely inside the Australasian strewnfield (fig. 10), without taking into account the size and location of the source crater of the Australasian tektites. The Chicxulub cratering event was therefore much smaller than the Australasian cratering event. Those who favor the terrestrial origin of tektites and microtektites must explain how the smaller Chicxulub cratering event could have caused mass extinction if there was no mass extinction caused by the Australasian tektite source crater at 0.77 Ma.

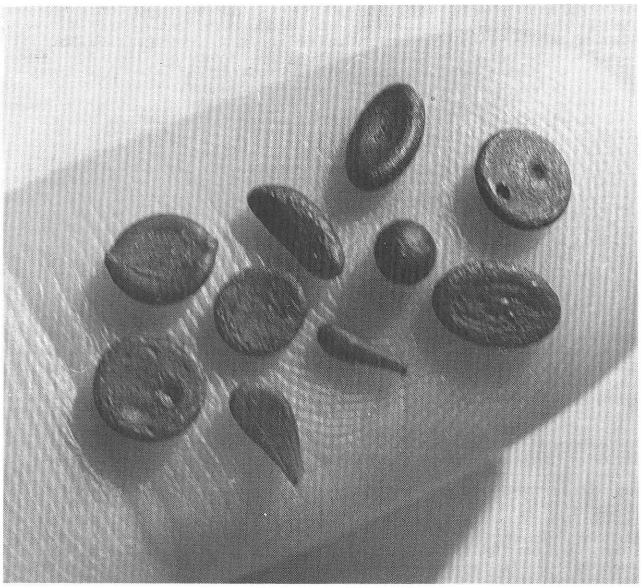


Figure 11. Ablated minitektites from Serpentine Lake, Central Australia. (Photographs courtesy of Dean R. Chapman.) These ablated minitektites provide strong aerodynamic evidence against a terrestrial origin for the Australasian tektites and microtektites. (See Chapman and Larson, 1963.) *A*, Minitektites with teardrop, oval, oblate, spherical, and disc shapes. A few show clear ablation flanges.

SUMMARY

K-T boundary sections are records of events during the transition from Cretaceous to Tertiary time. What is present in or absent from this record is critical to our understanding and reconstruction of the K-T events.

1. The principal source of Ir anomaly above the layer containing shocked quartz may be ablation products of stony meteorites and not vaporized impacting asteroids. If this is true, occurrences of Ir anomalies along stratigraphic hiatuses are likely to be more widespread and not correlated with any cratering events or occurrences of shocked quartz.
2. Two events are tentatively identified from records of the K-T boundary sections of Western U.S. interior basins: (1) the 35-km-diameter Manson crater, a probable source of the shocked quartz, but too small a crater to cause mass extinction and (2) the 180-km-diameter Chicxulub crater of the Yucatan Peninsula, Mexico, the probable source of the gorceixite-goyazite spherules. The two events were separated by the underclay, which may have required many years of accumulation as substrate of the peat in a peat swamp.

   It would be nice to be able to explain why the Ir anomaly and ejecta with shocked quartz are absent in the gorceixite- goyazite spherule layer if the source were the Chicxulub crater.
3. For those who favor a terrestrial origin for the 0.77-Ma Australasian tektites and microtektites, the following problems remain:
   - To overcome the principal obstacle of aerodynamic drag, a source crater several hundred kilometers in diameter is required to remove the atmosphere. This gigantic crater must be found and identified. Is it somewhere in Scandinavia?
   - In addition, the total absence of more than 95 percent of nonglass ejecta from the same source crater must be accounted for.
   - There was no mass extinction caused by the source crater for the Australasian tektites, so it is very unlikely that Chicxulub, which is much smaller, could cause mass extinction.
4. The Chicxulub crater and its various types of ejecta should provide the geologic and petrographic constraints for models of giant terrestrial craters. Is the gorceixite-goyazite spherule layer the only record Chicxulub left in the K-T boundary sections in North America?

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This paper could not have been written without generous help and provision of data from my colleagues and

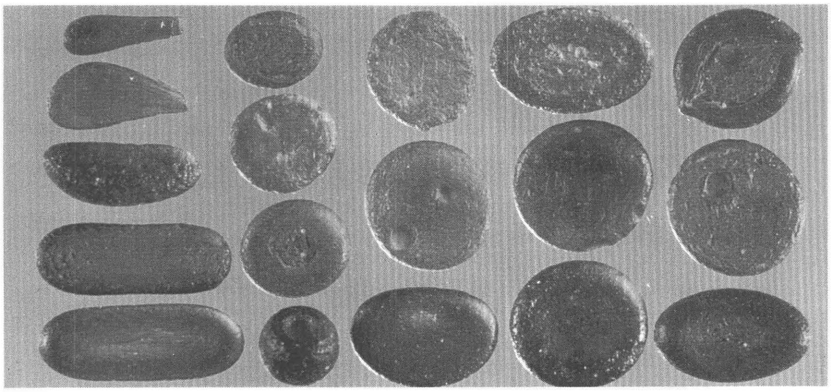

Figure 11.—Continued. *B*, Flattened minitektites, 0.007 to 0.043 g. A few are the same as in *A*.

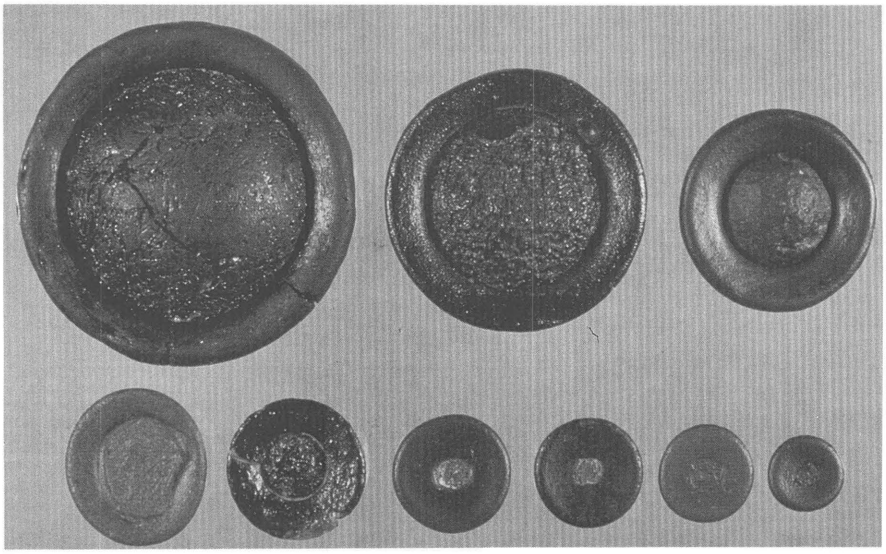

Figure 11.—Continued. *C*, Ablated flanged minitektite buttons, 0.08 to 7.9 g.

friends Glen Izett and Dean R. Chapman and the discussions I had with them. Some of the illustrations included here were provided by Glen and Dean. Glen showed me polished sections of various Cretaceous-Tertiary boundary sections and the contained impact-shock evidence from the interior basins of the Western United States and Haiti. Dean provided quotations and discussions of his current views regarding the major objection to terrestrial origin for the Australasian tektites, minitektites, and microtektites, and he provided photographs of ablated minitektites from Serpentine Lake, Australia. I am also grateful to my colleague Hugh Millard for the analytical data on Au and Ir concentrations in fusion crusts of the Pultusk and the Nuevo Mercurio HIV chondrites. I thank Roy Clarke, curator of the meteorite collection at the U.S. National Museum, for choosing and providing the fusion crust specimens of Pultusk and Nuevo Mercurio for the Ir analyses. I am also grateful for reviews by Chapman, Izett, and my colleagues Jean A. Minkin and Judith M. Back, and careful editing by John Watson.

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