Topics

Impact in the Caribbean and death of the dinosaurs

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New work on the 65-million-year-old Chicxulub crater in Mexico shows how giant impacts on Earth occurred. The geological evidence for the aftermath of the impact is currently hotly debated.

Fifteen years ago, the Nobel-prize-winning physicist Luis Alvarez and his research group from the University of California at Berkeley proposed that the dinosaurs were wiped out by the impact of a giant asteroid on the Earth at the end of the Cretaceous. At the time, there was no known crater of the right age and the right size. Between 1980 and 1990, various candidate craters were proposed, most notably the Manson structure in Iowa, USA, but none of these was ideal. The Chicxulub structure (Fig. 1), identified in 1990 on the Yucatán peninsula, southern Mexico, seems to fit the predictions made by Alvarez and his colleagues, but the geological evidence that it is a crater is hotly disputed.

At a recent meeting in Houston, Texas, USA, proponents of the impact hypothesis marshalled new information, and the focus was on the Chicxulub structure. Key topics for discussion were the nature of the crater itself, the physical evidence for impact (particularly the so-called tsunamite deposits), the chemical signature of the impact as indicated around the rim of the proto-Caribbean Ocean, and evidence in the Caribbean for sudden or gradual extinction.

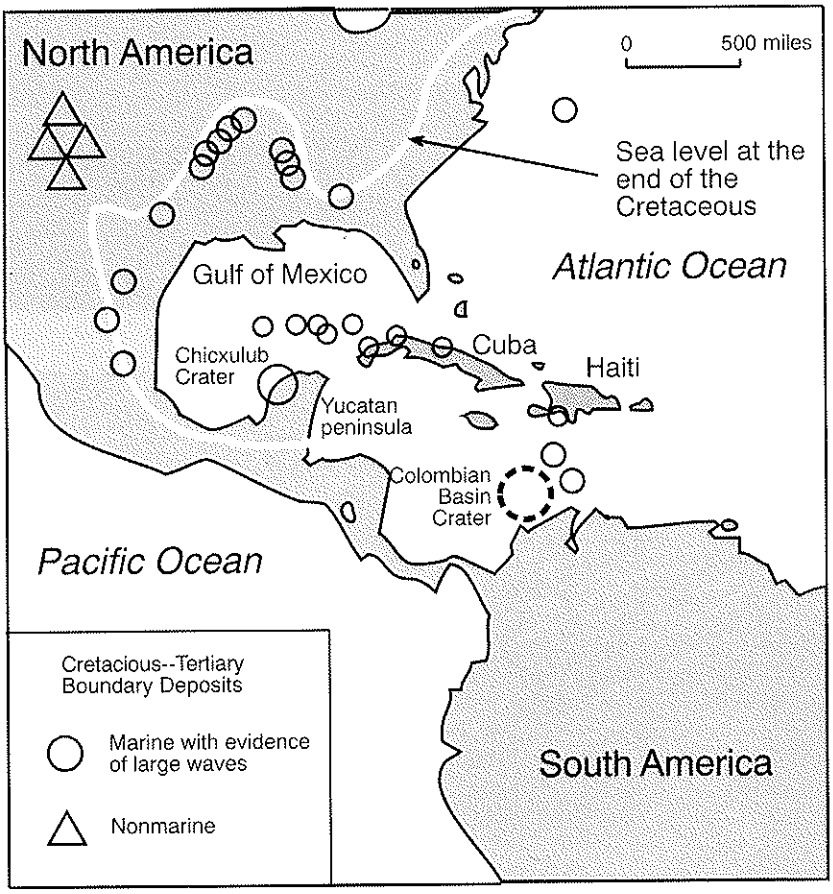


Fig. 1. Locations of the Chicxulub and Columbian craters in the Caribbean area, with an indication of the contemporary coastline. Sites of non-marine beds (triangles) and of marine beds with evidence of tsunami influence (circles) are shown. (Based on data from Hildebrand and colleagues.)

Impacts and extinctions

The extinction of the dinosaurs coincided with the extinctions of many other groups of plants and animals, most notably some other groups of large reptiles (the flying pterosaurs, and the marine plesiosaurs and mosasaurs), the ammonites (coiled marine molluscs), the rudists (reef-building thick-shelled molluscs), and most of the foraminifera (calcareous-shelled single-celled planktonic organisms). This set of extinctions formed part of a mass extinction event which was marked by the loss of perhaps 50% of species on the Earth. The event is dated as having occurred 65 million years ago, at the boundary between the Cretaceous and Tertiary periods, and it is commonly termed the KT event (K for 'kreta', chalk, and T for Tertiary).

The KT impact hypothesis, as proposed by Alvarez and colleagues in 1980, postulates that an asteroid, a large extraterrestrial rock, struck the Earth, ejecting exotic materials, such as iridium, across the world. Iridium is a metallic element, allied to gold and platinum, that is normally present in only tiny quantities on the surface of the Earth. It is found in meteorites and is believed to occur in the core of the Earth, but has also been found in increased abundance just at the KT boundary in dozens of localities worldwide.

The size of the postulated asteroid was estimated by back-calculation from well-established formulae that link the size of a projectile to the size of the crater it forms and the size of the plume, or dust cloud, thrown up by the impact (see Box 1). In order to create a plume that encircled the globe, the crater must have been 100–150 km in diameter, and the projectile must have been 10–15 km in diameter.

After 1980, three other indicators of impact were found in the KT boundary clays – shocked quartz, glassy spherules and the mineral stishovite. Quartz is the commonest constituent of rocks, but shocked quartz is very rare. Shocked quartz grains show multiple sets of parallel lamellae which were emplaced under the sudden high pressure of an impact. Glassy spherules are melt products that commonly occur in association with volcanic erup-

Box 1: Impact mechanics

The size of an impacting asteroid and the final diameter of the resulting crater can be calculated using scaling laws derived from observations of craters on the Moon and other planets. Additional information comes from experiments with projectiles, where bullets are fired into fixed targets. The major variables are the diameter, density and velocity of the impactor, its angle of impact and the density of the target rock.

The equations show that a 3-km asteroid with a density of 2200 kg m^{-3} striking the Earth vertically at a velocity of 25 km s^{-1} will produce an observed crater 31 or 37.5 km in diameter if it targets basaltic rocks or sedimentary rocks, respectively. A 10-km asteroid will produce a crater 100 km in diameter when targeting basaltic rocks or 122 km when targeting sedimentary rocks. Oblique impacts produce even larger craters. A crater size of 300 km, similar to the largest estimates for Chicxulub, requires an impacting body of 20–30 km diameter (Fig. 2).

The amount of energy produced by impactors of this size is truly enormous. A 10-km stony object with a density of 3000 kg m^{-3} striking the Earth vertically at 25 km s^{-1} would have kinetic energy of more than 107 megatonnes. Put into perspective, this is 1000 times more energy than is contained in all the world's nuclear arsenals. Ten to 100 times the mass of the object would shock-melt the impact site and perhaps twice the mass would be ejected into the atmosphere, mainly as dust containing exotic elements, such as iridium, from the impactor, which settle out later as a clay layer.

There is a greater than two-to-one probability that an asteroid would have its impact in the oceans, since two-thirds of the Earth's surface is covered by sea. The crater produced on the ocean crust would be broader and shallower than on land. Huge tsunamis would form, running up to devastate the ocean basin margin areas.

Fig. 2. The behaviour of a projectile, such as a meteorite, as it hits the sea bed. The object creates a crater and throws rock material and water high into the air. The meteorite itself vaporizes.

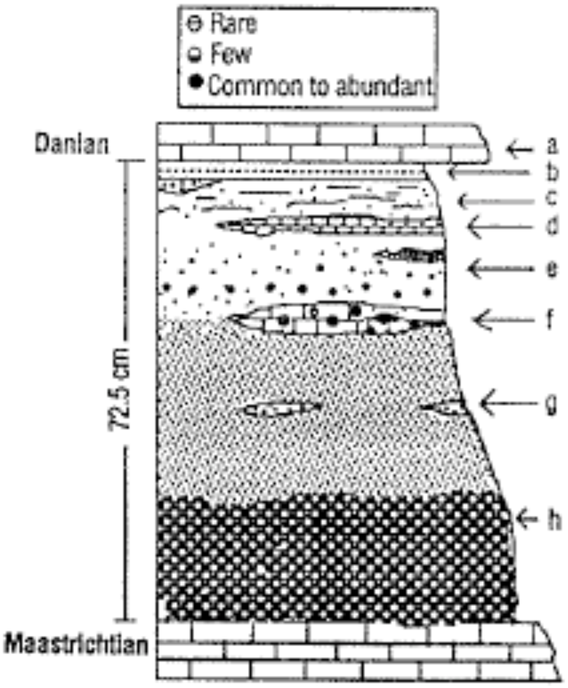
tions and with impacts. Stishovite is a rare silicate mineral produced only at high pressures (about 130 000 atmospheres) and temperatures (> 1200 °C), and identified first in Meteor Crater, Arizona. Stishovite in KT boundary clays is interpreted as evidence of the application of sudden extremely high pressures, presumably associated with an impact.

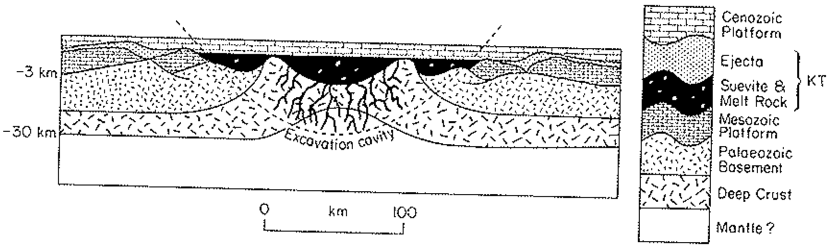
The impact is said to have caused catastrophic environmental disturbances which wiped out the dinosaurs and all the other terrestrial and marine forms that disappeared. The most popular killing mechanism, proposed originally by Alvarez and colleagues, is that the impact threw up a vast cloud of debris, most of which fell back to Earth. The finer debris, however, was injected into the upper reaches of the atmosphere to form vast clouds of dust which encircled the globe, cutting out light from the Sun and causing a temporary blackout lasting perhaps a year. This halted photosynthesis and plants died, followed by the animals that relied on those plants. It was later realized that such a dust cloud would also cause freezing, the 'nuclear winter' scenario, a further killing perturbation.

On the trail of the Chicxulub structure

The Chicxulub structure, buried beneath a pile of Tertiary platform carbonate sediments about 1 km thick, was first identified as a crater in 1981 in gravity and magnetic surveys of the Yucatán Peninsula. These show a ring-shaped structure, 165–180 km in diameter, set off from the surrounding undisturbed flat-lying sediments. The 1981 report, published in an obscure technical bulletin by Glen Penfield (Carson Services Inc., Perkasie, Pennsylvania) and Antonio Camargo (Petróleos Méxicanos, Mexico), also referred to a number of exploratory boreholes that had been made by Petróleos Méxicanos in the

Fig. 3. The KT boundary section at Beloc, Haiti, showing a succession from late Cretaceous chalk at the base, through a spherule layer (h), a layer of smaller spherules with lenses of coarse spherules (g), a coarse spherule-bearing marl lens (f), a graded sandy marl with lenses of micrite (c), a white-chalk lens (d), a laminated sandy marl with small lenses of coarse spherules (e), a fine-clay layer with high iridium concentration (b) and a limestone (a). The boundary sequence (beds h–b) is interpreted as an ejecta layer (h), followed by various physically disturbed horizons (g–c), the boundary clay (b) and then a return to background limestone deposition (a). (Based on material from Florentin and colleagues.)





1960s as part of that company's remit to search for oil. The company geologists had identified the circular structure from geophysical surveys as a possible oil trap, but little scientific attention was paid to the borehole data or to the 1981 report.

Independently, a series of pieces of evidence were focusing attention more and more on the Caribbean area as the likely site of a KT impact. In 1985, Jan Smit (Free University, Amsterdam) identified some massive chaotic sandstones found on the Brazos River in Texas at the KT boundary as tsunamites, sediments that had been tumbled and smashed up by the arrival of a massive tsunami on this ancient coastal site. Similar deposits were found also on Haiti, a Caribbean island that at the end of the Cretaceous lay on the eastern coastline of the proto-Caribbean sea (Fig. 3). The Haiti boundary layer also yielded abundant impact ejecta (the materials thrown up after an impact), large quantities of shocked quartz and glassy spherules, suggesting that it lay close to the site of impact.

This KT boundary layer, and others around the proto-Caribbean, were also thicker, at 0.5–3 m, than typical KT boundary layers elsewhere in the world, which typically reach only 1–2 cm. Probably the site of postulated impact could be located by assessing a gradient of indicators of proximality: thickness of the KT layer, abundance of shocked quartz and glassy spherules, intensity of shocking of the quartz grains, presence of tsunamites, and the like.

This was the forensic approach adopted by Alan Hildebrand of the Geological Survey of Canada, Ottawa, and colleagues, in the late 1980s. They homed in on the Caribbean area and searched libraries of aeromagnetic and gravity survey maps, and storehouses of core sections. They identified one possible crater on the floor of the Colombian Basin, 80 km from the South American coast. This structure is circular, 300 km in diameter and buried beneath 2 km of sediments. Until drilling is carried out, however, the age and geology of this postulated Colombian Basin crater is uncertain.

Hildebrand and colleagues identified a second possible Caribbean crater in 1990, also on the basis of geophysical data, as well as on the Petróleos Méxicanos boreholes. The only data on the boreholes available in 1990 were the written summaries of the rock sequences made by oil geologists 25 years earlier, and a few isolated rock samples. It was believed that the rock cores extracted from the boreholes in the 1960s had been lost in a warehouse fire and that it might take years before an expensive drilling programme could be organized to test the nature of the Chicxulub structure.

Fig. 4. (above) Cross-section of the Chicxulub impact basin, showing the underlying Cretaceous rocks and the Tertiary sediments deposited on top. The topography of the crater is perhaps exaggerated, as no account is taken of possible erosion. (Based on work by Sharpton and colleagues.)

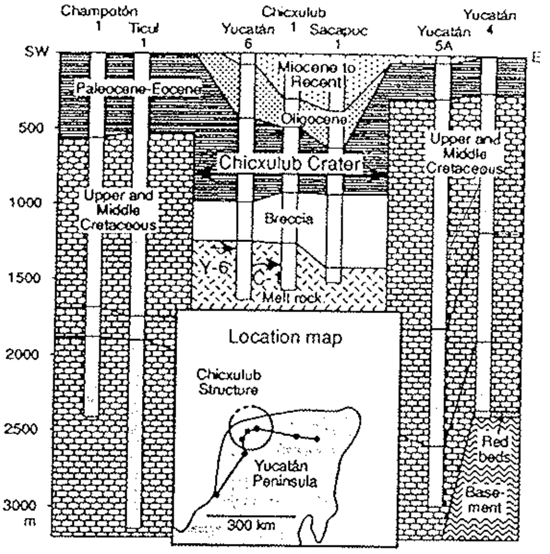
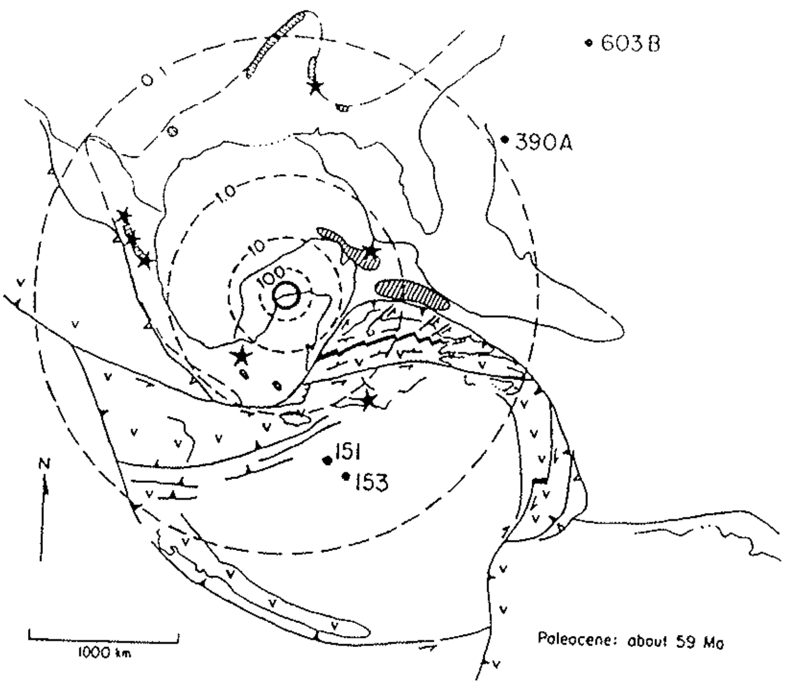


Fig. 5. (right) Cross-section of the Chicxulub crater based on the old PEMEX wells, three of which penetrate the crater itself. (Based on data from Ramos and Hildebrand and colleagues.)

Fig. 6. Isopachs (lines indicating equal thickness) of crater ejecta around the Chixculub strucure. (Based on work of Hildebrand and colleagues.)



Evidence for impact

The science of impact research has entered the realms of acceptable study in recent years. No-one has ever denied that meteorites strike the Earth from time to time and that occasionally some larger strikes have occurred – for example, the Tunguska comet, which exploded just before impact over Siberia in 1908 and flattened forests for 15 km around. Some recent craters, such as Meteor Crater in Arizona, are easy to see and to understand, but these represent impacts by objects at most a few tens of metres in diameter. The suggestion that the Earth, like the Moon, has been bombarded by comets and meteorites of larger size throughout its history was hotly denied by many.

Geologists were reluctant to accept even rather obvious older craters, such as the Ries crater, which was formed 15 million years ago. This structure is 22–23 km in diameter, and it is superbly well pre-

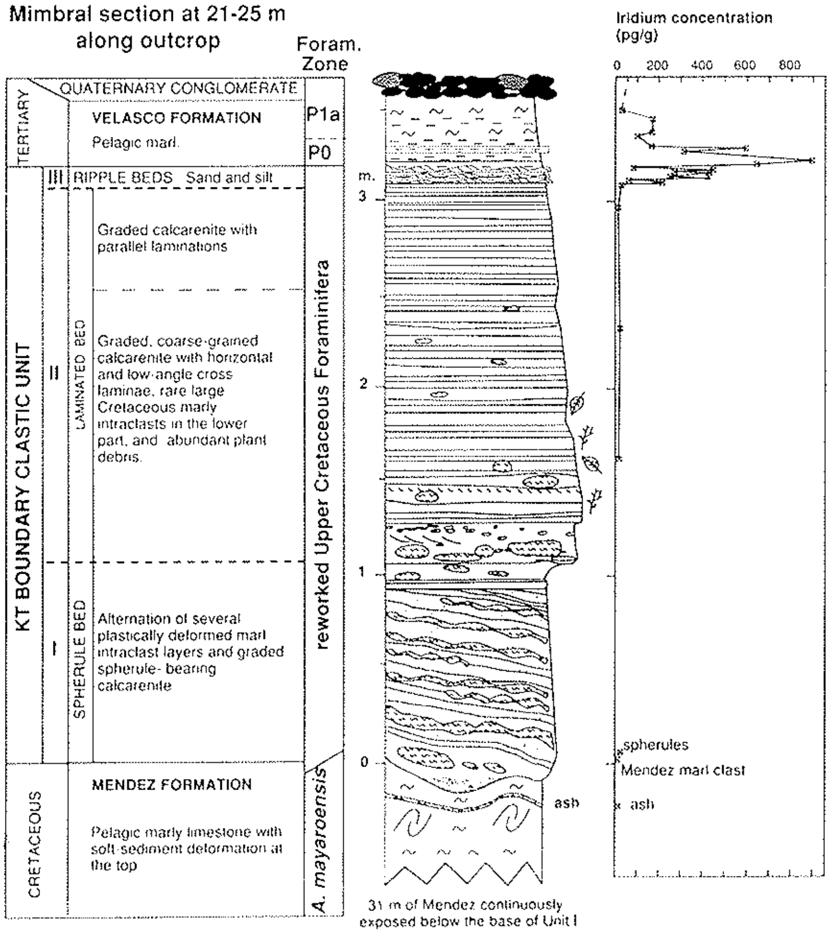


Fig. 7. Sedimentary sequence across the KT boundary at Mimbral, Mexico, showing a succession from limestones at the base, followed by alternate layers of deformed marl and graded spherule-bearing calcarenite, then a graded coarse-grained calcarenite containing rare marl clasts and plant debris, followed by a graded laminated calcarenite, a sand/silt layer with elevated iridium content towards the top, and a return to pelagic marls. (Based on work of Smit and colleagues.)

served. It is possible to climb to the top of the church tower in the ancient trading town of Nördlingen, located in the centre of the crater, and see the entire circular crater rim running round as a low range of hills in every direction. From the top of the rim, one may view the huge circle of low-lying rich farmland in the middle and the gradually sloping outer margin of the crater. The brecciated suevite in the crater and round its rim, together with the widely scattered ejecta blanket outside the crater, had long been known to geologists and yet they resolutely interpreted it as the remnants of a huge volcano. The epochal work of Eugene Shoemaker (US Geological Survey, Flagstaff) and Edward Chao (US Geological Survey, Reston, Virginia) in the early 1960s showed how all of the features just mentioned could only be explained if the Ries ring were interpreted as a crater, and their view eventually prevailed.

The advent of aerial and satellite photography and geophysical surveying has advanced impact science tremendously. Since 1970, many new giant-sized craters have been identified on all continents, many of them in the range of 10–200 km in diameter. Old craters are hard to recognize as they rapidly become eroded and often they become buried (as with Chicxulub), but boreholes may reveal the crucial impact melt rocks and breccias. Geologists now accept that there have been many major extraterrestrial impacts of the Earth, scattered randomly through geological time, and the study of such phenomena is not reserved for quacks and charlatans.

The Chicxulub crater

The Chicxulub investigation advanced enormously in 1992 when the supposedly missing boreholes from the 1960s were rediscovered. Virgil Sharpton of the Lunar and Planetary Institute, Houston, and colleagues were able to give details of the subsurface geology within and around the postulated Chicxulub crater, as eight of the original boreholes were in the region of the crater and three penetrated the central portion (Fig. 4).

The three boreholes near the centre passed through about 1 km of Tertiary limestones and marls, below which lay 100–200 m of breccias and crystalline silicate rocks (Fig. 5). This assemblage of rocks includes an unusual brecciated rock containing broken fragments of a variety of the local rocks, both the late Cretaceous sediments and deeper basement rocks, mixed with finer matrix and showing signs of the effects of high pressure and high temperature (deformed rock fragments, shocked quartz and feldspar grains, various kinds of melt glasses and impact melts). This rock type is termed a suevite and is very similar to suevite from its type locality in the Ries crater.

Below the suevite deposits within the Chicxulub crater, the boreholes penetrated thick sequences of impact melts, presumably generated below the zone of rock mixing. The boreholes located further from the centre of the crater penetrated thick successions of brecciated anhydrite and dolomite, the rocks that were being deposited in the shallow tropical proto-Caribbean sea during the latest Cretaceous. This brecciated zone diminishes in thickness from 1.5 km at a distance of 100 km from the centre of the crater, to 300 m at a distance of 200 km. Outside the central zone where the impact occurred, shock waves apparently radiated laterally and fragmented the surrounding rocks, and the effect diminished asthe distance from the impact site increased (Fig. 6).

The geophysical data suggest that Chicxulub is a multi-ringed impact crater, but there is some disagreement about its diameter and the number of rings in the structure. Alan Hildebrand and colleagues interpreted the Chicxulub crater as a double-ring or peak-ring crater 180 km in diameter, a figure revised to 170 km at the Houston meeting. Sharpton and colleagues, however, found two more distant rings, the outermost one at about 300 km diameter, based upon a gravity anomaly survey, which would make the Chicxulub structure the largest impact crater yet identified on the Earth. The question of the size of the Chicxulub crater has yet to be resolved.

There have been a number of vocal critics of the crater interpretation. Chuck Officer and Jack Lyons (Dartmouth College, Hanover, New Hampshire) and Arthur Meyerhoff (Tulsa, Oklahoma) have interpreted the Chicxulub structure as a volcanic sequence of late Cretaceous age. They point out that sedimentary clasts in the breccias above the melt layer contain fossils of late Cretaceous age, hence suggesting to them that the structure pre-dates the KT boundary. However, some of the 'late Cretaceous' fossils have been re-dated, as announced at the Houston meeting by L. E. Marín and colleagues (Universidad Nacional Autónoma de México, Mexico City), as lowest Tertiary in age. In any case, old exotic blocks typically lie above impact melt layers in impact craters. The ejecta deposits in and around craters may contain older sedimentary material which was excavated at the time of impact and thrown into the air. A well-known example is the Bunte Breccia of the Ries crater, which contains blocks of all sizes, including megablocks over 1 km in diameter, sampled from basement granite, and Triassic and Jurassic sediments that underlie the Miocene-age impact site. It is quite likely that a narrow drill core might penetrate one of these sedimentary clasts, confusing the age determination of the crater. In the case of the Chicxulub borehole, the so-called volcanic andesites that lie within the late Cretaceous sequence have been re-identified by Sharpton and colleagues as melt rock produced at the instant of impact.

The crater, whether 170 or 300 km in diameter, is clearly large enough for the KT impact (Luis Alvarez and colleagues had calculated a minimal diameter of 100 km), but its age had to be established to tie it to the KT extinction. Various analyses of the age of the Chicxulub structure itself, and of its postulated ejecta, seem to correspond closely to the date of 65.0 million years for the KT boundary, based on radiometric dating of the structure itself and of impact spherules collected some distance away (see Box 2).

Aftermath of impact

During impact, a meteorite penetrates deep into the rock and vaporizes, sending powerful shockwaves downwards and sideways into the surrounding rocks. The reaction to the impact is rapid, and vast quantities of the host rocks shoot upwards and sideways, creating a conical expanding crater. Larger blocks fall back within the crater and around the rim region, but smaller boulders, melt materials and mixed extraterrestrial and host-rock dust rise as a plume and spread widely. If there is any wind, the plume will move down-wind of the crater. An ejecta blanket is formed outside the crater rim and extending for a distance that is proportional to the size of the impact and the nature of the prevailing wind. Larger material falls out of the plume close to the crater. Finer dust may be lofted into upper parts of the atmosphere and may travel around the world.

Box 2: Dating of Chicxulub

The KT deposits within the Chicxulub structure have been dated using the argon–argon (Ar–Ar) isotope method, a considerable improvement on the earlier potassium–argon (K–Ar) isotope method. Both methods work on the same principle of recording the amount of radioactive decay of the isotope potassium-39 to argon-40. Since the rate of radioactive decay is constant, the ratio between the two isotopes gives an estimate of the absolute age of a rock.

The older ^{39}K–^{40}Ar technique required that two rock samples were analysed, one chemically for potassium-39 and one by melting for argon-40. This led to inevitable imprecision and errors of not less than 3%, quite a problem when trying to correlate rocks that are tens of millions of years old. The ^{40}Ar–^{39}Ar method removes the dual sample step and hence much of the inaccuracy. Small rock samples are irradiated in a nuclear reactor to change all the potassium-39 to argon-39. They are then incrementally heated to release the ^{40}Ar and ^{39}Ar gases, which, once captured, are quantified by mass spectrometry. The precision of this method may be up to 0.1%.

Carl Swisher (Institute of Human Origins in Berkeley, California) and colleagues analysed samples from the melt rocks at the centre of the Chicxulub crater by the ^{40}Ar–^{39}Ar method and came up with an age of 64.98 ± 0.05 million years. To correlate Chicxulub with the supposed ejecta deposits they also analysed tektites from Haiti and north-eastern Mexico, dating them at 65.07 ± 0.10 million years, an age statistically inseparable from that at Chicxulub. In a separate study, Glen Izett (United States Geological Survey, Denver) and colleagues also dated the Haitian boundary layer tektites and found an age of 65.06 ± 0.18 million years. These dates strongly suggest that the Chicxulub crater is indeed the source of the exotic deposits in the circum-Caribbean area, and that they all correspond to the KT boundary.

Traces of the fall-out from the impact provided early hints of the existence of an impact crater in the Caribbean. The KT boundary layer of the Beloc section on Haiti was thicker than in other parts of the world. It displayed abundant glassy spherules of exotic geochemical composition and, higher up, a layer of disrupted blocks of Cretaceous chalk, interpreted as evidence for a tsunami. The glass spherules were interpreted in 1991 by J.-M. Florentin and colleagues (Florida International University, Tamiami) as impact glasses, called tektites, which were formed by high-pressure and high-temperature effects at an impact site some distance away, and were lofted, together with other impact debris, and transported for 1000 km.

Since 1991, several teams of igneous petrologists and geochemists have investigated the spherules from Haiti and elsewhere in the proto-Caribbean region, and reports at the Houston meeting from Joel Blum and Page Chamberlain (Dartmouth College, Hanover, New Hampshire), M. Chaussidon and colleagues (CRPG/CNRS, Vandoeuvre, France) and Haraldur Sigurdsson and colleagues (University of Rhode Island, Narragansett) showed that the spherules were formed by melting of two rock types, one of granodiorite/dacite composition and the other a carbonate/evaporite mix. These match the late Cretaceous rocks underlying the Chicxulub structure, although there are problems, indicated by Christian Koeberl (University of Austria, Vienna), in matching the carbonate/evaporite glasses with what little is currently known about the late Cretaceous anhydrites and dolomites beneath the Chicxulub crater.

The supposed tsunamites in the KT boundary layer on Beloc and in numerous other localities in Texas and Mexico consist generally of coarse sandstones, but in places more dramatic deposits are found, with blocks of country rock tumbled randomly by some high-energy physical process and deposited in erosional channels. These have been interpreted by Joanne Bourgeois (National Science Foundation, Arlington, Virginia) and Jan Smit and colleagues as the deposits of a tsunami set off by the impact of a large asteroid into the waters of the proto-Caribbean (Fig. 7). These coarse clastic units are found only in the circum-Caribbean KT boundary sections, and here the spherules are incorporated in the coarse beds, and the layer enriched in iridium lies above. If the whole of the boundary layer sequence is interpreted as the result of a single impact event, then there are indications of multiple arrival times, with impact melt spherules arriving first, falling out of the air-borne plume. Then the tsunami wave-trains strike the shore, and finally the iridium-enriched dust settles out of suspension from high in the atmosphere.

The nature of these tsunamites was debated at the Houston meeting, and some of them at least have been reinterpreted by Bruce Bohor and W. J. Betterton (US Geological Survey, Denver, Colorado) as coarse channellized gravity or turbidity flows that may relate to an impact. On the other hand, W. Stinnesbeck and colleagues (Universidad Autónoma de Nuevo León, Nuevo León, Mexico) argue that the coarse clastic units are the result of turbidity currents and gravity flows during a period of low sea level and that they have nothing to do with any impact. The issue remained unresolved at the Houston meeting, despite field trips to Mexico and Texas to see some of the best examples. Sedimentologists present could see no clear evidence to determine whether the chaotic breccias had been deposited rapidly, perhaps by tsunamis, or over many thousands of years, perhaps as parts of turbidity flows. The problem stems from the fact, noted by Bourgeois, that modern tsunamites, such as some she studied in Chile which were deposited by massive waves in 1960, show no unique distinguishing characters.

The relative dating of the postulated tsunamites was also an issue at the meeting. D. Beeson (Chevron, New Orleans, Louisiana) and Gerta Keller (Princeton University, Princeton, New Jersey) suggested that most tsunami beds do not coincide with the KT boundary, a view roundly opposed by Jan Smit and colleagues, who argued that their critics have misinterpreted the exact positioning of the KT boundary.

The KT boundary has recently been established precisely in a rock section at El Kef, Algeria, to coincide with the dramatic decline in late Cretaceous foraminifera, and it coincides with the boundary clay and iridium anomaly. Typical Tertiary foraminifera begin to appear some 10–25 cm higher up the section, a thickness of rocks that may represent 5000 years of deposition. Smit places the KT boundary in the Caribbean sections at the point where Cretaceous microfossils begin to decline, and this corresponds to the base of the tsunami beds.

Killing

One issue that was not discussed extensively at the Houston meeting was how the impact killed off the dinosaurs, ammonites and foraminifera. Certainly, some of the single-cause catastrophic explanations, such as mass killing by temperature stress, by absence of light or by poisoning, cannot account for the seemingly random nature of the extinctions. There is little evidence for selectivity of what died and what survived. Dinosaurs and pterosaurs died out, but crocodiles, turtles, lizards, mammals and birds survived. The planktonic foraminifera were nearly wiped out, but other planktonic organisms were little affected.

The patterns of extinction of planktonic organisms in the Caribbean region were hotly disputed. Gerta Keller argued that the foraminifera died out in a stepwise manner, over some 0.4 million year spanning the KT boundary. A long-term pattern of extinction like this would suggest that either there had been no impact or that the impact was not significant in causing extinctions. Perhaps the foraminiferan species had died off because of long-term climatic change. Jan Smit denied Keller's interpretation and found that there were no extinctions of planktonic foraminifera before the KT boundary. He argues that problems have arisen because the fossil content of the sediments has been reworked to some extent by burrowing organisms, and microfossils are often mixed upwards, hence blurring the true pattern. He believes that if the sedimentary mixing is removed, the 0.4-million-year decline of foraminifera across the KT boundary would resolve to a single sharp mass extinction signal precisely at the boundary.

As for the dinosaurs, the matter is still far from settled. There is limited evidence in the proto-Caribbean area, but recent substantial studies in the North American continent have failed to resolve the question. Two teams recently attempted large-scale controlled field sampling in Montana to establish once and for all whether the dinosaurs had drifted to extinction over 5–10 million years or whether they had survived in full vigour to the last minute of the Cretaceous, when they were catastrophically wiped out. Needless to say, one team, led by David Archibald (San Diego State University, California), found evidence for a long-term die-off, and the other team, led by Peter Sheehan (Milwaukee Public Museum, Wisconsin), found evidence for sudden extinction. Each sampling exercise had involved teams of dozens of people, logging in one case an estimated 15 000 person-hours of field prospecting and in the other case a total of 150 000 identified specimens. How much more intensive does the programme have to be in order to establish what really happened?

Current studies of the Chicxulub crater and of the physical effects of large-scale impacts on the Earth are proving very fruitful. Making the link between impacts and extinctions is much harder.

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Another letter

Sirs: Eric Robinson's item about R. G. Carruthers (*Geology Today*, v.10, p.193, 1994) brought back a memory of what must have been an embarrassing incident for the lecturer concerned back in 1956 (I think). A group of undergraduates was transported to a site in the Vale of York, near Tadcaster, with the purpose of surveying and sampling what was described to us as a varved clay deposit containing enough tree leaves to enable a dating to be attempted. The lecturer concerned must have had the Carruthers message, as some of us carried with us the modified kitchen knives which Eric describes. However, while cutting my first 'clean' section, my colleagues and I discovered a plank of obviously planed-and-sawn timber encased in the 'varves'. After alerting our leader to this, it eventually transpired that the 'varves' were, in fact, the tailings of unwanted clay from a gravel working. This shows the benefits of maintaining an open mind and not making up your mind about a problem until evidence is obtained. – from MICHAEL BAMLETT, 6 Harmer Crescent, Cringleford, Norwich NR4 7RX.