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 marshaled 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 tsunamiite 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.

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 eruptions.
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 megaatonnes. 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 shockmelt 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.

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 Mexicanos, Mexico), also referred to a number of exploratory boreholes that had been made by Petróleos Mexicanos in the sedimentary sequence at Beloc, Haiti, showing a succession from late Cenozoic chalk at the base, through a spherule layer (b), 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 (e), a white chalk lens (d), a laminated sandy marl with small lenses of coarse spherules (c), a fine-clay layer with high iridium concentration (b) and a limestone (a). The boundary sequence (beds h–b) is interpreted as an eureka 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.)

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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 tsunamiites, 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 tsunamiites, 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 Petroleos Mexicanos 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.

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...
The Chixculub crater

The Chixculub 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 Chixculub 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 Chixculub 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 m from the centre of the crater, to 300 m at a distance of 200 m. Outside the central zone where the impact occurred, shock waves apparently radiated laterally and fragmented the surrounding rocks, and the effect diminished with distance from the impact site increased (Fig. 6).

The geophysical data suggest that Chixculub 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 Chixculub 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 Chixculub structure the largest impact crater yet identified on the Earth. The question of the size of the Chixculub 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 Chixculub 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. Marin 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 ejected 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 Bure Breccias 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 ejected, 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 debris material and host material are scattered over 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.

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, Miami) 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. Chaussiddion and colleagues (CRPG/CNRS, Vandoeuvre, France) and Harald 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 underlaying 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 tsunamiites 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 crossional 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 circm-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

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**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 "K–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 "Ar–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 "Ar and 40Ar 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 "Ar–Ar method and came up with an age of 64.98 ± 0.05 million years. To correlate Chicxulub with the supposed ejected 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.
extinction like this would suggest that either there had been no impact or that the impact was not significant. Perhaps the Fernandina species had died off because of long-term climatic change. Jan Smit denied Keller’s interpretation, arguing that there were extinctions of planktonic foraminifera before the K/T boundary. He argues that problems have arisen because of the way in which the sediments have been dated and that there is no compelling evidence for an impact.

As for the dinosaurs, the matter is still far from settled. There is limited evidence in the Cretaceous-Tertiary (K/T) boundary across the North American continent. These teams have been working for a long time, and it is not clear whether or not there was a single event or whether it was caused by a series of smaller impacts. So the question of whether or not there was a single impact remains open.

Another letter

Sir: Eric Robinson’s article about G. B. Carruthers (GEOLOGY Today, v. 10, p. 1998) brings to mind an embarrassing incident for the Lettner concerned back in 1955 (J. Ind.). A group of geologists was travelling in a valley of New York near Dakesburg, with the purpose of surveying and sampling. What was described as a varved clay deposit containing enough rare leaves to enable a dating to be made was found. The fossil leaves must have had the Carruthers message, as some of them were carried by the modified kitchen knives which Eric describes. However, while cutting my first ‘clay’ section, Michel B. Balthoff, 6 Harner Crescent, Cinglefield, Norwich, England 10 MR 78X.