Figure 13.5 Plant fragments in the base of the massive sandstone unit at Arroyo El Mimbral, north-eastern Mexico. *(Iain Gilmour, Open University.)*

the massive sandstone. However, there is no evidence within the sandstone of trace fossils of any burrowing animals suggesting that the whole deposit was formed in days rather than millennia. If you look at the graphic log in Figure 13.4, you can see another crucial piece of evidence: the ripple marks at the top of the sequence.

- ❍ What do the palaeocurrent directions determined from these ripple marks and shown in Figure 13.4 suggest about the nature of the current that deposited these sandstones?
- ● They indicate a series of different current direction flows, at times in opposite directions.

In fact, when the palaeocurrent directions indicated by these ripples were determined, some 200 different directions were found. This was evidence consistent with the effects of large waves interacting with each other as they hit land but not dense bottom currents, which generally only flow in one direction.

Other sedimentary sequences in the Gulf of Mexico region also seem to indicate some of the localized effects of the Chicxulub impact. At Blake Nose, off the coast of Florida in the Atlantic Ocean, both geophysical studies and examination of drill cores indicate extensive folding and slumping of the sedimentary rocks directly underlying the K/T boundary ejecta. This has been interpreted as resulting from a massive failure of the North Atlantic continental margin that was triggered by the impact. It has been speculated that such extensive disruption of the sea-floor could have resulted in the release of large quantities of methane gas, often trapped in some oceanic sediments, which could have had a significant effect on the Earth's climate.

13.2 Global effects

There is little direct evidence of the effects of a large asteroid or comet impact. The 1994 impact of a series of 2-km-sized fragments of comet Shoemaker-Levy 9 into the atmosphere of Jupiter provided some information on the kind of processes that can happen. For the Chicxulub impact, however, much of what is postulated to have happened is based on our understanding of the impact process from two sources. The first are laboratory experiments involving the high-velocity impact of small projectiles of known composition into targets of known composition. Typically, the projectiles are a few millimetres in diameter and the velocities achieved in the experiment range up to around $9\,km\,s^{-1}$. From these experiments, it is possible to scale the process up to larger impacts, a process that provides useful information on various aspects of the impact event including the effects of high-velocity impact on various types of rock and the trajectories of ejecta from a crater. A second source of information comes from hydrocodes. Hydrocodes are large computer programs that can be used to simulate numerically a highly dynamic event, especially those that include shocks. While they cannot supersede the information provided by real impact experiments, hydrocodes are an invaluable tool for extending to planetary scales the limited results from laboratory experiments.

- ❍ Look again at Figure 12.8. What are the three main rock types that would have comprised the target rocks for the Chicxulub impact?
- ● The underlying metamorphic basement rocks, which were probably highly crystalline, an evaporitic sequence with abundant anyhydrite ($CaSO_4$) and gypsum ($CaSO_4.2H_2O$) and a sequence of limestones that would predominantly have been composed of calcium carbonate ($CaCO_3$).

Hydrocode modelling of the Chicxulub impact event suggests the impact vaporized a large quantity of sedimentary rock, producing gases whose physical and chemical properties had an effect on the Earth's climate due to adsorption of radiation or chemical reactions. During the impact event, thousands of cubic kilometres of rock and dust were ejected from the crater, and modelling suggests large amounts of water, CO_2 and SO_2 would have been released into the atmosphere. Estimates of around 300–2000 km^3 of vaporized sediments yield sulfur masses of around 100–200 Gt (1 gigatonne (Gt) = 1×10^9 tonnes), and about 1000–1500 Gt of CO_2 that were released almost instantaneously into the atmosphere. The quantity of gases released varies between different model calculations. In addition, the marine sediments that comprised the Chicxulub target rocks also contained halogens (chlorine, bromine), which, when released into the upper atmosphere, destroy the ozone layer. This would have led to a substantial increase in the flux of ultraviolet radiation at the Earth's surface.

13.3 Climatic implications

Before the discovery of the Chicxulub structure, studies of the impact-related climatic effects focused on the short-term climate change produced by dust in the atmosphere. Indeed, this was the 'killing mechanism' that the Alvarez group proposed in their 1980 paper. Calculations on the effect of this dust in the atmosphere suggested that there would have been a drastic cooling event due to interception of sunlight by high-altitude dust, lasting for a few months to about a year. However, once it was realized that the target contained carbonate and sulfate sedimentary rocks, scientists began exploring the possible climatic effects of a massive release of CO_2 and sulfur-bearing gases to the atmosphere.

As noted above, the hydrocode simulations of the Chicxulub impact event indicate a production of 1000–1500 Gt of CO_2.

- ❍ For comparison, calculate the total mass of CO_2 in the present-day atmosphere from the mass of C given in Table 6.1. Note that 1 Gt = 10^{12} kg, and assume (for ease of calculation) that the atomic masses of C and O are 12 and 16, respectively.
- ● According to Table 6.1, the present-day atmosphere contains 0.76×10^{15} kg of C. The mass of CO_2 is therefore $[(12 + 32)/12] \times 0.76 \times 10^{15}$ kg = 2.79×10^{15} kg, or 2790 Gt. Hence the estimated yield of CO_2 from the Chicxulub impact amounts to rather more than a third to a half of that present in the atmosphere today — a rather alarming thought, should such an event recur.

These estimates of impact-released CO_2 should, however, be compared to the inferred global atmospheric inventory of CO_2 at the end of the Cretaceous, which is estimated at around 9000 Gt. Impact degassing of the target rocks at Chicxulub would then produce an increase of 20% in the CO_2 atmospheric inventory. It has been estimated that this amount may increase to as much as 40% if the asteroid impacted at a lower angle since laboratory experiments indicate that there is an increase in the vaporization of the surface layers of a target as the impact angle, measured from the surface, decreases. Was this enough of an increase in CO_2 to cause a catastrophic climate change? Probably not: climate models indicate that this level of increase in the atmospheric inventory of CO_2 might lead to a global temperature increase of around 1.2 °C.

We can examine the climatic effect of the injection of sulfur into the stratosphere by looking at the climatic effects associated with volcanic eruptions. Long-lived stratospheric aerosols, such as SO_2, tend to cool the Earth's atmosphere system by reflecting an additional amount of energy back into space (Section 7.1.3). In terms of the amount of gases injected into the stratosphere, the largest-known explosive volcanic event in the late Quaternary was the eruption of Toba, in Sumatra, about 73 500 years ago. Estimates indicate that it lofted about 1 Gt of SO_2 into the stratosphere for a predicted cooling of about 3.5 °C in the year following the eruption. The amount of sulfur added to the stratosphere by the Chicxulub impact, estimated by the hydrocode simulations, would have been between 100 and 200 Gt; this would correspond to around 200–400 Gt of SO_2, more than two orders of magnitude greater than any volcanic eruption in the geological record.

- ❍ Why is it hard to infer the effect that such a large load would have had on the Earth's climate?
- ● The magnitude of any climate forcing is not a linear function of the amount of sulfur-bearing gases injected into the upper atmosphere and, as we saw in Section 7.1, is limited by the presence of H_2O in the stratosphere.

However, larger amounts of sulfur-bearing gases will take longer to decay, therefore prolonging the climate forcing in time. It is evident, though, that a Chicxulub-type injection of sulfur-bearing gases (and water vapour) in the stratosphere must have produced devastating changes to the end-Cretaceous global climate lasting for perhaps several years or even decades.

13.4 A question of cause and effect

The present consensus of scientific opinion is that the impact–extinction hypothesis provides the only coherent explanation for the origin of the K/T boundary, relating features as diverse as the dinosaur extinction in the Hell Creek Formation in Montana, the extinction of planktonic foraminifers at Gubbio in Italy, a negative shift in carbon-isotope values at the K/T boundary in New Zealand, the disappearance of ammonites at Zumaya in Spain, an iridium anomaly at Poty in Brazil, impact diamonds at the K/T boundary in Colorado, shocked zircon crystals from Saskatchewan, Canada, and shocked quartz crystals in the South Pacific. It is the global nature of the evidence that is impressive: the same evidence being found time and again around the world.

The consensus is by no means unchallenged: hypotheses requiring more gradual processes such as climate change are vociferously argued. Those more sceptical of the impact–extinction hypothesis have suggested that the selectivity of the pattern of extinctions, for example the survival of particular faunal groups, is more compatible with a gradual extinction scenario than an impact-related one. Similarly, the survival of some species or even genera only to become extinct shortly after the boundary, and the disappearance of some groups of organisms beforehand such as the inoceramids, has been cited as evidence for gradual or stepwise extinction.

The impact–extinction hypothesis does demand that the extinctions that define the end of the Mesozoic Era took place fairly rapidly as a result of, and thus not before, the impact. However, the fact that the inoceramids or some species of foraminifers went extinct before the K/T boundary does not contradict a later catastrophic extinction. Similarly, the persistence of some groups of animals through the boundary, even if they went extinct soon after, does not contradict the possibility of impact-caused extinctions either. While many effects of the Chicxulub impact were immediate, longer-term effects seem unavoidable as well.

We do not have a sufficient understanding of the complexity of Late Cretaceous ecosystems to reach firm conclusions about extinction mechanisms for both gradual and abrupt scenarios. Even present-day ecosystems are poorly understood and those of the Late Cretaceous are far removed from observation and analysis. Whatever the extinction scenario, it seems therefore inappropriate to claim that a selective pattern of extinction is compatible with one mechanism but incompatible with another.

13.5 The end of an era

The impact–extinction hypothesis also brought about the end of another era. Not, as many thought, the central role played by uniformitarianism in the Earth sciences. There never was any real conflict between the impact–extinction hypothesis and uniformitarianism. Many scientists had simply failed to make the connection between small meteorites that are observed to fall from the sky all the time and large impact events. Rather, it was recognized that strict adherence to a principle that invoked slow, gradual uniform rates of change to explain the Earth's history was inappropriate in light of the increasing evidence for periods of rapid environmental change throughout the Earth's history.

The controversy surrounding the K/T boundary continues. Some scientists remain firmly opposed to the idea that an impact played any role in the faunal turnover at the end of the Mesozoic, de-emphasizing the abruptness of the boundary and its importance. The irony of this position was not lost on Graham Ryder, a lunar geologist, who surmised it thus:

> '… [opponents] give the impression that it is those who invoke an impact who have required a particular paleontological significance, for instance that impact proponents *claim* abrupt extinction. Yet it has never been the case that an impact was inferred and that then there was a search for associated extinctions. It is an ironic reversal that some paleontologists chose to reduce the significance of the boundary after the impact was inferred. Rather than evaluate the record in the light of an impact, they chose to construct inappropriate straw men.'

13.6 Summary

- The immediate, local effects of the Chicxulub impact would have been severe. The impact occurred in relatively shallow water (100 to 200 m deep) on a carbonate platform, and an ejecta blanket tens of metres thick has been found 250 to 350 km from the crater centre in the region of the Mexico–Belize–Guatemala borders.
- In north-eastern Mexico, high-energy, massive coarse-grained sandstone deposits that grade upwards into finer sandstone and siltstone layers, the latter enriched in Ir, impact diamonds and spinels, have been interpreted as tsunami deposits produced by tidal waves generated by the impact.
- Hydrocode modelling, computer-based numerical simulations of the impact, are one means by which we can assess the possible global effects of such a large-scale impact event.
- The impact occurred in a thick sedimentary sequence of carbonates and evaporites and hydrocode modelling suggests that large quantities of the target rocks were vaporized by the impact, releasing large amounts of water, CO_2 and SO_2 into the atmosphere.
- Initial studies on the effects of the Chicxulub impact focused on the role of dust ejected from the crater and calculations suggested that there would have been a marked lowering of temperatures following the impact due to the interception of sunlight by high-altitude dust. Once it was realized, however, that the target contained carbonate and sulfate sedimentary rocks, the possible climatic effects of a massive release of CO_2 and sulfur-bearing gases to the atmosphere also had to be considered. Long-lived stratospheric aerosols, such as SO_2, tend to cool the Earth–atmosphere system by reflecting an additional amount of energy back to space.

13.7 Further reading

ALVAREZ, W. (1997) '*T. rex* and the crater of doom', Princeton University Press, Princeton, 185pp.

GLEN, W. (1998) *The Impact–Extinction Debates*, Stanford University Press, Stanford, California, 371pp.

SMIT, J. (1999) 'The global stratigraphy of the Cretaceous–Tertiary boundary impact ejecta', *Annual Review of Earth and Planetary Sciences*, **27**, 75–113.

The research papers presented at the 'Snowbird' series of conferences on the K/T boundary mass extinction are published in the following Geological Society of America Special Papers, listed chronologically:

SILVER, L. T. AND SCHULTZ, P. H. (eds) (1982) 'Geological implications of impacts of large asteroids and comets on the Earth', *Geological Society of America Special Paper 190*, 528pp.

SHARPTON, V. L. AND WARD, P. D. (eds) (1990) 'Global catastrophes in Earth History', *Geological Society of America Special Paper 247*, 631pp.

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KOEBERL, C. AND MACLEOD, K. G. (eds) (2002) 'Catastrophic events and mass extinctions: impacts and beyond', *Geological Society of America Special Paper 356*, 579pp.