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EDITORIAL

It is often said that research articles are published in refereed journals after the referees and the editors have 'cut away the verbiage', to come up with answers to such questions as what was the objective of the study? What was done to realise that objective? What was the result of the investigation? What is the meaning or the impact of these research findings? The assumption with this scenario is that 'the editors are always able to distinguish the woods from the forest.' Most of the time I reckon that the editors are able to and that is how they survive, as editors.

The six original research papers which appear in this issue, volume **5 (1)**, illustrate the concept of answering the questions posed above very clearly. In the first paper, researchers compared the performances of selected three sewage treatment plants in Zimbabwe. Their findings indicate that Chitungwiza and Marondera treatment plants are inefficient while the Crowborough treatment plant is very efficient with good quality effluent. The second paper, from the engineering sciences, addresses the objective question right from the outset: 'A failure investigation of a welded waste heat boiler steel shell that developed transverse cracks was carreid out in 1996 to determine the cause of failure as well as propose measures to be adopted to prevent similar failures in the future.' The conclusion of the paper summarizes the investigation in that 'high pH was responsible for the occurrence of cracking as a result of caustic embrittlement.'

The third paper from the animal sciences answers from the outset 'what is the objective of the study?', that is, an investigation into the effects of incorporating duckweed into broiler finisher diets on performance and carcass composition. The conclusion from the results automatically answers the objective in that duckweed can be incorporated in boiler finisher diets up to 10 percent level without compromising growth performance and carcass composition.

The remaining three original papers, that is, vesicular arbscular mycorrhizal fungi prevalence and diversity in Zimbabwean soil (soil science); preparation of water insoluble crosslinked mucilage from *ruredzo* (*Dicerocaryum zanguebarium*) (biochemistry); and another animal science paper, intra-herd production levels of milk yield of Zimbabwean Holstein cows follow suit. It is envisaged that the referees and editors of JASSA will maintain and encourage this clarity in presentation of published papers.

The final paper in this issue is an inaugural lecture by Professor T.G. Blenkinsop, 'Meteorite Impacts on earth and on the Earth Sciences.' Astrologists have often said that 'meteorites are both the bringers of life and death on earth.' Professor Blenkinsop's inaugural lecture tackles this subject in such a compelling way that even non earth scientists like myself find the subject exciting. The economic, environmental and biological consequences of meteorite impacts on earth are examined and explained by Blenkinsop in a way that demystifies meteorite impacts.

C. F. B. Nhachi
Editor-in-Chief

Meteorite Impacts on Earth and on the Earth Sciences

Inaugural Lecture, Prof. Tom G. Blenkinsop

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Plate tectonics has become established during the last thirty years as a coherent explanation for the major features of the Earth today. The formation of new crust at mid-ocean ridges, the movement of relatively rigid lithospheric plates over the softer underlying asthenosphere, and the collision of plates throwing up the Earth's major mountain ranges, are familiar concepts to many people. However, recent discoveries in the Earth sciences challenge us to a newer concept of the Earth's evolution. These discoveries indicate that large meteorite impacts have had enormous effects on the Earth, perhaps most dramatically illustrated 65 million years ago, when an impact at Chicxulub in the Caribbean may have been responsible for mass extinctions (including the dinosaurs) on a global scale. The evidence for these catastrophic events is surprisingly enigmatic in the geological record, and has been the subject of intense scientific debate and disagreement. Some of the major types of direct evidence for meteorite impacts include the craters formed by impact, and the effects of impact on rocks, including melting, the formation of shatter cones, and a whole variety of small-scale features that are revealed under the microscope. Perhaps paradoxically, these microstructures are the most unambiguous evidence for meteorite impacts, because they formed under radically greater stresses, temperatures and strain rates than those of plate tectonic processes, and are therefore quite distinct from plate tectonic microstructures. These features of meteorite impacts on Earth are illustrated by examples from several known impact sites, including the Vredefort structure in South Africa and a possible impact structure at Highbury south of Mhangura in Zimbabwe. Large meteorite impacts on Earth have significantly augmented Earth's mineral resources since the formation of the Earth, by creating diamonds in the ultra-high pressure conditions of impact, by providing structures that trap petroleum, and possibly by creating base metal deposits. The likely environmental consequences of impacts include a searing heat wave followed by global cooling, causing episodes of mass extinction that may occur in cycles. There is some controversial evidence for the theory that the first life on Earth itself may have been transported here on meteorites from Mars. The possibility of a major meteorite impact on Earth in the near future emphasizes the dramatic nature of these recent discoveries, which are having deep impacts in the Earth sciences, possibly even constituting a scientific revolution.

Tribute

I would first of all like to pay tribute to my predecessor in this august post. Twenty years ago, Prof. J. F. Wilson delivered his inaugural lecture with the ambitious title 'Rocks, minerals, space and time' . Prof. Wilson's contribution to geology in Zimbabwe is enormous and seminal, and even today it is stimulating new research in the department of geology. His work has been an inspiration to this lecture, and in some ways, his theme has been continued directly in this lecture, which will consider Earth in the context of the heavens.

Impacts in the Earth Sciences

Today I want to tell you about a major upheaval that is happening in the Earth sciences. I am not talking about Plate Tectonics, which many of you will know of at least in outline. That revolution occurred over 30 years ago, and must rank as one of the major academic achievements of the twentieth century in any discipline. It inspired a whole generation of Earth scientists, myself included, to take up the study of the Earth, and then it left us wondering what new discovery could ever be as exciting or far reaching in the Earth sciences again. After that intense, original and brilliant science, we felt flat and perhaps a little disappointed that we could not hope for another such revelation in our lifetimes; a discovery that would demand our full scientific attention, and capture the popular imagination.

But such a paroxysm may have occurred in the last five years. My guess is that few of you will know much about it and it is my intention today to fire your imaginations with some of these new concepts. To whet your appetites, what I am going to describe to you is regarded by several authorities (for example, Gould 1995) as a scientific revolution in the making. I am lucky that my own specific research interest has a tangential relevance to this revolution, and I shall try to show just a few aspects of this towards the end of the lecture. For the most part, however, what follows will be a summary of the vast amount of research carried out by specialists in many other fields.

'Revolution' of course is used in this context in the sense of the great philosopher of science Thomas Kuhn, who suggested that science progresses by periods of intense change when the whole current framework of ideas is replaced by another scheme, or 'paradigm'. This 'revolution', as he called it, occurs quite suddenly, after a period of relative stasis in knowledge. The seed of the revolution is the accumulation of a body of data that can not be accommodated within the existing framework of knowledge. One of the heralds of an impending scientific revolution are attempts to modify the existing orthodoxies to accommodate these uncomfortable observations. The scientific edifice looks increasingly dog-eared, until a new idea arises that can explain both the old and new data much more efficiently: a new paradigm is born. In the period after the paradigm shift, science reverts to background or normal research, which has the basic effect and intention of supporting the new construction. I suppose that many of us felt after the Plate Tectonic revolution that we were destined to mere 'background' scientific activities, and would never be part of a revolution in the Earth sciences. What I am about to describe to you does not fit perfectly into the Kuhnian paradigm for scientific revolutions, but it does contain many of these elements.

Plate Tectonics — A current view

Let us begin by summarizing what we know of the major processes that shape the Earth today, that is the features of plate tectonics. The Earth consists of a number of layers arranged like an onion: at the centre we have the molten metallic inner core, surrounded by the solid outer core. The vast majority of the Earth is the solid mantle, overlain by a mechanically strong, but thin layer, that we call the lithosphere.

Above the lithosphere are two layers which are not dealt with in many traditional geology textbooks, but which are now viewed as integral and highly important in the Earth's evolution: the hydrosphere (the layer of liquid water that covers much of the Earth's surface) and above that, the atmosphere. There is yet another layer which we now view as having major significance in the physical evolution of the Earth: the layer containing life, the biosphere. Incidentally, another major exciting discovery of the last few years is that the biosphere extends to depths and conditions in the Earth which were previously thought to be absolutely inimical to life: bacteria have been found at depths of over 1 km in granite, and whole new ecosystems of worm-like creatures are now known to exist on and near vents of hydrothermal fluids erupting at temperatures of 300°C on the ocean floors. The first life on Earth may have prospered around these hydrothermal vents, quite different environments from what we used to consider as life nurturing conditions until a few years ago.

This system of layers in the Earth is in constant motion. Most importantly to us as geologists, the lithosphere moves with respect to rest of the mantle, and parts of the lithosphere move with respect to each other. The parts of the lithosphere that move are relatively rigid and called 'plates' as in plate tectonics. There are twelve major plates on the Earth, of which the African plate, on which we are sitting, is one of the most interesting. There are a number of areas of the Earth, such as the Caribbean, where plate boundaries are not clearly delineated, and other areas, such as the Himalayas, where the boundary between plates occupies a large volume, which is not commensurate with the idea of rigid plates. An interesting post-plate tectonic revolutionary problem is the nature of such areas where the plate boundaries are not single planes as postulated in the early ideas of plate tectonics.

Two plates can move away from each other, which happens at chains of largely submarine mountains in the oceans called Mid Ocean Ridges. Two plates can also slide past each other — as for example along the west coast of north America, where the Pacific plate is sliding northwest relative to the North American plate. Two plates can converge towards each other, one sliding underneath the other as the Pacific plate slides underneath Asia alongside Japan. These processes shape the major features of the Earth's surface: submarine mountains where plates move apart, subaerial mountains where they converge.

Plates move at average speeds of 5 cm/year: about the same rate that your fingernails grow. This motion is sometimes very abrupt: energy is released in devastating Earthquakes. Plate boundaries are also responsible for the majority of volcanic activity on the planet. Both at divergent and convergent boundaries, a variety of processes operate that promote melting of the mantle, intrusion of the melt into the rocks of the lithosphere, and eruption of some of the melt in volcanoes. Plate tectonics thus accounts for some of the most dramatic manifestations of the dynamic Earth, earthquakes and volcanoes: indeed, it was through these features that the plate boundaries were first delineated.

New plates are created at the divergent type of plate boundary, and old plates are consumed — or rather, returned to the mantle, at convergent plate boundaries. Thus we see that plate tectonics is merely occurring in the upper layer of a much larger system of movement in the Earth, which we now know to involve much of the mantle in a giant circulating system - essentially a huge convection cell driven by the internal heat of the Earth.

Uniformitarianism and Catastrophism

We have built up a picture of a dynamic Earth in constant motion, with material rising to the surface in some places, and returning to the mantle in others. Evidence for the processes that we see operating on and in the Earth today can be found in the record of the rocks for the greater part of Earth's 4.6 billion years (Ga) history. Plate tectonics, then, would meet with the approval of two of the most important figures in the history of geological research - James Hutton and Charles Lyell, who together lay the foundations of an Earth science philosophy called 'Uniformitarianism' in the eighteenth century. One phrase of James Hutton sums up their ideas: 'The present is the key to the past'. In other words, the processes that we see today shaping the Earth also occurred in the past, and can be used to interpret the observations that we can make in ancient rocks. This is a fundamental statement and truly nothing less than an entire philosophy of Earth science, and was arguably the most important revolution in the Earth sciences before plate tectonics.

Uniformitarianism overturned an earlier concept called Catastrophism, which suggested that the major features of the Earth arose in gigantic upheavals that we do not generally witness today. Perhaps the success of the plate tectonics revolution this century may be due to the fact that it is essentially uniformitarian, at least in the consideration of many today.

Meteorite Impacts — A return to Catastrophism ?

This comfortable, established, picture of an Earth governed by a set of well-understood internal processes has been overturned in the last five or so years. It has been suggested long ago that the Earth bears the scars of giant meteorite impacts in the past: for example, the famous American geologist G.K. Gilbert speculated that Meteor crater in Arizona was a meteorite impact crater in the last century. It has also been appreciated for some time that the formative years of the Earth from its origin at 4.6 Ga were dominated by impacts until about 3.8 Ga. Much of the intensely pock-marked appearance of the Moon's surfaces dates from this period, and indeed the Moon itself probably formed at 4.5 Ga ago following the impact of a body on Earth with about one tenth of the Earth's mass. However, we do not see the evidence of this early bombardment on Earth because of the motion of the Earth's plates, which continually erase the evidence as the dynamic crust is involved in subduction and orogeny, and because of the intense chemical and physical processes of weathering and erosion at the Earth's surface, which act rapidly (on a geological time scale) to obscure the topographical effects of craters.

The evidence for the importance of meteorites in the early evolution of the Earth-Moon system is uncontroversial. What has changed in the last five years is the realization that meteorites have had major impacts on the subsequent and recent history of the Earth, and most importantly of all, on life and evolution. This is a profound challenge to the way that geologists have thought about the Earth, and has been strongly resisted by some. One view of this change would be to suggest that Catastrophism must once again be on the geological agenda, but towards the end of this lecture, I shall show that in terms of underlying philosophies, the recognition of the role of impacts in the geological record is no more than the ultimate logical conclusion and vindication of Uniformitarianism.

The Evidence for the Meteorite Impacts on Earth

It is appropriate to review the evidence for meteorite impacts on Earth because there is still some debate about their importance. Once we have established reliable criteria for impacts, we can begin to link geological events to specific known impacts, and even to deduce the existence of impacts that were previously unknown. It would be appropriate at this stage to also mention that a rearguard action is still being fought over much of the evidence for impacts, and that there are ambiguities and even contradictions that remain to be resolved over some of the evidence.

Indirect Evidence: The flux of material in space

The first line of evidence is an indirect, but important argument. Astronomical observations tell us that the Earth, like all bodies in the solar system, exists within a flux of material that orbits the Sun, inevitably leading to collision and accretion of material from space. Astronomers can make estimates of the flux of these bodies that show clearly how many objects and of what size may have Earth-crossing orbits, and what proportion of them may collide with Earth in a given time. We are oblivious to most of this of course: sand to dust-sized particles enter the atmosphere and ablate completely, leaving no visible evidence of their existence. Such sub-millimetre particles have an astonishing flux of 40 000 tonnes of material per year. Shooting stars are the only record of many collisions. Some material, however, makes it through our protective atmosphere to arrive at the ground in a solid state: meteorites. Objects greater than 150 m can survive intact through the atmosphere: smaller objects fragment.

The larger bodies, dealt with here, are conventionally classified into asteroids and comets, but the trend in astronomical science today is to view all of these small bodies in the solar system as closely related. Comets and asteroids probably formed in similar locations but were later perturbed into different orbits, and some asteroids are probably burned out comets. Distinctions between them are based only on telescopic appearance and present day orbits, neither of which has much genetic significance.

Astronomical observations suggest that there are 300 ± 150 Earth-crossing asteroids in the solar system, most of which have diameters less than 3 km. Five asteroids with diameters above 2 km are estimated to collide with Earth every 1 million years. Comets pass through the Earth's vicinity about ten times less frequently than asteroids of the same size, but they have a mean impact velocity 3.3 times greater than asteroids and can be much larger. Comets at least 10 km in diameter are expected to collide with Earth once every 100 Ma.

In July 1994, we witnessed one of the most spectacular events in human experience ever to have occurred in the solar system: the collision of the fragments of comet Shoemaker-Levy 9 with Jupiter. The comet broke into 21 separate nuclei before impact, and these shot into the rotating surface of Jupiter at speeds of 60km/s, creating fireballs that rose up to 3 000 km into Jupiter's stratosphere and leaving a trail of pock marks across the planets face. The kinetic energy of the largest fragment, about 3 to 4 km across, was equivalent to six trillion tonnes of TNT, and would have created a crater 60 km across on earth (Beatty and Goldman, 1994). There does not need to be any more dramatic testimony of the process of impact. I remember the incredible excitement of seeing a new impact crater coming into view as Jupiter rotated through a relatively small telescope on the lawn of a house in Mount Pleasant. It was a moment of immense scientific excitement and awe.

Direct Evidence of Meteorite Impacts on Earth

(i) Craters. Craters are the largest and most spectacular manifestations of meteorite impacts. Much research has been directed at understanding the physics of the cratering process, some of it involving experiments in which projectiles are fired at high speed into buckets of sand or water: they sound like a school-boys paradise. This research tells us that impacts have devastating effects on both the meteorite and the target. Much of the meteorite is vaporised or fragmented on impact, which occurs at speeds of tens of kilometres per second. A shock wave radiates through the Earth, instantaneuously compressing and heating material. Rock near the impact is fragmented and ejected into the atmosphere in a stream of particles, excavating the crater. The experiments give us a formula that relates the size of the crater to the mass of the impactor: for example, an impactor of 10 to 20 km diameter will generate a crater with a diameter of 300 km.

After formation, the crater walls collapse inwards under gravity, expanding the expression of the impact. Smaller meteorites produce simple bowl-shaped craters, but immediately after larger meteorite impacts, the central area directly under the point of impact rises up to form the 'Central Uplift', and multiple crater rims may be formed. Some craters are slightly elliptical: this has been attributed to oblique impact. All these features are clearly seen on meteorite craters on the Moon, Mercury and some planetary satellites, as well as in some terrestrial examples.

Unfortunately, as we have seen, craters are rarely preserved on Earth because of the dynamic motion of plates, and because of weathering and erosion. Nevertheless, examples do persist as spectacular topographic craters, such as the famous Meteor crater in Arizona, and as more subtle expressions in the landscape, such as Manicouagan in Canada. Still more subtle craters have been identified by remote sensing and geophysical techniques such as gravity and magnetic studies. We have an excellent example of the latter in Zimbabwe, where a circular structure 15 km in diameter centred on the Highbury area, between Chinhoyi and Mhangura was first identified from Landsat images. Subsequent work by Sharad Master showed that the topography and drainage also define a circular structure, and that there is a topographic uplift of some 50 m in the centre of the structure. By comparing the effects of known geological events on the structure, it is thought to have formed between 1.8 and 1.0 Ga ago. Confirmatory evidence for an impact origin comes from microstructures similar to the ones described below, which were found in rocks near the centre of the structure.

A much larger approximately circular structure has been identified in the Caribbean, centred on the Yucatan peninsular in Mexico. This feature, approximately 300 km in diameter, is known as the Chicxulub structure, and was created by an enormous meteorite impact 65 Ma ago. It is thought to be responsible for the 'Cretaceous Tertiary (K-T)' boundary mass extinction of many species of life, including the dinosaurs.

Even where no topographic or subtle potential field effects exist, craters can be identified from the geological patterns that they produce. The Vredefort Dome in South Africa is an example of this situation, a structure which has caused over a century of vigorous geologic debate. Only now is a concensus emerging that the Vredefort Dome was created by a giant meteorite impact at 2023 Ma. The large scale geological manifestation of the impact is an approximately concentric disposition of rock types. This in itself does not make an impact crater, and alternative hypotheses have been advanced for the Dome, such as explosions of gas accumulated in deep in the Earth (cryptoexplosions) and tectonic processes. However, an impact origin is now largely accepted because of the diagnostic evidence from the type of smaller-scale features discussed below. Part of the reason for the controversy in the case of Vredefort is that only about half of the structure outcrops at the surface: however, the other half is confidently known to exist from potential field studies. The geology of the rocks exposed in the Dome show that the central parts were once at the base of the crust, while the outer parts were at mid to upper crustal levels. The impact caused the whole crust to bend upwards. The original diameter of the structure was 300 km, making it one of three largest known impact structures on Earth, together with Chicxulub in the Caribbean and Sudbury in Canada.

As a result of recent research, more than 150 craters that can be reliably associated with meteorite impacts are now known on Earth. Their number is increasing every year as more geologists become aware of the signs to look for. There is a higher crater density in the northern hemisphere. This is not due to any astronomical, geological or even dire divine reason, but a perfectly predictable outcome of the greater knowledge of the geology of the northern hemisphere. The potential for the future discovery of craters in Africa is exciting.

It is very satisfying that the predicted cratering rate from astronomical observations matches the recent geological record fairly well. For example, asteroid impacts should create about three craters at least 10 km in diameter in continental crust every million years (Weissman, 1990b), and we know of two 10 km diameter craters younger than 1.1 Ma, one of which is Lake Bosumtwi in Ghana. Astronomical observations suggest that craters greater than 20 km should form at a rate of $5.9 \pm 3.5\ 10^{15} km^2 a^{-1}$, compared to the estimated rate of $5.6 \pm 2.8\ 10^{15} km^2 a^{-1}$ (Shoemaker, 1998).

(ii) Shatter cones. Shatter cones are striated surfaces of rocks arranged in a conical pattern, typically on a metre scale. Some of the finest examples, and the most intensively studied, are associated with the Vredefort Dome. They are thought to form by dynamic fracture of rocks in the shock wave radiating away from the impact site. Shatter cones have not been without controversy as indicators of impact: recently some work in South Africa has revealed that similar but smaller features can be formed in stream beds by bolders bouncing onto the underlying rocks.

(iii) Melting - Pseudotachylite. Highly distinctive rocks consisting of large clasts in a fine-grained, dark matrix were recognised and described from the Vredefort Dome in the early part of this century by Shand (1916), which he called pseudotachylite. There has been intense debate about the origin of pseudotachylite at Vredefort and elsewhere, and whether it is necessarily an indicator of impact. In summary, it is now recognised that the dark matrix of the pseudotachylites at Vredefort represents a quenched molten rock, and that it was generated by the Vredefort impact. Other pseudotachylite occurrences are associated with impact structures, but yet others are clearly related to tectonic fault movements, so that pseudotachylite is not diagnostic of impact.

(iv) Microstructures. Microstructures are microscopic features that testify to deformation. Perhaps paradoxically, microstructures are the most unambiguous evidence for meteorite impacts, because they formed under radically greater stresses (up to 100 GPa), temperatures (up to 10 000 °C) and strain rates (10^6 to $10^9 s^{-1}$) than those of plate tectonic processes, and are therefore quite distinct from plate tectonic microstructures.

Planar Deformation Features (PDFs). Planar Deformation Features are intracrystalline zones of optical and/or crystallographic contrast with the host crystal, typically of the order of micrometres wide and with spacings of 2 to 10 μm as seen under the optical microscope. Quartz is the mineral in which shock characteristic deformation is best developed and has been most extensively studied. PDFs in quartz occur in sets parallel to crystallographic directions. As many as 18 different sets may form in one grain. It is necessary to turn to the Transmission Electron Microscope (TEM) to study PDFs in more detail. About ten times more PDFs are visible in the TEM than under the optical microscope (Goltrant *et al.*, 1991), and PDFs have spacings from 1 to 10 μm and thicknesses of ≤ 1 μm under the TEM. The lamellae can be subdivided into narrow transformation lamellae (< 10 nm wide) which are only visible in the TEM, and wide transformation lamellae (50 to 500 nm wide) which are the optically visible lamellae, and which may contain a finer scale sub-lamellar structure of pillars at high angles to the lamellae boundaries, which is clearly revealed by etching (Gratz *et al.*, 1996).

PDFs form by solid state transformation at low pressures and by melting of thin bands at higher pressures. They may be easily altered after formation, which means that they may not always be detected as distinct features with the properties given above.

Rather similar features to PDFs are observed in shocked zircons, which appear as planar features continuous across the whole grain occur with a spacing of 5 μm or less. It is uncertain whether these features are analogous to PDFs in quartz. Zircon grains may also have a granular, polycrystalline texture of 1 μm zircon crystals ('strawberry texture'), which has been observed in zircon from laboratory experiments and at several confirmed impact sites, including the Vredefort Dome, but never in other circumstances: this texture may therefore be diagnostic of impact.

Mosaicism is a pattern of domainal lattice misorientation seen as a 'mottled' pattern under the optical microscope. Remnants of planar features associated with mosaicism in quartz suggest that the mosaic domains may have formed by the intersection of two sets of PDFs (Leroux and Doukham, 1996). Mosaicism has also been described from other minerals, for example feldspars, olivine and pyroxene (Hörz and Quaide, 1973).

Diaplectic glass is a distinctive type of silica glass that occurs in homogeneous patches and associated with some types of PDF. Langenhorst's (1994) model for the formation of diaplectic glass suggests that it forms by quenching of a melt before shock pressure is completely released. Diaplectic glass in natural impact rocks recrystallizes during annealing to characteristic textures which depend on the shock pressure reached. For shock pressures less than 35 GPa, the glass becomes brown. Microstructures of spherical α-quartz single crystals, all in the same orientation, called ballen, form at higher pressures. At still higher pressures, the ballen have different crystallographic orientations (Grieve *et al.*, 1996). In 1998 I made the exciting discovery that ballen structure exists in samples that I collected in Ghana some years ago. The samples come from the Bosumtwi crater, which has a diameter of about 10 km, and formed about 900 000 years ago. The origin of the crater has been vigorously debated: some have suggested a volcanic origin. However, these ballen microstructures and other shock features clearly confirm the impact origin of the crater.

High Pressure polymorphs of quartz — Coesite and Stishovite. Experiments demonstrate that one of the most abundant rock-forming minerals on Earth, humble quartz, changes into exotic different physical forms (polymorphs) at very high pressures, known as coesite and stishovite. Coesite in some shocked samples appears as colourless-brown, 100 to 200 μm sized aggregates of individual grains less than 1 μm in size, often enclosed by diaplectic glass or isotropic quartz with abundant remnants of PDFs (Grieve *et al.*, 1996). The aggregates may be aligned on crystallographic planes. Coesite associated with pseudotachylite veins from the Vredefort Dome is colourless, with high relief, and very low birefringence (Martini, 1991). It is either massive or forms radiating needles up to 100 μm long. Stishovite, the highest pressure polymorph of silica, can be distinguished from coesite by a higher birefringence and a brownish colour (Martini, 1991). It occurs in the same two habits described above for coesite.

Lechatelierite is a silica glass which may contain flow structures and vesicles, and may occur as veins within quartz with PDFs. The vesicles and flow structures demonstrate that lechatelierite forms as a quench product from a melt under low pressure, in distinction from diaplectic glass.

(v) Tectites, microtectites and spherules. Tectites are rounded silicate glass bodies usually less than a few centimetres in diameter (Glass, 1990). They are usually black, but may be translucent, brown or green. Tectite glass has flow structures and abundant inclusions of lechatelierite and other minerals. Three major types of tectite are recognized:

- Splash forms: spheres, disks, dumbell and teardrop shapes.
- Ablated forms, which are similar to splash forms but with an additional flange.
- Muong Nong types, which are larger, layered chunks of tectite glass.

Tectites occur over large areas of the Earth's surface called strewn fields, demonstrating that they were deposited from the atmosphere. Terrestrial and lunar volcanism, and meteorite impact, have been proposed as possible origins for tectites, but a number of arguments favour the impact hypothesis (Glass, 1990). Flow structures demonstrate that tectites were molten: the flanges of ablated forms were formed during a second period of melting. Lechatelierite inclusions suggest temperatures of 2 000°C, far greater than volcanic temperatures. The chemical composition of tectites shows that they were derived by melting of sediments and not from terrestrial or lunar igneous rocks. Furthermore, the tectites in at least two strewn fields can be linked to proven impact craters: tectites in Czechoslovakia came from the Ries crater in Germany, while the Ivory Coast strewn field is derived from the Bosumtwi crater in Ghana.

Microscopic tectites (microtectites) have been described from several sites at the Cretaceous-Tertiary boundary, and associated with impact at the Chicxulub site in Mexico (for example, Olsson *et al.*, 1997). Many of these microtectites are spherical, with diameters of 0.2 to 5 μm, and composed of clays or calcite. Some contain a core of glass, suggesting that the clays formed by devitrification. Flow structures in the glass, and associated shocked grains, demonstrate the impact origin of these spherules.

(vi) Diagnostic impact microstructures. The identification of microstructures that are diagnostic of impact has profound implications for the understanding of the evolution of the Earth. The subject has been very controversial, with much debate on the extent to which shock-induced microstructures could be produced by volcanic eruptions or other endogenous processes as alternatives to meteorite impact.

PDFs in impact shocked rocks have similar analogues in tectonically deformed rocks, but subtle features can distinguish the two in the Scanning and Transmitting Electron Microscopes: PDFs are one of the strongest and most diagnostic pieces of evidence for impact. The distinctive features of shocked zircons have only been reported so far from impact-related rocks. Likewise, while coesite itself is not diagnostic, the particular habit of coesite in shocked rocks is quite unique. Diaplectic glass can be formed by static compression at 25 to 35 GPa, but this is much higher than any pressures recorded by rocks at the surface of the Earth: diaplectic glass remains a diagnostic indicator for shock pressures. These features constitute a strong array of microstructural tests for impact, which must often be employed when larger scale diagnostic evidence is lacking.

Explosive volcanism and deep-seated explosive activity are possible alternatives to meteorite impact as a source of shock waves, as mentioned in the case of Vredefort. Controversy exists over what pressures may be obtained in volcanic explosions; estimates range from values within the field of crustal metamorphism (0.5 GPa) to values as much as 10 GPa. Planar microstructures, mosaicism and Brazil twins in volcanic rocks have been claimed as shock microstructures, but much of this evidence has been strongly refuted. The case for shock features related to volcanism or deep-seated explosive activity is not strong.

(vii) Siderophile element anomalies. One of the key early pieces of evidence for the current appreciation of the global significance of meteorite impacts was the discovery by Alvarez and others in 1980 of a layer of clay 65 Ma old, with the element iridium concentrated by an order of magnitude compared to the background values. This element is of special interest because it is strongly depleted in the Earth's crust relative to solar system abundance. Similar iridium anomalies have been discovered in sediments of 65 Ma age from many different parts of the world in both marine and non-marine sediments. Along with iridium, several other 'siderophile elements', (those that have affinities to iron), including gold and the PGE elements, were found to be enriched in layers of the same age. Furthermore, the abundance of these elements with respect to each other was quite uncharacteristic of terrestrial rocks, but matched certain classes of meteorites very well. The only reasonable explanation of all these data is that the geochemical anomalies were caused by the disintegration of meteorites that were sufficiently large to have their ejecta blasted into global atmospheric circulation.

Economic consequences of meteorite impacts on Earth

One of the most fascinating recent geological discoveries has been that diamonds are associated with meteorite impact structures. Polycrystalline diamonds up to 1 cm have been found in the Popigai impact crater, which is a Siberian impact crater with a diameter of 100 km, and in the Ries and Chicxulub craters (Koerbel *et al.*, 1997). Diamond is nothing more or less than a polymorph of carbon, but on Earth, it is only formed at depths in the lithosphere of 120 to 200 km. The diamonds that we find so rarely on or near the Earth's surface have been formed at these depths and transported upwards in Kimberlite pipes during an exceptional type of volcanic process. The diamonds associated with meteorite craters, however, are found in rocks that show no evidence for having been at such depths in the Earth, and clearly formed during the intense, instantaneous pressures during impact, by solid state transformation at pressures of 35 to 60 GPa.

Another fascinating economic consequence of meteorite impact has been the discovery of petroleum in several impact structures in oil fields of the midwest in the U.S.A, for example the Ames structure in Oklahoma, and similar phenomena are known from Alaska and the CIS (Reimold, 1995). Petroleum forms by the slow decay, burial and heating of organic compounds in the crust, and then accumulates in favourable structures called traps. In the cases mentioned above, the traps were created by meteorite impacts. Not long ago, a much more radical explanation for the association between meteorite impacts and oil was proposed by the maverick astronomer, Thomas Gold. He suggested that the major oil reserves in the world were derived from the underlying mantle, and accumulated nearer the surface of the Earth where it had been fractured by meteorite impacts. In fact, his theory persuaded the Swedish government to drill deep into the Siljan ring impact structure in Sweden to look for oil reserves. Unfortunately none were found, and we are left with the more prosaic but orthodox interpretation that biogenically-derived oil can accumulate in meteorite impact structures when they occur in suitable rocks.

The Sudbury impact structure in Ontario, Canada contains a major massive sulphide body that has been a major producer of nickel, copper and platinum group elements. The ore bodies are considered to have formed in a large impact melt sheet. A number of other mineral deposits occur in impact structures, including clays, carbonates, zeolite, coal, gypsum/anhydrite, flourite, diatomite and phosphate.

Environmental consequences of meteorite impacts on Earth

The environmental consequences of a large meteorite impact can be modeled to some extent, partly because of the improvements in Global Circulation Models made for climate forecasting, and through efforts to predict the consequences of nuclear explosions. Immediately following a large meteorite impact, there would be a searing blast of heat around the world as the kinetic energy of impact was partly converted into heat. This would create forest fires and burn vegetation on a worldwide scale: evidence for such fires following the Cretaceous-Tertiary event has been found in the form of an ash layer in the geological record. Following this temperature rise after some days to weeks, the opposite and longer term effect would begin: ash from forest fires, smoke, dust and other impact ejecta would obscure the Sun's radiation to cause global cooling over a period of years, a scenario known as the global icehouse. For some of this period there would have been almost total darkness over the whole world due to the dust in the atmosphere. There may also be a subsequent global greenhouse effect due to the gases injected into the atmosphere: this might follow shortly after an impact in an ocean because water would wash out the dust from the atmosphere (for example, O'Keefe and Ahrens, 1982). These changes make the sort of disasters caused by El Nino insignificant.

Other environmental consequences would depend on the type of target rock. Evaporites, such as those found in many tropical areas today, would vaporize and contribute huge quantities of sulphur to the atmosphere. This would combine with water to form sulphuric acid, creating acid rain on a global scale. Acid rain would also follow from the fusion of atmospheric nitrogen and oxygen into nitrous oxides. Other elements ejected from the impact and dispersed around the world in the atmosphere could create various types of noxious environments.

Biological consequences of meteorite impacts on Earth

The global fires followed by freezing conditions, darkness, and perhaps acid rain and other pollution, would be extremely rapid, major changes in environment, to which organisms would be unable to adapt, leading to extinction of many species. We know that extinctions have occurred on a massive scale in the past. One of these is clearly at a similar time to the Cretaceous-Tertiary impact at 65 Ma in the Caribbean, and this is one of the most dramatic in the popular mind because it apparently marked the end of the reign of the dinosaurs on Earth. Fifty percent of marine invertebrate species, including the ammonites, became extinct at this time, as well as 75 percent of all species on Earth. Ninety percent of the biomass on Earth was destroyed (Sims, 1997).

However, there has been considerable difficulty in proving that the impact was the cause of the extinctions, because some extinctions apparently began before the date of the impact, suggesting that terrestrial causes were responsible. We now understand that much of this apparent decline in diversity can be explained by the

Signor Lipps effect, named after the authors of a famous paper called 'Sampling bias, gradual extinction patterns and catastrophes in the fossil record', published in 1982, but only gaining credence in subsequent years. Signor and Lipps concentrated on the fact that the fossil record is not continuous. Fossils of any species are not preserved at all times, but only in favourable circumstances. Moreover, the sampling of fossils is far from complete, relying as it does on the limited even if industrious activities of paleaontologists. Thus the date of the youngest rocks in which a particular species is discovered is usually older than the date of its last existence on Earth.

If species diversity is measured at any one point in this discontinuous process, it will inevitably show an apparent decrease in diversity in the preceding interval. This elegant piece of logic shows us why diversity appears to decline before an instantaneous extinction event, and dispels some of the last remaining doubt about the link between the death of the dinosaurs and the Chicxulub impact, although the exact mechanism is still being debated. The validity of the Signor Lipps effect has been convincingly proven by attempts to overcome the sampling bias: closer scrutiny has revealed that the ranges of both ammonites and dinosaurs extended right up to, but not beyond, the Cretaceous-Tertiary boundary. The brilliant essayist Steven Jay Gould has called this problem 'looking for a dinosaur in a haystack' (Gould, 1995).

The Cretaceous-Tertiary mass extinction is only one of at least five mass extinctions known in the last 600 million years of Earth history. Others were much more dramatic: for example, at the end of the Permian era, 225 million years ago, 96 percent of all marine invertebrate species were exterminated. The most recent large mass extinction occurred in the late Eocene, 34 Ma ago. In the graph showing these mass extinctions, there is an apparent cyclicity, with a period between 26 and 30 Ma. This fascinating and dramatic observation, which was first brought to light by Raup and Sepkoski in 1984, has been the cause of considerable speculation. However, the science used to demonstrate the periodicity has also been severely criticized, to the point that cyclicity is not accepted by many paleaontologists. Defining and dating mass extinctions are still major problems.

Despite this doubt, astronomers have attempted to find possible reasons to explain periodic mass extinctions, assuming that they were caused by meteorite impact (Weissman, 1990a, b). Two possibilities are related to the Oort cloud of comets, a shell of comets that is postulated to exist around the sun at tens of thousands of times the earth-sun distance, containing 1 million billion comets. The Oort cloud has never been observed but its existence can be inferred from the orbits and frequencies of long period comets. One of the hypotheses for the apparent cyclicity of mass extinctions is that an undiscovered companion star to the Sun, called Nemesis, passes through the Oort cloud every 26 Ma and sends a shower of comets towards Earth. A second theory is that the Sun's oscillation across the central plane of the Milky Way (the galactic plane) leads to periodic encounters with Giant Molecular Clouds that might contribute directly to environmental disturbances, as well as perturbing the Oort cloud (Yabushita and Allen, 1997). A third possibility is that an as-yet undiscovered planet beyond Pluto periodically disturbs a disk of comets that may exist there. None of these theories has been thoroughly demonstrated.

In summary it should be said that the evidence for periodicity of extinction is not strong because of difficulties in dating extinction events and in defining them - as we have seen from the Signor Lipps effect. Furthermore, all the astronomical theories for periodicity can be strongly criticized, and firm links between extinction and impact can not be made for most so-called mass extinctions. The important conclusion, as emphasised by the Shoemakers, is that at least the 65 Ma and probably the 34 Ma mass extinctions are clearly associated with impacts.

Mass extinctions, whatever their causes, are followed by diversification of new species, since large niches, or even holes, in ecosystems are suddenly created for organisms to fill. It can be argued, therefore, that the flux of impacting bodies on Earth has been instrumental in determining the rate of evolution of life on Earth, possibly augmenting it considerably.

Did life arrive on Earth on a meteorite ?

In 1996, a group of scientists reported that they had discovered biogenic materials and microfossils in a meteorite that was found in Antarctica (McSween, 1997). The composition of the meteorite clearly demonstrates that it came from Mars. This announcement was greeted with astonishment and incredulity throughout the world. One scientist stated: 'If the hypothesis is confirmed, it will rank amoung the great discoveries of all time.' That 'if' reveals a whole string of serious difficulties with the initial report. For a start, the organic matter need not have a biological source. Secondly, there is some evidence that it was derived by contamination with Antarctic ice meltwater, or even by laboratory contamination. The quantities of organic matter involved are so small that contamination is always a serious risk in this sort of investigation. Other criticisms are that the purported microfossils are too small to be viable (they are 30 to 150 nm in size - smaller than any terrestrial nanofossils), and finally that the atomic scale structure of the crystals includes types of lattice defects that are incompatible with organic growth.

Despite the knowledge from studies of other meteorites that pre-biotic organic molecules arrive on Earth on meteorites, the hypothesis of life on the Martian meteorite looks doubtful, although the idea of life arriving from space on meteorites has been promoted, without any firm evidence, for some time. Is it also relevant to point out that the results from this research were published just as NASA were planning the Mars exploration program and seeking support for this effort ?

Future Meteorite Impacts on Earth

In March 1989, the previously unknown asteroid 1989FC passed within 700 000 km of the Earth. This distance is less than twice the distance to the Moon, and the proximity of the asteroid's path caused some initial alarm. Meteorites of all sizes will certainly continue to arrive on Earth. The prospect of a Cretaceous-Tertiary sized impact is chilling. This event released ten orders of magnitude more energy than the atomic bombs dropped on Japan at the end of the second world war: not ten times more, but ten orders of magnitude more ! When will this happen again ? The last major mass extinction was 34 Ma ago; longer ago than the claimed periodicity in extinctions. The real answer is that no-one knows when the next major impact will occur, but can I quote from an article entitled 'Cosmic collisions and galactic civilizations' by Ostro and Sagan (1988): 'Sooner or later human civilization must confront the asteroid / comet collision hazard or become extinct'.

Conclusion

Catastrophism or Deeper Impact Uniformitarianism

How curious it is that the new knowledge I have described to you raises one of the oldest debates in the philosophy of Earth science: that between Uniformitarianism and Catastrophism. I would like to suggest that although meteorite impacts have evidently caused major catastrophies on earth, they are not a manifestation of Catastrophism in the sense of the underlying philosophy. Rather, they are events that have happened in the past and will do so in the future. The flux of material in space that we observe at present allows us to extrapolate back in time to interpret the record of the rocks, in true Uniformitarian fashion. The collision of Shoemaker Levy 9 with Jupiter was merely a dramatic, but unecesssary, confirmation of this principle. I have chosen to talk about the effects of meteorite impacts on earth and on earth science not because of the recent release of two popular films on the subject, but because I hope to have shown you that it is one of the most fascinating and far-reaching branches of earth science today.

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