deriding the fear of comets and entially making light of the cosmos, eteenth-century science created a nate of opinion in which geological formitarianism and Darwinian natural ection could be seen as the inevitable, nbined explanation of evolution on Earth. s explanation has been in serious iculty since the dramatic discovery ten rs ago of a huge global concentration of mic material deposited at the time of the ious dinosaur extinction. Astronomers, physicists and Earth scientists generally now joining together to work out a new ader picture of our celestial and estrial environment involving tastrophic events, which may lead us to inge completely our understanding of the nner in which biological evolution urs. This new understanding, once tled, can be expected to have a quite found influence, affecting not just ence but most aspects of human affairs well. The nature of the physical evidence l many of the scientific arguments rently being deployed are explored here the first time in a series of semi-technical ers for general readership, which were sented at a gathering of invited experts he field during the 1988 Meeting of the tish Association for the Advancement of ence in Oxford.

UNIFORMITARIANISM AND THE RESPONSE OF EARTH SCIENTISTS TO THE THEORY OF IMPACT CRISES

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Summary. The doctrine of uniformitarianism strongly influences the way Earth scientists view the evolution of this planet, through a tradition which uses the modern world as a model for the past, assumes gradualistic changes, and shuns catastrophic explanations. Yet Gould's analysis of uniformitarianism shows that it is a confused mixture of two ideas. One of these ideas, "methodological uniformitarianism" is merely a reformulation of the basic assumption of scientific methodology. The other idea, "substantive uniformitarianism", or gradualism, is simply wrong. Internally consistent evidence now supports a temporal correlation of large-body impact with the mass extinction at the Cretaceous-Tertiary boundary. The past rate

of large impacts on the Earth is in good agreement with the rate predicted from observations of orbiting objects. Large-body impacts are not *deus ex machina* explanations; they are inevitabilities. Yet because of the influence of uniformitarianism, many geologists and paleontologists prefer to explain mass extinctions by gradualistic mechanisms which require unlikely combinations of unrelated causal events. Earth science is now at a point where it can no longer afford to be shackled by a dogma of the nineteenth century. Although many Earth processes may in fact be gradualistic, others definitely are not. Strict uniformitarianism should be relegated to the status of a corollary to Occam's razor, and we should be prepared to accept the conclusions to which our evidence drives us.

The content of uniformitarianism

Since 1980, a great deal of physical and chemical evidence has been found to support the hypothesis that a large extraterrestrial body collided with the Earth at the time of the Cretaceous-Tertiary boundary, about 65 million years ago, and was coincident with widespread biological mass extinction at that time (Alvarez *et al.* 1980, Ganapathy 1980, Smit & Hertogen 1980, Kyte *et al.* 1980, Smit & Klaver 1981, Orth *et al.* 1981, Alvarez 1983, Luck & Turekian 1983, Montanari *et al.* 1983, Bohor *et al.* 1984, Alvarez 1986, Raup 1986, Hsu 1986, Alvarez 1987, Izett 1987, Muller 1988).

In the past three years, several articles (Sloan *et al.* 1986, Patrusky 1986-1987, Archibald 1987, Courtillot & Cisowski 1987, Hallam 1987, Officer *et al.* 1987, Crocket *et al.* 1988) have presented objections to the impact hypothesis. These recent articles favour the view that the Cretaceous-Tertiary mass extinction was not sudden, and was the result either of gradual changes in sea-level, ocean chemistry or climate, or an unusual pulse of volcanism. Although one or another of the present authors could argue on technical grounds with the data and conclusions in these papers, we think it may be more interesting to view these articles in perspective, as a case study in the philosophy of Earth history.

A careful reading of the anti-impact articles shows that they contain only weak arguments which purport to contradict the impact explanation for the terminal-Cretaceous mass extinction. The logic underlying the papers is, rather, that it is simply not *necessary* to invoke an impact, because the relevant physical, chemical, and paleontological data can also be explained by other phenomena, such as volcanism or a sea-level fall.

Why should the view that there is no *necessity* to invoke an impact carry any weight? Most Earth scientists will recognize the attempt to minimize the role of impacts in Earth processes as a manifestation of the doctrine of uniformitarianism. This term refers to a time-honoured but vaguely defined view that the present is the key to the past and that explanations of Earth history by gradual processes are preferable to explanations invoking sudden, and typically violent, processes. Gould (1965) has analyzed the intellectual content of uniformitarianism and has shown that it has two main formulations: "substantive uniformitarianism" is the notion that no geologic process has ever proceeded at a different rate in the past than it does now (a clearly false assumption), whereas "methodological uniformitarianism" is the refusal to accept miraculous explanations (an unnecessary admonition at this stage in the development of science).

It is a widespread view among geologists that uniformitarianism, as developed by Charles Lyell in the first half of the nineteenth century, provided an essential antidote to biblically inspired *ad hoc* catastrophism in the eighteenth and nineteenth centuries. However, Gould (1984, 1987) has also shown that this interpretation does injustice to the scientific catastrophists. He also points out that Lyell used the rhetorical trick of giving the same name to the very different concepts of substantive and methodological uniformitarianism, in order to push a rigidly gradualistic view of geological processes which can now be seen to be far from correct. Lyell was successful and uniformitarianism has subsequently been passed along from generation to generation as a cultural heritage of geology and paleontology. In our view, the uncritical acceptance of the doctrine now interferes with the rational development of the Earth sciences. Shea (1982) has shown in detail how this interference operates, in an essay entitled "Twelve fallacies of uniformitarianism".

Thus, methodological uniformitarianism, in its modern form, basically boils down to Occam's Razor (Shea 1982). It plays a useful role in the conservative approach scientists must take to unorthodox ideas, many of which will succumb to the testing process. But fallacies embedded in Lyellian uniformitarianism have delayed the acceptance of important advances in geology, particularly with regard to the role of catastrophic processes. One example is the case of the 'catastrophic flood' hypothesis for the origin of the Channeled Scablands of eastern Washington, proposed long ago by Bretz (1923), and not accepted until the 1950s (Gould 1984).

Catastrophic impacts : a geologic process

At the present time, the influence of substantive uniformitarianism is seen in the reluctance of many geologists to accept impact as a significant and inevitable geologic process. Impact structures on the Earth have commonly been attributed to unexplained "cryptoexplosions", and they still seem to be of little interest to a large segment of the general geological community. As one of us has written, "Most geologists just don't like the idea of stones the size of hills or small mountains falling out of the sky" (Shoemaker 1984).

Similarly, the reality of mass extinctions is contested by a few scientists who, following Lyell's view (Gould 1987), interpret apparently abrupt evolutionary events as evidence for gaps in the stratigraphic record. Thus it is little wonder that attributing a mass extinction to an impact provokes discomfort among many Earth scientists, and a search for alternative explanations is a natural response. If the heritage of uniformitarianism leads one to doubt the importance of impacts, one's scientific response to the evidence for a major impact at the Cretaceous-Tertiary boundary must be to show (1) that the evidence does not fit an impact scenario, and/or (2) that it does fit some other cause or causes.

Since no one has maintained that the primary lines of evidence (*i.e.* the anomalous iridium and other noble metals occurring with chondritic or Solar System abundance ratios, microspherules, shocked minerals and lithic fragments, osmium isotopic ratios, and worldwide distribution of at least the better studied of these features) are incompatible with a major impact, skeptics have argued that deposition of these features continued too long to have been due to an "instantaneous" impact event. At one time it was argued (Officer & Drake 1983, Payne *et al.* 1983) that the Cretaceous-Tertiary boundary iridium anomaly was deposited in some areas during a time of normal geomagnetic polarity, and thus could not be synchronous with the iridium deposition in other areas which are well documented as having occurred during a time of reversed polarity. But after the studies suggesting occurrence of the iridium anomaly in a normal–polarity zone were shown to have been incorrect (Alvarez *et al.* 1984, Butler & Lindsay 1985, Shoemaker *et al.* 1987), that argument disappeared. The approach now (Courtillot & Cisowski 1987, Officer *et al.* 1987) is to argue that anomalous iridium deposition continued for as much as 10^4–10^5 years, within the 500,000–year reversed polarity interval 29R, which contains the extinction event. This argument has been supported by citing those stratigraphic sections in which anomalous iridium is spread over the greatest stratigraphic interval. However, spreading out of a narrow peak into a broad one is a natural effect of sediment disturbance by burrowing organisms, redeposition by currents, and chemical remobilization. We argue that it is more difficult to concentrate an originally broad distribution into a narrow spike than it is to smear out a sharp one.

The second necessity for those arguing against an impact is to show that the evidence is compatible with some other mechanism. For example, strongly shocked clasts of quartz, feldspar, quartzose sedimentary rocks and granite have been found in the Cretaceous-Tertiary boundary clay (Bohor *et al.* 1984, Bohor *et al.* 1987, Izett & Bohor 1987). Individual quartz grains have as many as seven sets of well-developed shock lamellae, are indistinguishable from shocked quartz found at known impact craters (French & Short 1968), and represent one of the strongest lines of evidence for an impact. In a recent paper, Carter *et al.* (1986) claim to have found shocked quartz grains in volcanic ejecta. However, the geologists who have studied the shocked minerals and rock clasts from the Cretaceous-Tertiary boundary layer (Bohor *et al.* 1987; Izett & Bohor 1987) have shown that these grains are very different from the quartz grains found in volcanic rocks by Carter. The occurrence of the shocked lithic fragments in the boundary layer, in particular, argues against a volcanic origin. The supposed shocked quartz grains from volcanic ejecta contain only single sets of lamellae, a feature also found in quartz which has undergone slow, tectonic deformation. Even Carter appears to agree that the supposedly shocked quartz he has studied from volcanic ejecta differs from the quartz of the Cretaceous-Tertiary boundary and from impact craters, which all workers agree have been shocked (Kerr 1987).

A problem faced by the authors contesting the hypothesis of a major impact at the Cretaceous-Tertiary boundary is that even if a non-impact explanation can be found for each line of critical evidence, the same non-impact explanation does not seem to work for all of them (Alvarez 1986). To explain all the features of the Cretaceous-Tertiary boundary, Officer *et al.* (1987) requires two different kinds of volcanism. Violent, explosive volcanism is offered to explain the shocked quartz although, as noted above, it is probably an insufficient explanation. A great outpouring of basaltic lava is offered to explain the microspherules and iridium anomaly (although measured basalts are much lower in iridium than the peak values observed in the Cretaceous-Tertiary boundary). Major violent eruptions are produced by magmas high in silica and extremely low in iridium, whereas the highest iridium-bearing magmas are basaltic. Basalts have low silica content, are seldom quartz bearing, and are not known to give rise to cataclysmic eruptions of the type associated with highly silicic magmas. There is virtually no geographic overlap between flood basalts and major violently eruptive silicic volcanic centers. So Officer *et al.* (1987) propose a general increase of world volcanism at the time of the Cretaceous-Tertiary boundary, citing a few local areas where such an increase is inferred. This increase is not general, however, as Kauffman (1985), for example, has shown that the volume of volcanic ash deposited in the Western Interior Basin of North America in the Maastrichtian (latest Cretaceous) is the lowest recorded for any part of the Cretaceous in this area.

Further compounding the difficulties with incompatibility of causes, Officer *et al.* (1987) attribute much of the biological extinction event to a sea-level fall at the time of the suggested volcanic maximum. However, a global volcanic pulse suggests rapid mantle convection, which implies rapid sea-floor spreading, which in turn implies an increased volume of the mid-ocean ridges because of the lower density of the hot material they incorporate. This should yield a sea-level rise, not a fall (Pitman 1978). We conclude that the suggested styles of volcanism are incompatible in a single volcanic region, and that a world-wide pulse of both kinds of volcanism is neither documented nor compatible with a sea-level fall.

Eustatic sea-level fall and large-scale volcanism would be expected to continue over a substantial time interval, probably exceeding a million years, and to have produced selective extinctions, perhaps concentrated in the regions of active volcanism. However, the main extinction event, which coincides with the iridium anomaly at the Cretaceous-Tertiary boundary, was abrupt (probably 1-100 years) and affected ecologically and genetically diverse taxa (*i.e.*calcareous and siliceous plankton, diverse tropical to temperate molluscs, brachiopods, bryozoa, foraminifera, vertebrates and angiosperms), including groups at the evolutionary peak of their development (planktic foraminifera, nannoplankton and shallow-water molluscs). The rates and patterns of extinction across the Cretaceous-Tertiary boundary do not fit the predictions of the volcanic or sea-level mechanisms.

In essence, Officer *et al.* (1987) do not argue strongly against an impact, but they consider it unnecessary. Their proposed alternative, however, appears to us to be an unlikely combination of causes not known to have occurred together in the Earth's past. On the other hand, the impact hypothesis is compatible with all the known data, and impacts are events that are known to occur – impact craters are found on all the rocky planets and satellites, including the Earth and the Moon. About 80 Earth-crossing asteroids have been discovered telescopically, including objects up to about 10 km in diameter – the size of the proposed Cretaceous-Tertiary impactor (Wetherill & Shoemaker 1982, Shoemaker 1983, Shoemaker & Wolfe 1986, Shoemaker *et al.* 1988). Our present catalogue of impacting bodies, moreover, is very incomplete; on the basis of the rate of discovery in systematic surveys, Shoemaker *et al.* (1979) estimated that the population of Earth-crossing asteroids larger than 1 km in diameter is about 20 times greater than the set now known. The total rate of collision of these objects with the Earth is consistent with the geologic record of impact cratering over the last 120 Myr on the carefully studied shield areas of North America and Europe (Grieve 1984). Comet nuclei must also be included in the list of known impactors, and the recent spacecraft missions to Halley's Comet (Keller *et al.* 1986, Sagdeev *et al.* 1986) demonstrated once and for all that solid nuclei up to 10 km in diameter, and probably much larger, occur on Earth-crossing orbits. We cannot continue to exclude large-body impacts from the list of known geological processes.

Conclusion

Echoing the view of Goodman (1967) and Shea (1982), one of us has argued that "Perhaps it is time to recast uniformitarianism as merely a sort of corollary to Occam's razor, to the effect that if a set of geological data can be explained by common, gradual, well-known processes, that should be the explanation of choice, but that when the evidence strongly supports a more sudden, violent event, we will go where the evidence leads us" (Alvarez 1986). We submit that impact and the resulting environmental disturbances provide a far more likely causal mechanism for the Cretaceous-Tertiary mass extinction than a combination of apparently incompatible geological events. The impact theory is in accord both with Occam's Razor (uniformitarianism in its modern form) and with the general spirit of uniformitarianism, understood in the sense that processes such as impacts, which are known to occur or are statistically predictable, are better explanations for events in Earth history than are unknown mechanisms and *ad hoc* combinations of incompatible events.

Although we are persuaded that a large-body impact played a central role in the terminal-Cretaceous mass extinction, we are also of the opinion that the evidence argues for a more complicated story than a single large impact causing a single great extinction. Students of large-body impacts and of mass extinction have found both reason to predict, and evidence to support, multiple impact events, complex environmental effects, and a complicated fabric of extinction which differs from one mass extinction to the next (Perch-Nielsen *et al.* 1982, Lewis *et al.* 1982, Muller 1985, Glass *et al.* 1985, Kauffman 1986, Muller & Morris 1986, Shoemaker & Wolfe 1986, Hut *et al.* 1987, Keller *et al.* 1987). We believe that science has much more to gain from an open-minded exploration of the evidence for catastrophic events in Earth history than from a continuing insistence on fitting all our data into a nineteenth-century uniformitarian viewpoint.

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CATASTROPHISM IN GEOLOGY

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Summary: An historical survey is presented of ideas relating to the concept of "catastrophism" in geological studies during the last two centuries. It is noted in particular that the opposing concept of "uniformitarianism", in which there is assumed to have been an overall constancy of geological processes through time so that there is no need to invoke catastrophic change, is now considered rather extreme. During the nineteen sixties and seventies, a neo-catastrophist viewpoint has increasingly emerged in various branches of geology. Mass extinctions and their possible causes — bolide impact, climate, volcanism and sea-level change for example — are each considered in the context of this developing framework.

Catastrophism in the Nineteenth Century

Geology began to emerge as an independent science at the transition from the eighteenth to the nineteenth century. If prime credit can be directed to any one person in particular it was the German mineralogist Abraham Werner rather than the Scotsman James Hutton, despite the claims of generations of British geologists. Werner's "neptunean" system involved far more than the supposed aqueous origin of basalt; it was the foundation of historical geology and proved