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What Next?
Current Problems and Future Investigations

8.1. IDENTIFICATION OF NEW IMPACT STRUCTURES

Despite the apparent abundance of impact structures (~150 now known), the terrestrial record remains both incomplete and biased, and it is essential to continue the search. The present number of known impact structures is still ≤25% of the total presumably still preserved on the land areas of the Earth (*Trefil and Raup,* 1990; *Grieve,* 1991). Even worse, the processes of geological destruction active on the Earth have strongly biased the observed distribution. Most known impact structures have ages of <200 Ma, and small, easily eroded structures are strongly underrepresented in the record (*Grieve,* 1991; *Grieve and Pesonen,* 1992, 1996).

The identification of more impact structures, accompanied by accurate age-dating, is essential to improve this database. With better data, we can explore some important and unanswered questions: What is the actual impact rate of various-sized extraterrestrial objects on Earth? Is the bombardment rate variable, nonrandom, or even periodic? What are the relative importances of asteroids and comets as impacting bodies? With a larger suite of impact structures, it will also be possible to identify well-preserved examples that can provide detailed information about cratering mechanics and geological effects. Finding new impact craters is also a challenge to our abilities and our imaginations: How much of the preserved impact record on Earth can we discover with the techniques we now possess, and where are the pieces of this record located?

Current searches for new impact structures are now especially active in Fennoscandia (*Pesonen and Henkel,* 1992; *Pesonen,* 1996), Africa (*Koeberl,* 1994b), and Australia (*Glikson,* 1996b; *Shoemaker and Shoemaker,* 1996). An important component of these searches has been the discovery of subsurface impact structures from geophysical data (*Corner et al.,* 1997; *Hart et al.,* 1997; *Gostin and Therriault,* 1997). Until recently, the sea floor has been largely ignored in the search for impact structures, and only a few submarine impact structures have been identified (e.g., *Jansa and Pe-Piper,* 1987; *Poag,* 1996; *Dypvik et al.,* 1996). The special problems of submarine impact structures are finally receiving attention. There is new interest in searching for impact structures beneath the present oceans, and scientists are beginning to explore the unusual geology of submarine impact events in a few impact structures that formed underwater but are now accessible on land (*Therriault and Lindström,* 1995; *Lindström et al.,* 1996). Even so, all the submarine structures so far identified have formed on the shelf areas of adjacent continents. The deep ocean basins, which probably received about three-quarters of the projectiles that struck Earth in the last ~200 m.y., still remain to be explored, although evidence for one recent small impact in the South Pacific has been discovered (*Gersonde et al.,* 1997). Amid this current activity on sea and land, the search for the source crater that produced the Australasian tektite strewnfield remains a prominent and nagging problem for the future.

8.2. IMPACT EVENTS AND EXTINCTIONS

A firm connection between one large impact event and one major biological extinction has now been solidly established between the Chicxulub structure (Mexico) and the K/T event (*Alvarez et al.,* 1980; *Sharpton et al.,* 1992; papers in *Ryder et al.,* 1996; *Alvarez,* 1997). Research on the K/T problem has now largely turned away from debating the existence of the impact and is now focused on closer studies of the consequences. Paleontologists are studying the finer details of the extinction itself: the duration of the overall event, the relative timing of the disappearances of different species, and the various environmental stresses and "kill mechanisms" implied by the geological record.

At the same time, a major geological effort, involving geophysical surveys and new drilling projects (e.g., *Sharpton et al.,* 1993, 1996b; *Morgan et al.,* 1997), is concentrating on the Chicxulub structure itself, to determine more accurately the size of the structure, the energy released by the impact, and the amounts of volatile materials (water vapor, CO_2 and SO_2) released from melted and vaporized target materials (ocean water, limestones, and evaporites) (papers in *Ryder et al.,* 1996; *Pope et al.,* 1994, 1997; *Yang and Ahrens,* 1998). These data are needed to accurately estimate the global environmental stress and to complement the paleontological studies of the extinction. In addition to its tie to the K/T extinction, the Chicxulub structure itself, because of its relative youth and immediate burial after formation, is the best-preserved terrestrial impact structure of its size discovered to date, and the geological studies will also yield a wealth of information about the cratering mechanics and geological effects involved in such large, rare impact events.

Despite the strength of the connection between Chicxulub and the K/T extinction, it has not yet proved possible to establish a similar firm link between an impact event and any of the half-dozen or so other major extinctions recorded in the last 700 m.y. However, there are growing indications of a link between impact events and the lesser extinction observed about 35 m.y. ago near the Eocene-Oligocene boundary (*Montanari et al.,* 1993; *Clymer et al.,* 1996; *Langenhorst and Clymer,* 1996; *Glass et al.,* 1998). All the essential ingredients seem to be present: a significant extinction, a layer of impact debris (including microtektites) at the boundary, and two candidate impact structures in the ≥90-km-diameter range: Popigai (Russia) (*Bottomley et al.,* 1997) and Chesapeake Bay (USA) (*Koeberl et al.,* 1996a). A layer containing shocked quartz has also been found at the older (205 Ma) Triassic-Jurassic boundary, a location also characterized by a major biological extinction (*Bice et al.,* 1992).

8.3. DISTAL IMPACT EJECTA

An important and unexpected resource for future studies of terrestrial impacts are the thin layers of distal ejecta that are distributed over continental to global distances from the impact site. In the past, it was considered unlikely that such thin deposits could be preserved in the geologic record, and little consideration was given to finding and identifying them. This attitude has changed drastically, chiefly as a result of studies at the K/T boundary, where the distinctive global ejecta layer from the Chicxulub impact structure was conclusively identified even before the structure itself was located. Distal ejecta layers have also been identified from other structures, e.g., Manson (Iowa) and Acraman (Australia), and it is now generally accepted that microtektite layers also represent distal ejecta.

Although only a few distal ejecta layers from particular structures have been identified so far, the potential importance of such layers has been increased by new methods of study and analysis. Layers of impact-crater ejecta can now be clearly distinguished from similar sedimentary or volcanic units (e.g., ash-fall beds) by the presence of such unique features as spherules, quartz PDFs, and iridium anomalies. Current geochemical techniques are sensitive and precise enough — even if delicate and time-consuming — to extract important information about the impact event from small particles, and it is possible, in many cases, to determine from a small sample of ejecta the age of the impact or the geochemical characteristics of the target rock involved.

Distal ejecta layers in the sedimentary record have a large and unexplored potential to provide critical insights into the impact history of the Earth (*Grieve,* 1997). Systematic identification of distal ejecta layers in long-duration sedimentary sections can yield independent estimates of the impact rate over geologic time. Ejecta layers linked to known large impact structures can improve our understanding of the crater formation process and the areal extent of the environmental effects. In some cases, it may be possible to obtain good age-dates on impact events from the stratigraphic ages of the ejecta. Some individual ejecta layers may also indicate the existence of unsuspected and undiscovered impact structures, as was the case with the Chicxulub structure and for a Late Devonian impact event recently recognized in the western USA (*Leroux et al.,* 1995).

8.4. CARBON CHEMISTRY IN THE IMPACT ENVIRONMENT

The uniqueness of the high-pressure shock-wave environment below the developing impact crater has long been appreciated, but there are recent indications that equally unique conditions above the impact point also produce unusual and lasting effects. At the moment of impact, a high-temperature vapor plume, with temperatures of thousands of degrees, expands outward and upward from the impact point (*Melosh,* 1989, pp. 68–71). This plume, as it interacts with the atmosphere, plays a major role in ejecting material from the crater to great distances (e.g., *Alvarez et al.,* 1995). This extreme environment also produces a variety of unusual and still-baffling chemical changes.

Carbon compounds in impactites have recently revealed a variety of exciting and puzzling features, some of which may reflect the instantaneous high-temperature environment within the vapor plume. Diamonds have long been known to be a shock-metamorphic product in carbon-bearing target rocks (e.g., *Masaitis,* 1998; *Masaitis et al.,* 1972; *Koeberl et al.,* 1997c), but more recent studies have discovered tiny **nanodiamonds**, unrelated to preimpact target graphite, that apparently formed in the vapor phase and then were deposited in suevite breccias (*Hough et al.,* 1995) and in ejecta at the K/T boundary (*Carlisle and Braman,* 1991; *Hough et al.,* 1997).

A different form of carbon, **fullerenes**, has also been discovered in terrestrial impact environments. These recently discovered "soccer-ball" carbon molecules (e.g., the C_{60} molecules called "buckyballs") have attracted attention because of their stability and unusual chemical characteristics (e.g., the ability to "cage" other atoms) (for background and details, see *Aldersey-Williams,* 1995). Because of their stability, it has been suggested that fullerenes could form in the outflows from high-carbon stars and could be common in both the interstellar medium and in meteorites, although fullerenes have not yet been conclusively identified in either location. However, fullerenes have been identified in the K/T ejecta layer (*Heymann et al.,* 1994) and in the carbonaceous Onaping Formation, an impact breccia at the Sudbury structure (Canada) (*Becker et al.,* 1994, 1996). The presence of fullerenes in such impact-produced deposits, their possible extraterrestrial origin, and the implications of their presence for the origins of life on Earth have focused considerable multidisciplinary attention, particularly from exobiologists, on impact processes in general and Sudbury in particular.

Carbon in impact structures, and its behavior during impact events, is an area of research that currently contains a few exciting observations, enclosed in a large number of unanswered questions. Carbon is generally absent in impact structures; impactites with significant carbon contents (>0.5 wt%) are known only from Sudbury (Canada) (*French,* 1968b; *Avermann,* 1994) and Gardnos (Norway) (*French et al.,* 1997). The source(s) of this carbon has not been established; possible sources are the projectile (e.g., carbonaceous chondrite meteorites or comets), Earth's atmosphere, or yet-unrecognized carbonaceous target rocks. It is also possible that the carbon has been introduced into the impactites during later metamorphism. Identifying the sources of carbon in these impactites, and distinguishing between impact-related and postimpact carbon, requires careful sampling and sophisticated analyses in the future.

The problem of carbon in the impact environment leads directly to large and longstanding questions about the origin of the solar system, the formation of planets, and the origin and history of life on Earth. Are any carbon and organic molecules present in the incoming projectile destroyed by the impact event, or can they survive to contribute to the subsequent origin of life? What does the formation and survival of diamonds and fullerenes in impact events tell us about the physical conditions in the vapor plume or the nature of Earth's atmosphere at the time of impact? Impact structures, especially those with carbonaceous impactites, preserve the results of unique natural experiments in prebiotic chemistry and the behavior of carbon compounds under extreme conditions. Interdisciplinary studies to explore these problems should be an important part of future impact studies.

8.5. POSTIMPACT PROCESSES AND EFFECTS

Past research on impact events has concentrated on the formation of the impact structure and its immediate effects: shock-metamorphic features, generation of impact melts, and biological extinctions. It is now recognized that the large amounts of mechanical and thermal energy deposited in the impact site produce longer-term effects, and there is new interest in identifying and studying impact effects that persist during the period (10^2–10^6 yr) in which normal geological processes resume in the region affected by the impact event.

The thermal energy deposited in an impact structure as shock heating and impact-melt formation can produce hydrothermal activity and related ore deposits similar to those that result from more conventional geological processes. Such postimpact activity is frequently expressed in the secondary alteration of the impact melts themselves (*Dence,* 1971; *Newsom et al.,* 1986; *McCarville and Crossey,* 1996). However, in larger structures, the combination of large volumes of melt and extensive hydrothermal circulation may produce new sedimentary deposits and associated ore bodies, e.g., the Vermillion Formation at Sudbury (Canada) (*Grieve and Masaitis,* 1994).

The postimpact sediments that fill some impact structures may preserve a record of the important transition between impact-related effects and postimpact geological history. At the buried Chicxulub structure (Mexico), the thick crater-fill deposits have a special importance because they may preserve the immediate postimpact history of waning impact effects and biological recovery after the K/T event. At other impact sites, crater-fill sediments may preserve the only available long-term record of postimpact geological and environmental processes that originally affected a much wider region (*Beales and Lozej,* 1975; *Partridge et al.,* 1993; *Grieve,* 1997).

The overall shape and general geological characteristics of impact structures have been well established by extensive research, and these features can serve as important markers for determining postimpact erosion and deformation (*Grieve,* 1991). This knowledge is also important for identifying and reconstructing highly deformed impact structures, such as Sudbury (Canada) (*Wu et al.,* 1994), in which the presently preserved feature may represent only a fraction of the size of the original impact structure (*Therriault et al.,* 1997).

8.6. PETROGENESIS OF IGNEOUS ROCKS: IMPACT MELTS

The impact melt rocks preserved in terrestrial impact structures represent unique, important, and virtually unstudied laboratory experiments in the formation, emplacement, and crystallization of igneous rocks. Future studies of impact melts can provide unique insights into these longstanding geological problems. Impact melt bodies occur in a range of sizes, from small and rapidly cooled pods and dikes up to the huge Sudbury Irruptive with its associated ore deposits. These bodies have formed, nearly instantaneously, in a single melting event, from surrounding target rocks that can generally be sampled and characterized. The largest and best-preserved impact melt bodies are found as sills in the crater-fill deposits, and they have cooled uniformly without any addition of new magma. Their history and cooling environment can be well constrained by information about the crater shape and the impactite deposits associated with them. As igneous rocks, impact melts provide a degree of simplicity, information, and context that is only rarely found in endogenic igneous rocks, and study of them will provide fundamental information on all igneous rocks.

Detailed comparative studies of terrestrial impact melt rocks and endogenic igneous rocks can also improve current models for impact crater formation and impact melt generation. Is the current assumption that impact melt bodies are homogeneously mixed target rock really correct at all scales? Is there time for chemical and mineralogical differentiation in large bodies of impact melt (e.g., the Sudbury Irruptive), or do the systematic variations observed have some other cause? What can terrestrial impact melts tell us about the origin and chemistry of the very large bodies of impact melt associated with the largest lunar impact basins?

8.7. IMPACTS AND THE EARLY EARTH

Even the largest and oldest known terrestrial impact structures [Sudbury (Canada) and Vredefort (South Africa)] are only about 2 b.y. old and were only about 200–300 km in diameter when they formed. They are therefore both small and young by comparison with the earlier history of impact events in the solar system. Preserved impact features on the Moon, Mercury, and other planets exceed 1000 km in diameter and are >4 b.y. old, and the ancient and heavily cratered surfaces of the Moon and other planets show that this period was a time of intense bombardment, when impact rates were hundreds to thousands of times the present low values (Fig. 1.13) (*Taylor,* 1975; 1982, Chapter 3; 1992, Chapter 4; *Hörz et al.,* 1991; *Spudis,* 1993).

Earth could not have escaped the heavy bombardment of extraterrestrial objects at this time, and the present scarcity of old and large terrestrial impact structures reflects the continuous geological destruction and recycling of old terrestrial rocks. We therefore face a major problem in exploring the impact history of Earth: Just when impact events become more frequent, larger, and potentially more important (≥3.8 Ga), the available record of these events becomes increasingly destroyed. Are Sudbury and Vredefort the largest and oldest impact structures that we can find preserved on Earth? Or can we find the traces of larger and more ancient impact events and understand their effects?

The evidence from other planets leaves no doubt that large impacts on Earth were not only a major, but in fact the dominant, process during early geologic time (≥3.8 Ga). Comparisons with the lunar highlands (*Grieve,* 1980; *Grieve et al.,* 1990) suggest that as many as 200 impact basins ≥1000 km in diameter may have formed on Earth during this period, accompanied by exponentially larger quantities of smaller structures. Plausible geological effects of these catastrophes include the formation of huge volumes of impact melts, the triggering of widespread endogenic volcanism from beneath a thin Archean crust, and the creation of early continental nuclei (*Frey,* 1980; *Grieve,* 1980; *Glikson,* 1993, 1996a). The effects above ground could be equally disastrous. Large impacts could blast away existing atmospheres and then replace them with water and other volatiles carried in the projectiles themselves. The development of life on Earth could have followed an intermittent path in which existing life forms were destroyed by large impacts and new ones formed from the organic compounds brought in by the projectiles. Even in relatively recent times (≥2.5 Ga), sporadic large impacts could have produced major changes in the igneous and tectonic histories of Earth (*Glikson,* 1993, 1996a).

The search for traces of such events faces several problems. The old rocks that would preserve them are scarce and often highly metamorphosed, making it difficult to distinguish impact effects from the results of normal geological processes (e.g., *Weiblen and Schulz,* 1978). A second problem is uncertainty about what very large impact structures would look like, even if well preserved. Larger impact structures (D > 200–300 km) will generate relatively larger amounts of melt, producing a wide, relatively shallow structure dominated by melt rather than by more familiar impactite breccias (*Grieve and Cintala,* 1992; *Cintala and Grieve,* 1998). Such structures might easily be removed by erosion or mistaken for endogenic bodies such as sills and lopoliths. The possibility that the well-known Bushveld Complex (South Africa) might be such a melt-rich impact structure (*Rhodes,* 1975) has so far proved to be negative (e.g., *French,* 1990a), but the debate and the searches go on.

Despite these difficulties, it may still be possible to recognize the traces of ancient impact events. Distinctive shock features such as shatter cones and pseudotachylite breccias can be preserved in even highly metamorphosed rocks, as can distinctive geochemical signatures (e.g., iridium anomalies) in breccias and impact melts. It may also be possible to recognize distal ejecta units from ancient impact events, and such an origin has been proposed for the unusual spherule layers found in >3-b.y.-old rocks of the Barberton Mountain Land (South Africa) (*Lowe and Byerly,* 1986; *Lowe et al.,* 1989) and in 2.6-b.y.-old sediments in Australia (*Simonson,* 1992; *Simonson and Davies,* 1996; *Simonson et al.,* 1997). Definite shock-metamorphic effects have not yet been found in these spherule beds, and their origin is still debated (e.g., *French,* 1987; *Koeberl et al.,* 1993; *Koeberl and Reimold,* 1995), but the mere preservation of such distinctive units in such ancient rocks is an encouraging sign for future searches.

A related possibility, speculative and exciting, is that even thicker (10–100 m) layers of ejecta from large impact structures may be preserved among the long-studied formations of **diamictites**, unusual breccias currently regarded as the products of glacial activity or other unusual sedimentation processes (*Oberbeck et al.,* 1993; *Rampino,* 1994). These units are an important target for future searches, and they should be examined anew for shock-metamorphic effects (e.g., *Reimold et al.,* 1997b).

The increasing importance of meteorite impacts in Earth history, the growing recognition of preserved impact effects in the geological record, and the ease with which impact events can be recognized by their shock-metamorphic effects have combined to show geologists the importance of new searches in the field. In the future, as geologists discover more ancient rocks, or as they reexamine formations discovered long ago, the possibilities of impact — and the key signatures of impact events — should be kept in mind.

During the brief history of meteorite impact geology, all past predictions about the importance of impacts and the range of their effects have turned out to be inaccurate and unimaginative underestimates. Although a lot has been learned in the last couple of decades, there is no reason to expect that today's estimates will turn out to be any more accurate. We must now do what geologists have always done when suddenly faced with ideas that are new, exciting, poorly explored, and only dimly understood. We must take the new ideas out into the field and look at the rocks again.