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IMPACT PHENOMENA AS FACTORS IN THE EVOLUTION OF THE EARTH

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ABSTRACT

Large terrestrial impacts result in appreciable effects on the local geology and in regional seismic activity. Impact in recent geologic time, however, is not a significant global geologic process compared to many endogenic processes. This may not have been true in early earth history when the impact flux was considerably higher. It is estimated that 30-200 large impact basins could have been formed on the early earth. These large impacts may have resulted in extensive volcanism and enhanced endogenic geologic activity over large areas. Initial modelling of the thermal and subsidence history of large terrestrial basins indicates that they created geologic and thermal anomalies which lasted for geologically significant times. The role of large-scale impact in the biological evolution of the earth has been highlighted by the discovery of siderophile anomalies at the Cretaceous-Tertiary boundary and associated with North American microtektites. Although in neither case has an associated crater been identified, the observations are consistent with the deposition of projectile-contaminated high-speed ejecta from major impact events. Consideration of impact processes reveals a number of mechanisms by which large-scale impact may induce extinctions. Although impact has been largely ignored as a terrestrial geologic process, it is apparent that it must be considered in both the early geologic and more recent biologic evolution of the earth.

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INTRODUCTION

Data from bodies which have preserved portions of their earliest crusts, such as the moon, Mercury, Mars, and some of the Jovian and Saturnian satellites, indicate that impact cratering was a dominant process in early surface and upper crustal evolution. Although at a much diminished level, impact continues to influence the local geologic evolution of many bodies and, in particular, the surface evolution of bodies lacking an atmosphere. Ground truth data provided by terrestrial impact structures have played an important role in attempts to model impact phenomena. Geoscientists, however, have largely dismissed or ignored impact as a geologic process on the earth. This is understandable as endogenic activity has done much to erase the terrestrial record of impact. Nevertheless, approximately one hundred terrestrial hypervelocity impact structures, ranging up in diameter to ∿ 140 km, are currently recognized. This paper discusses some possible implications of impact for the evolution of the earth, with particular emphasis on early crustal and biological evolution.

TERRESTRIAL IMPACT CRATERS

Many of the details of the impact process can be found in papers in Roddy et al. (1977), Shultz and Merrill (1981), and references therein and need not be repeated. Rocks subjected to hypervelocity impact and thus to shock pressures above their Hugionot Elastic Limit, ∿ 5-10 GPa for crystalline rocks, are characterized by shock metamorphic effects. Details of shock metamorphic effects can be found in French and Short (1968), Markushev (1981), and others. They are the principal criterion for identifying terrestrial impact structures. Relatively small terrestrial craters have a bowl-shaped form, with a breccia lens of allochthonous material below the floor of the crater and a depth/diameter ratio of the crater in the autochthonous target rocks

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of 1/3-1/4. The breccia lens, which may contain a basal pool of impact melt, is the result of the inward collapse of the initial or transient cavity formed by excavation and displacement of the target rocks by the cratering flow-field. At diameters > 2 km in sedimentary targets and > 4 km in crystalline targets, the final crater is characterized by depth/diameter ratios of < 1/10 and an uplifted central core of shocked rocks forming a central peak and/or rings. The relatively shallow form is the result of uplift of the floor and collapse of the rim, which probably took place during and subsequent to transient cavity formation. The mechanisms generally considered responsible for modification are elastic rebound of the compressed floor and/or large-scale gravitational collapse of the transient cavity and surrounding area.

Summaries of the geology and geophysics of many terrestrial craters can be found in Dence et al. (1977) and Masaitis et al. (1980). In some instances, the unusual geologic environment produced by large impact structures has influenced the deposition and exposure of ore deposits; e.g., Ni-sulphides at the Sudbury structure (Morrison, 1982) and uranium at the Carswell structure (Johns, 1970). Significant reservoirs of hydrocarbons are also located within some structures; e.g., Boltysh (Yurk et al., 1975), Viewfield (Sawatzky, 1977), and Red Wing Creek structures (Brenan et al., 1975). Impact has a profound effect on local geology, disrupting the physical and chemical equilibrium of the target rocks and resulting, in some cases, in structures with lateral dimensions greater than the largest volcanic constructs. For example, the $\sim$ 100 km Manicouagan structure, Canada, resulted from the release of $\sim 10^{23}$ J of energy virtually instantaneously at one point on the earth's surface. This corresponds to 10^2-10^3 times the energy released annually by all earthquakes. Material originally several kilometers deep was uplifted to the surface, $\sim 10^3$ km^3 of the target rocks were melted, and the effects of the impact are visible over an area of 2×10^4 km^2 (Grieve and Head, 1983). One regional effect of large-scale impact will be seismic activity. The fraction of

impact energy converted to seismic energy is $\sim 10^{-4}$ and the relationship: $\log SE = 1.44\ (M) + 5.24$, where SE is seismic energy in Joules and M is surface wave earthquake magnitude (Båth, 1966), indicates that a Manicouagan-sized event would result in a magnitude 11 earthquake. Analyses of ground motions in nuclear explosions (Cooper, 1977) suggest that peak displacements of a few centimeters might be expected $\sim$ 1000 km from such an impact event.

IMPACT AND EARLY CRUSTAL EVOLUTION

The crater production rate in the earth-moon system was extremely high and rapidly declining $\sim$ 4.6-3.9 by ago. During this early period, impact was a fundamental geologic process on the moon. Large impact basins form the basic topographic, tectonic, and stratigraphic framework of the moon and impact was responsible for the characteristics of the second order gravity field and upper crustal seismic properties of the moon (Grieve, 1980b). The overwhelming effect of impact on lunar rocks dating from this period is evidenced by $\sim$ 90% of the returned lunar highlands samples being impact breccias or melt rocks, with Monte Carlo simulations indicating that the average lunar highland sample was affected by a minimum of 1-2 impact events (Hörz <u>et al</u>., 1976).

No known terrestrial rocks date from the period of intense bombardment and the earth's crustal evolution during the first 800 my of its history is conjectural. The oldest terrestrial rocks have ages of 3.5-3.8 by, although ages of 4.1 by have recently been reported on reworked zircons from Australia. The lack of an earlier crust may indicate that thermal and mechanical instabilities resulting from intense mantle convection and/or bombardment inhibited the preservation of continental sialic crust. If a terrestrial crust and lithosphere did exist during a portion of the period of intense bombardment, the effects of impact might be, to a first approximation, similar to that on the lunar highlands crust. The number of impact craters produced can be

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estimated from the cratering record in the lunar highlands, corrected for the larger gravitational cross-section of the earth, the effect of the higher escape velocity on impact velocity, and the effect of higher gravity on final crater dimensions.

Corrections for gravitational cross-section and impact velocity are functions of approach velocity. For approach velocities of 6-10 km s^{-1}, which is the model r.m.s. approach velocity for the residual planetesimal swarm (Wetherill, 1977), it is estimated that the earth will collect 2-4 times as many bodies of the same mass as the moon and the resultant craters will be $\sim$ 1.5 times larger, depending on the energy-diameter scaling relationship used. As the size-frequency distribution of primary craters approximates $N \propto D^{-2}$, where N is a cumulative number and D is diameter, this translates to a correction factor of 4.5-9 for the number of craters of equivalent diameter. The cratering rate for the lunar highlands is $\sim 6 \times 10^{-3}$ km^{-2} for D > 4 km (Basaltic Volcanism Study Project, 1981) and the lower factor of 4.5 with $N \propto D^{-2}$ gives $\sim$ 200 impact basins with D > 1000 km on the earth in the period 4.6-3.9 by. This estimate is considerably higher than previous minimum estimates of $\sim$ 30-60 basins with D > 1000 km, which were based on approach velocities of 15-20 km s^{-1} (Frey, 1980; Grieve, 1980a). This may be unrealistic as it requires a significant number of bodies in the residual planetesimal swarm, compared to the one or more of mass 10^{23}g needed to account for basin formation on the moon (Wetherill, 1977).

Given the number of impact structures, it is possible to estimate parameters such as the cumulative exogenic energy added to the early earth, the production of impact melt, and the extent of crustal fracturing. Even for minimal estimates of the number of impacts, the values for additional exogenic energy and impact melt production are of the same magnitude as present-day processes of internal heat losses and island-arc volcanism, respectively (Grieve, 1980a). Among the effects of

large-scale impact on an early terrestrial crust will be the formation of topography on the order of a few kilometers, enhancement of the sub-impact thermal gradients in the lithosphere and asthenosphere due to uplift of originally deep-seated materials, and the potential for subsequent eruption of basalt due to adiabatic decompression. Given that the earth has a relatively thin lithosphere, which is likely to have been even thinner during its earliest history, it is possible that large basin-sized impacts could bring the asthenosphere to the surface, leading to volcanism over large areas. Consideration of these effects led Frey (1980) to suggest that large impact basins on the early earth would produce proto-ocean basins floored by basaltic crust.

Following impact, however, a number of processes act to modify large impact basins. These are: thermal contraction and subsidence from the loss of post-shock and uplift heat, topographic degradation by erosion and relaxation, and loading of the basin. Some of these effects, as they apply to impact basins on the moon, have been examined, with the result that lunar impact basins appear to have had appreciable effects, on timescales of 10^6-10^8 y, on the thermal, volcanic, and tectonic history in and around the basins (Bratt et al., 1982; Solomon et al., 1982). Preliminary models of the evolution of a large terrestrial impact basin have been undertaken. A 1000 km basin, the form of which was constrained by data from smaller terrestrial structures (Grieve, 1980a), was formed in a model lithosphere 80 km thick with a thermal gradient of $20^{\circ}C\ km^{-1}$, overlying an asthenosphere with a thermal gradient of $0.5^{\circ}C\ km^{-1}$. Sub-impact temperatures were calculated as a function of time from finite difference solutions of the transient heat conduction equation in a cylindrical geometry. The post-impact thermal anomaly, created by post-shock waste heat and uplift of deep seated materials, decreases with time as heat is transferred to the surface (Fig. 1). The initial thermal anomaly and the thermal anomaly after 24×10^6 y are shown in Figure 1. Substantial conductive cooling occurs on a time scale of $\sim 10^7$ years.

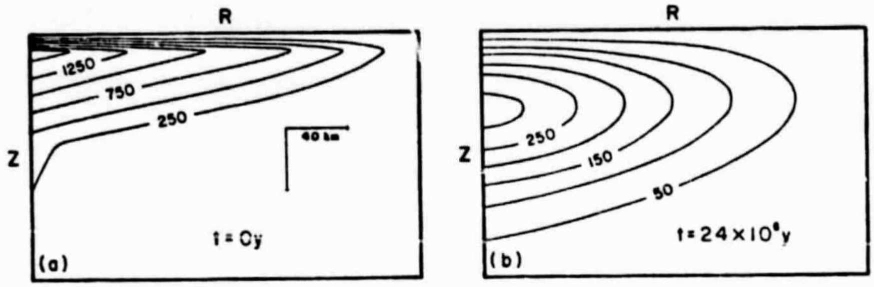

FIGURE 1. Vertical section of thermal anomaly beneath model 1000 km impact basin. R is radial distance and Z depth. Contours are for temperatures in excess of pre-impact thermal gradient. (a) Initial post-impact anomaly; (b) After 24 x 10^6 y. See text for details.

Isostatic adjustment of the basin will occur on a time scale of $2\mu/\rho_m gD$ (Parmentier and Head, 1981), where ρ_m and μ are the density and viscosity of mantle material underlying the basin and g is the acceleration of gravity. For the model basin, isostatic rebound will occur in times on the order of 10^4 years for $\mu=10^{22}$ poise. On longer time scales the basin floor will subside due to cooling and thermal contraction of underlying material. The thermal subsidence as a function of time, at several distances from the basin center, is shown in Figure 2. Thermal subsidence will be concentrated near the center, where a maximum subsidence of $\sim$ 2 km occurs after $\sim 10^8$ years. In addition, the basin may be dynamically loaded by volcanics, sediments and water, which will cause further subsidence. For example, a sediment load with density ρ_s = 2.7 g cm^{-3} and ρ_m = 3.3 g cm^{-3} will cause a 1000 km basin with an original depth of $\sim$ 3 km to isostatically subside by an additional factor of 1.8; i.e., the original floor will subside to a depth of $\sim$ 5.4 km. This is in addition to thermal subsidence, which will contribute significantly to the thickness of sediments, particularly near the center.

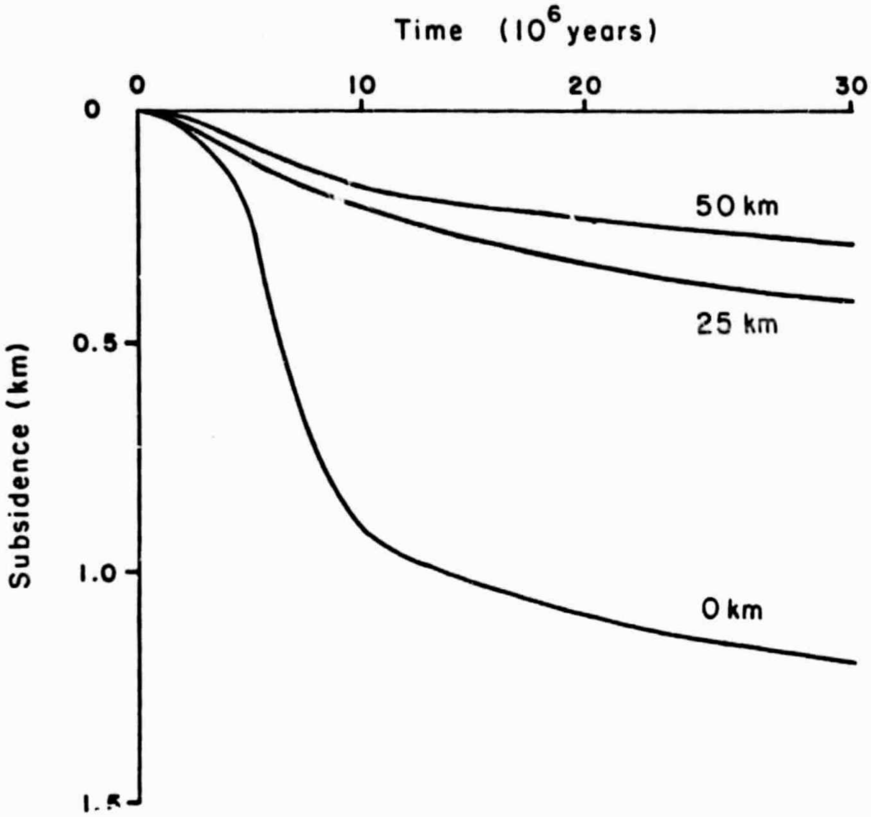

FIGURE 2. Thermal subsidence at various distances from the center of 1000 km basin, based on post-impact cooling model, as a function of time.

The initial modelling described above does not account for several effects, which may be important in determining the magnitude and rate of thermal subsidence. First, loading of sediments into the basin will reduce the rate of heat loss to the surface and the rate of thermal subsidence. It has been suggested that if subsidence due to loading took place on time-scales shorter than the

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decay of the enhanced thermal gradients below the basin, then the intra-basin materials: impact melt and breccia, post-impact volcanics, and sediments, may have been thermally metamorphosed and even partially melted to give sialic magmas (Grieve, 1980a). Second, the thermal anomaly created by the impact will likely result in the upward transport of heat by solid-state convection and, therefore, the faster cooling of material at depth. Convective flow will also cause horizontal spreading of the thermal anomaly resulting in thermal subsidence less concentrated near the basin center. Thus, convection will influence both the rate and radial distribution of thermal subsidence. These effects and the relative rates of subsidence and heat loss will be the subject of additional modelling.

IMPACT AND RECENT EVOLUTION

Recently, some authors have suggested relationships between large impacts and such phenomena as magnetic reversals and certain plate movements (Glass et al., 1979; Clube and Napier, 1982). These suggestions, however, are highly speculative. The most likely global effects of very large impacts will be coupled through the atmosphere and hydrosphere to climatic and biological changes. This thesis has been highlighted by the discovery of high siderophile abundances at Cretaceous-Tertiary boundary sites throughout the world (Alvarez et al., 1980; Ganapathy, 1980; and others) and apparently contemporaneous mass extinctions. This geochemical evidence is consistent with the global dispersion of projectile-contaminated, high-speed, early-time ejecta (Grieve, 1982; O'Keefe and Ahrens, 1982) and it is difficult to argue against a major impact as the source of the siderophiles. The hypothesis of impact-induced extinctions is the subject of discussion and is considered in detail in Geological Society of America Special Paper 190 (1982). There is no known impact structure commensurate in size ($\sim$ 100-200km) and age ($\sim$ 65 my) with that required by the siderophile anomaly at the Cretaceous-Tertiary boundary. Three structures with D > 25 km in the USSR: Kamensk, Kara,

and Urst-Karska have ages of 60 ± 5 my (Masaitis and Mashchak, 1982) but they may not represent a significant increase over the expected number of craters, provided they represent the total population of structures of this size and age (Grieve, 1982). The lack of an appropriate impact structure, however, may not be a problem, as Nd and Sr data suggest the presence of basaltic oceanic material within the boundary layer and thus an oceanic impact (Shaw and Wasserburg, 1982).

A number of impact-induced extinction mechanisms have been suggested: (i) Injection of stratospheric dust, leading to the destruction of food chains (Alvarez et al, 1980). The atmospheric flows generated by a large impact are sufficient to distribute stratospheric particles world-wide in a few hours (Jones and Kodis, 1982) and the debris cloud would reduce the amount of light below that required for photosynthesis for several months (Toon et al., 1982). (ii) Short-term heating of the atmosphere and uppermost ocean layer by the kinetic energy of ejecta, followed by cooling due to dust (O'Keefe and Ahrens, 1982). (iii) Poisoning by noxious chemicals (Hsü, 1980) and/or alteration of atmospheric chemistry by large quantities of NO and the rainout of HNO_3 (Lewis et al., 1982). It is clear that there are a number of impact-related effects which could sufficiently stress the biosphere to lead to mass extinctions. It is not yet clear, however, which if any was responsible for the Cretaceous-Tertiary boundary.

Searches are currently underway for other siderophile anomalies in the geologic record. An Ir anomaly has been discovered in Antarctic ice and associated with the 1908 Tungska event (Ganapathy, pers. comm.) and with North American microtektites, age 34 my (Alvarez et al., 1982; Ganapathy, 1982). This latter impact event has been linked to the terminal Eocene biological and climatic changes (Alvarez et al., 1982) but, as with the Cretaceous-Tertiary, there is no known associated impact structure. The Popigai structure, USSR, is approximately the correct age, 39 ± 9 my, and is sufficiently large,

D ∿ 100 km (Masaitis et al., 1975), that it might be expected to have produced global effects. Geochemical evidence, however, indicates that it is not the source crater for the North American tektites (Shaw and Wasserburg, 1982).

Table 1. Major extinction events and large impact structures of similar age.

Extinction Event	Age	Impact Event	Diameter	Age
		Kara	50 km	60 ± 5 my
Cretaceous-Tertiary	65 ± 1 my	Urst-Karska	25 km	60 ± 5 my
		Kamensk	25 km	65 my
Norian (L. Triassic)	214 ± 6 my	Manicouagan	100 km	210 ± 4 my
Permian-Triassic	245 ± 5 my			
		Charlevoix	54 km	360 ± 25.0 my
Frasnian (L. Devonian)	365 ± 10 my			
		Siljan	52 km	368 ± 1.0 my
Ashgillian (L.Ordovician)	421 ± 4 my			

Data Sources: Grieve (1982), Masaitis et al., (1980) and Sepkoski (1982).

Sepkoski (1982) recognizes five major, and a number of lesser, extinctions during the Phanerozoic. These are listed in Table 1, along with known large impact structures with similar ages. It is tempting to speculate on correlations between specific impact structures and extinctions; e.g., McGhee (1982). Such correlations, however, are premature. Most impacts occur in the oceans. If all extinction events were related to impact, only ∿ 25% should correlate with known land structures. The cratering record is incomplete and age estimates of both extinction and impacts have attached imprecisions (Table 1). Furthermore, there are a number of large structures which are not temporally associated with major biological perturbations (Grieve, 1982). Extinctions are a complex problem. They may be multi-causal and there are questions on their severity, ages, and time-spans. To estab-

lish firmly a correlation between an extinction event and a known crater would require more than a temporal overlap (Table 1). Some geochemical evidence in the form of similar siderophile anomalies in the stratigraphic record and the impact melts within the structure would provide much needed additional confirmation.

SUMMARY REMARKS

Although individual impacts may have significant effects upon local geology and seismically affect large regions, it is apparent that the global geologic effects of impact do not compare with modern terrestrial geologic processes. This may not have been the case, however, during early earth history when the impact flux was considerably higher. As no recognizable evidence of the large multi-ring basins, which should have been produced at this time, is preserved, it is difficult to assess the extent to which large-scale impact influenced the early crustal evolution of the earth. It seems likely that large impacts would have intensified and localized endogenic activity such as volcanism, sedimentation, and tectonism. Whether or not this activity was sufficient to modify impact basins into stable areas of new sialic crust is not clear and requires additional detailed modelling. At this time, however, large-scale impact cratering must be regarded as having a potentially important effect upon early crustal evolution.

The case of large impacts affecting the biological and climatic evolution in more recent time is relatively convincing. The evidence for a major impact at the Cretaceous-Tertiary boundary is restricted to geochemistry. The discovery, however, of a similar anomaly associated with North American tektites, which are generally recognized as having an impact origin, strengthens the case for the Cretaceous-Tertiary impact. Large impacts have several mechanisms through which they may affect both climate and the biosphere but interactions in the atmosphere-hydrosphere-biosphere system are complex and

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not well known and, at present, no one extinction mechanism is clearly advocated. Given the potential of large impacts to disrupt the biosphere, it is difficult to understand why virtually all large impact events do not have associated extinctions. This may be a recognition problem due to the lack of a complete fossil record or may mean that the biosphere must be already stressed before impact can produce widespread extinctions. Alternatively, the Cretaceous-Tertiary impact may represent a singular event. Although the exact relationship of major impact events to mass extinctions may not be clear, it is apparent that large sporadic impacts must be given consideration as a viable mechanism for mass extinctions and climatic changes on earth. Whatever the case, the discoveries at the Cretaceous-Tertiary will be the focus of considerable scientific study and, if nothing else, have forced a wide audience of scientists to consider impact as a process affecting the earth's evolution.

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