Impact Processes on the Early Earth

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At the beginning of the solar system, impacts and collisions were dominant processes. After an early collision that may have led to the formation of the Moon, both Earth and Moon suffered intense post-accretionary bombardment between about 4.5 and 3.9 billion years before present. There is evidence from lunar rocks for an intense "Late Heavy Bombardment" at about 3.85–3.9 Ga, which must have had severe consequences for Earth as well, even though no terrestrial record has yet been found. Several 3.4 to 2.5 Ga old spherule layers in South Africa and Australia and two impact craters near 2 Ga represent the oldest terrestrial impact records found to date. Thus, the impact record for more than half of Earth's geological history is incomplete, and there is only indirect evidence for impact processes during the first 2.5 billion years of Earth history.

KEYWORDS: Impact processes, Late Heavy Bombardment, shocked minerals, Hadean, impact craters

IMPORTANCE OF CRATERING PROCESSES

The importance of impact processes on a planetary scale has been recognized only fairly recently, after it became evident that not only our Moon (FIG. 1), but all other bodies in the solar system with a solid surface are covered with meteorite impact craters (FIG. 2). Impact cratering is a high-energy event that occurs at more or less irregular intervals (although over long periods of time, an average cratering rate can be established). Recognition of the vestiges of impact events on Earth is difficult because terrestrial processes either cover or erase the surface expression of impact structures. Important witnesses of impact processes are melted, shocked, and brecciated rocks that are found either directly at or within a crater, or have been transported, in some cases considerable distances from the source crater. The latter are called ejecta.

To determine if certain rocks are related to an impact or not, criteria must be identified that allow us to distinguish the effects of such processes from those resulting from normal terrestrial geological processes. Only the presence of diagnostic shock-metamorphic effects and, in some cases, the discovery of meteorites (or traces thereof) are evidence for an impact origin (cf. Koeberl 2002). Most shock features are microscopic (FIG. 3). The same two criteria apply also to distal impact ejecta layers and allow researchers to confirm that such material originated in an impact event at a possibly still-unknown location. Currently, 172 impact structures have been identified on Earth based on these criteria (see http://www.unb.ca/passc/ImpactDatabase for information and updates). With one exception, all of these are younger than 2 Ga (billion years).

Another important line of evidence for impact processes comes from geochemical indications of an extraterrestrial component in breccias or melt rocks. Only elements that have high abundances in meteorites and low contents in terrestrial crustal rocks are useful for such studies – for example, the siderophile platinum-group elements (Ru, Rh, Pd, Os, Ir, and Pt) and other siderophile elements (e.g. Co, Ni). Better still are isotopic tracers for extraterrestrial components; the isotopic compositions of the elements osmium and chromium are mainly used. These methods allow the very sensitive determination of the presence of an extraterrestrial component (down to 0.1% for Os isotopes) and, in the case of the Cr isotopic method, even allow us to determine the type of impactor.

ACCRETION OF THE EARTH, AND THE MOON-FORMING IMPACT

The planets – including Earth – formed by collision and hierarchical growth, starting from small objects, i.e. from dust to planetesimals to planets. Late during the accretion of Earth (some time around or after 4.5 billion years ago), when Earth had acquired about 70–90% of its final mass, it probably collided with a Mars-sized body. This is the prevailing hypothesis for the origin of the Moon (e.g. papers in Canup and Righter 2000), and it is thought that most of the Moon was derived from the impactor. Accretion of the Moon from the proto-lunar disk followed very rapidly. The volatile-poor and refractory-rich composition of the Moon
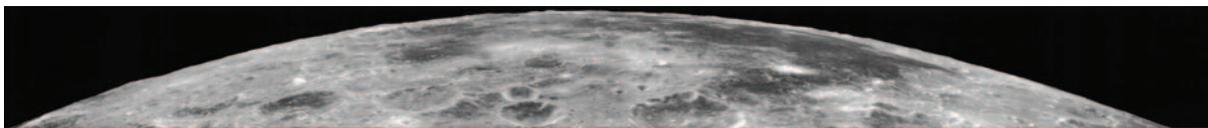

FIGURE 1 Densely cratered part of the surface of the Moon (APOLLO 17, PHOTO P-2871)

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FIGURE 2 Heavily cratered ancient highlands dominate the Arabia quadrangle on Mars. FROM VIKING IMAGE PIA00172; WIDTH OF IMAGE 1000 KM

FIGURE 3 Micrograph (crossed polarizers) of shocked quartz grain from ejecta of the Manson crater (USA), demonstrating the characteristic "planar deformation features" (PDFs). These features are straight, penetrate the whole crystal, and occur in more than one orientation. Wavy lamellae, observed in some quartz grains, are not characteristic of shock.

agrees with such a formation mechanism. The impact event is thought to have been the last of the major collisions involved in the accretion of Earth. The consequences of such an event for the proto-Earth would have been severe, ranging from almost complete melting and formation of a magma ocean, thermal loss of pre-existing atmosphere, changes in spin rate and spin-axis orientation, to accretion of material from the impactor, directly or through rapid fallout from orbital debris.

The period on Earth between the end of accretion and the beginning of the continuous terrestrial rock record is commonly referred to as the Hadean Eon. Its terminal boundary on Earth was suggested to be at 4.2 Ga based on zircon geochemistry (Cavosie et al. 2005), while on the Moon it is equated with the formation of the Orientale basin.

EARTH AFTER THE GIANT MOON-FORMING IMPACT EVENT

The terrestrial rock record, in the form of crustal rocks, extends back through only about 89% of the history of the planet to ~4.0 Ga (with the oldest rocks showing very limited exposures at Isua and Akilia, Greenland, and Acasta, Canada). Rare detrital zircon grains in rocks from Western Australia have ages up to 4.4 Ga (Wilde et al. 2001). It is likely that the Moon-forming impact led to large-scale melting of the Earth at ~4.5 Ga (Halliday 2006) and the formation of an early magma ocean. Mantle temperatures in the Hadean were much higher than today (heat flow was about five times higher) due to greater concentrations of radioactive elements and to thermal energy released during the impact of late accretionary bodies. Because of higher mantle temperatures and the temperature dependency of the dehydration reactions that control how much water is recycled to the mantle, the Hadean mantle was drier than its modern counterpart. Most of Earth's water was contained in an ocean, which already existed probably as early as 4.2 Ga (Cavosie et al. 2005); its volume may have been up to twice that of today's oceans (Russell and Arndt 2005).

The nature and abundance of the earliest crust on Earth have been debated, but comparison with other planets indicates a basaltic crust. Russell and Arndt (2005) suggested that high-degree melting of hot, dry Hadean mantle at
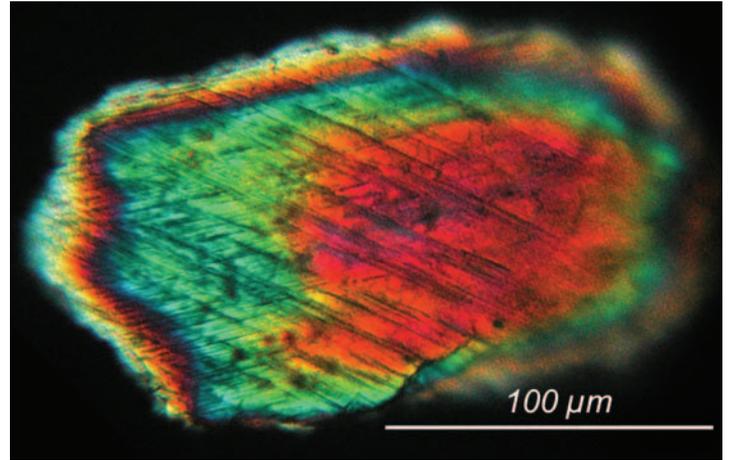
ocean ridges and in plumes resulted in an oceanic-type crust about 30 km thick, overlain in places by extensive and thick mafic volcanic plateaus; 'continental' crust, by contrast, was relatively thin and mostly submarine. Characteristics of the 4.4–4.0 Ga zircons indicate a composite granitoid source. Thus, at least minor amounts of felsic igneous rocks existed during the Hadean, produced from remelting of basaltic crust that sank back into the mantle. The Hadean oceanic crust was much thicker than today, as thick as or thicker than the Early Archean continental crust. Due to the larger ocean mass, a greater area of Earth's surface was flooded. In contrast to today, most of the continents were submerged, and only mountain ranges at convergent margins and vast volcanic plateaus occasionally breached the ocean surface. Thus, the Hadean Earth was most probably characterized by a thick basaltic crust covered by an ocean, with very little dry land mostly composed of felsic rocks (granitoids) (FIG. 4).

Grieve et al. (2006) calculated that early large-impact events could lead to the formation of felsic crust on the Hadean Earth. They found that, on Earth, impact melt volumes exceed transient crater volumes at transient crater diameters greater than approximately 500 km. Thus, the initial basaltic Hadean crust would have been reprocessed to produce pockets of felsic crust by crystal fractionation. Scaling of lunar impact basins yields a cumulative melt production related to the formation of such basins on the Hadean Earth of about 10^{11}–10^{12} km^3. Grieve et al. (2006) suggested that the cumulative felsic rocks produced through differentiation of such impact melt pools could approach a volume equivalent to 50% of today's continental crust.

There is evidence (involving the short-lived ^{146}Sm–^{142}Nd decay; half-life 103 Myr) that Earth's upper mantle had already undergone some differentiation shortly after accretion (e.g. Boyet and Carlson 2005). Evidence for recycling of early crust, coupled with the higher heat flow, seems to demand that plate tectonics, even in limited form, and accretion of felsic crust were operating shortly after the solidification of the magma ocean. Alternatively, the impact mechanism suggested by Grieve et al. (2006) may also account for the production and recycling of differentiated early crust.

The magma ocean may have been shorter lived than previously thought, and differentiation and recycling could have started shortly after the Moon-forming impact. Variations in the oxygen isotope composition of zircons with ages of 4.2 Ga indicate that these zircons grew in evolved granitic magmas and that low-temperature surficial processes, including diagenesis, weathering, and low-temperature alteration, were operating (e.g. Cavosie et al. 2005). Thus, liquid water seems to have been present on the surface of Earth early on, and granitic (not just basaltic) pockets of continental crust were present (Valley et al. 2002); we can infer that the frequency of meteorite impacts during the time span between 4.4 and 4.0 Ga may have been less than previously thought.

These zircons are the only record that has persisted from Hadean times. It would be interesting to study them (or at least their cores, as most of them have younger overgrowths) for shock effects, although this may be difficult due to later annealing and because any early Hadean crust would have been destroyed at around the same time as massive impacts reshaped the surface of the Moon.

A LATE HEAVY BOMBARDMENT AT 3.9 Ga?

In contrast to the youthful age for most of Earth's crust, the surface of the Moon displays abundant evidence of an intense bombardment at some time between its original crust formation and the outpourings of lava that form the dark mare plains. The ages of the highlands have been interpreted to represent either a short and intense 'late' heavy bombardment (LHB) period at 3.85 ± 0.05 Ga (e.g. Ryder et al. 2000) or the tail end of an extended post-accretionary bombardment (Fig. 5).

The lack of lunar impact melts older than ~3.95 to 3.92 Ga can be taken as evidence that there were no significant impact events on the Moon prior to that time, in agreement with the 'cool early Earth' between about 4.4 and 4.0 Ga (Valley et al. 2002). All large impact basins on the Moon have formation ages of about 3.8 to 4.0 Ga (the magma that
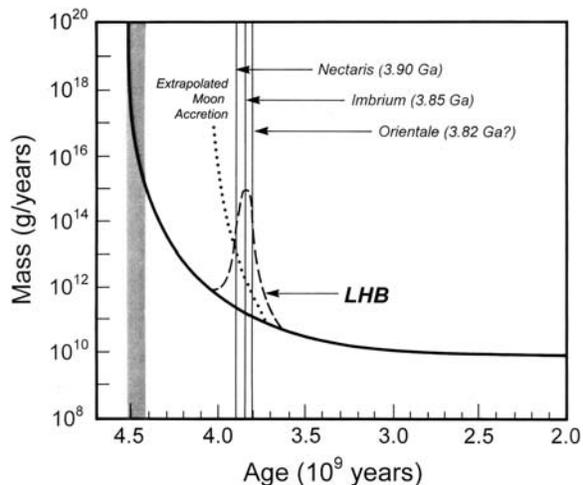
FIGURE 4 A possible view of the early Earth, sometime between 4.4 and 4.0 billion years ago. There is now evidence of rather clement conditions starting several tens of millions to 300 million years after the Moon-forming impact event. The young Moon is much closer to Earth than today and does not yet have any of the maria that dominate its Earth-facing side today. Towards the end of planetary accretion, a higher impact rate than today led to a barrage of both Earth and Moon. One medium-size impact event can be seen occurring in the right side of the image, while several smaller events are happening on the Moon. An ocean dominates the surface of Earth, but island-arc formation and associated intense volcanism indicate the presence of early continental crust. The Earth is covered by a dense, CO_2-dominated atmosphere. PAINTING BY DONA JALUFKA 2005

FIGURE 5 Various interpretations of the mass flux (accretion rate) on the Moon. Ages of the most important impact basins are indicated. The solid line is the present-day background flux extrapolated back to the origin of the solar system. LHB indicates the spike in the accretion rate representing the Late Heavy Bombardment. The dotted line indicates an accretion curve that includes the masses of the basin-forming projectiles; this curve is unlikely to be correct, because it implies accretion of the Moon at 4.1 Ga. The gray band marks the age of the Moon obtained from measurement of radiogenic isotopes. AFTER KOEBERL 2006

filled these impact basins to form the maria is younger, at about 3 Ga) (Ryder et al. 2000). Work on lunar meteorites has confirmed that there was considerable bombardment of the Moon in the 60 million years between 3.90 Ga and ~3.84 Ga (e.g. Kring and Cohen 2002). An independent argument in favor of an LHB can also be made using the masses of basin-forming projectiles on the Moon, as shown in Fig. 5. Back-extrapolating the masses of basin-forming projectiles accreting onto the Moon between 3.8 and 4.0 Ga leads to the conclusion that the present-day mass of the Moon can be accounted for if it formed at about 4.1 Ga instead of 4.5 Ga. The exact mechanism that produced this spike in impact flux in the inner solar system is not known, although the delayed migration of Uranus and Neptune towards the outer solar system and the resulting distur-bance of Kuiper Belt objects may provide an explanation (Gomes et al. 2005).

The question arises as to whether or not any evidence of this bombardment is preserved on Earth. In any given time span, Earth was subjected to a higher impact flux than the Moon because Earth has a larger diameter and a much larger gravitational cross-section. The oldest rocks on Earth, from Acasta in Canada and the Isua/Akilia area in Greenland, are the obvious places to conduct such a search. Unfortu-nately, searches for an extraterrestrial signature based on platinum-group elements and for shocked zircons in the earliest rocks from Greenland have so far been unsuccessful (Koeberl et al. 2000). This could be for several reasons. First, the number of samples studied was probably too small. Second, it is possible that very large impacts form more melt than shocked rocks, leading to a preservation problem. Third, it is not certain that the rocks at Isua really have an age >3.8 Ga (e.g. Lepland et al. 2005).

Tungsten isotope anomalies found in ca. 3.85 Ga metasedi-mentary rocks from Greenland were interpreted to indicate an extraterrestrial component as a result of the LHB (Schoenberg et al. 2002). However, it is difficult to under-stand why a similar meteoritic signal would not show up in the platinum-group element abundances, as high W abun-dances are not common in meteorites. In fact, Frei and Rosing (2005) used the chromium isotope method on Isua rocks and found no trace of an extraterrestrial component. Thus, little or no evidence of an LHB phase at 3.85 Ga has been found so far on Earth.

IMPACTS AND THE ORIGIN OF LIFE ON EARTH

The impact rate in the inner solar system between the Moon-forming event and ~4.0 Ga seems to have been lower than previously assumed. If the impact energies associated with the lunar bombardment between about 4.4 and 3.9 Ga are scaled up to Earth (Ryder 2002), they may not have been high enough to produce ocean-evaporating, globally steril-izing events, in agreement with the conclusions of Valley et al. (2002). Compared with the LHB of the Moon, the impact flux on Earth from ca. 4.4 to 3.9 Ga may have been sub-dued, and the impacts themselves during that time could have been thermally and hydrothermally beneficial.

However, if the LHB really happened, severe environmental changes would have occurred on Earth at about 3.85 Ga. During this cataclysm, Earth would have undergone impact events an order of magnitude larger than those affecting the Moon and would have experienced many more such events than the Moon had to endure. Hundreds of objects with sizes similar to those of the Imbrium and Orientale impactors must have struck Earth during the basin-forming era. Nonetheless, even an Imbrium-sized impactor scaled to terrestrial collision energy would have had only 1% of the

energy needed to evaporate Earth's oceans and would have vaporized only the upper few tens of meters of ocean. The impact would have produced a transient atmosphere of hot silicate vapor, which would have heated the ocean from above. Even impacts orders of magnitude larger would have been far from sufficient, boiling off only a few hundred meters of ocean water (see, for example, Ryder 2002).

LATER (EARLY ARCHEAN) IMPACT EVENTS

In the absence of any conclusive impact record in the old-est rocks on Earth, we need to look at 'younger' rocks. The earliest 'real' rock record of impact events has been dated at ~400–500 million years after the end of the LHB. This record takes the form of (distal?) impact ejecta layers (e.g. Simonson and Glass 2004). Spherule layers, interpreted as possible impact debris layers, have been documented in 3.47–3.2 Ga Archean successions in the Barberton Greenstone Belt (South Africa) (Fig. 6A) and Pilbara Craton (Australia). Unlike modern impact deposits, many of these spherule layers show extreme enrichments in platinum-group ele-ments, and they lack shock features, but Cr isotope anom-alies in samples from some of these layers seem to support the presence of an extraterrestrial component (Kyte et al. 2003). Similar spherule layers (of ca. 2.63–2.5 Ga age) have
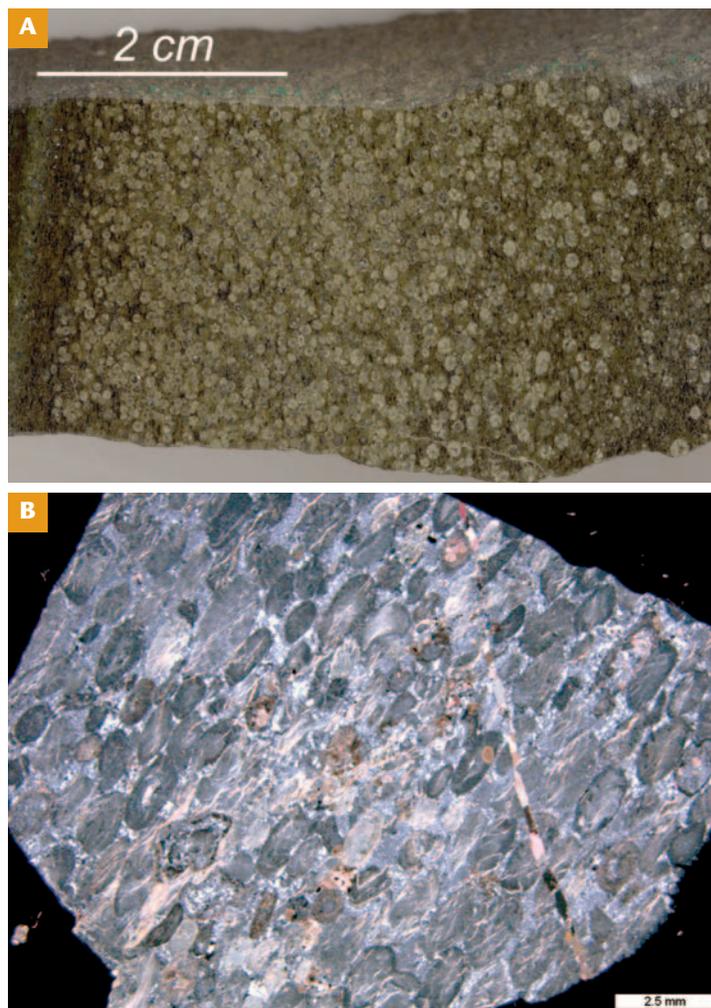
FIGURE 6 (**A**) Well-sorted, millimeter-sized spherules in a 3.48 Ga impact-derived layer, Barberton, South Africa. (**B**) Image of tectonically deformed spherules from one of the impact-derived spherule layers at Barberton, South Africa. Cross-polarized view of an optical thin section. The mineralogy of the spherules is most likely of secondary origin and comprises quartz and sericite.

been found in the Hamersley Basin in Australia and in the Monteville Formation of the Transvaal Supergroup in South Africa (Fig. 6A, B); these Australian and South African layers may be correlated with each other. The spherules are mostly quenched melt droplets, up to a few millimeters across, some of which may have formed by condensation from vapor clouds (Fig. 6). The spherule layers are coarse grained and have been interpreted to reflect high-energy depositional events in otherwise low-energy, quiet-water environments. The original mineralogical and chemical compositions of the spherules have been almost completely changed by alteration (Fig. 6B). Until recently, no shocked quartz – commonly regarded as unambiguous evidence for a hypervelocity impact event – has been found in distal ejecta horizons older than ~600 Ma; an exception is a single shocked quartz grain from the 2.63 Ga Jeerinah impact layer in Australia (Rasmussen and Koeberl 2004). The exact number of impact spherule layers is not known, as it is not clear which ones might correlate with each other, but a minimum of seven different events in the age ranges 3.4–2.5 Ga and 2.1–1.8 Ga have been identified.

Unfortunately, no definitive criteria for the identification of Archean impact deposits have yet been established. So far no source craters have been found for the South African (Barberton and Monteville) or Australian spherule layers, and given the scarcity of the Early Archean geological record, it is unlikely that they will ever be found. It is not clear why impact events in the Archean would predominantly produce large volumes of spherules, whereas they are mostly absent from post-Archean impact deposits (i.e. those for which source craters are known). Distal ejecta from the 1.85 Ga Sudbury impact structure also have spherules (Addison et al. 2005). Some (comparatively small) spherules are associated with ejecta from the 65 Ma Chicxulub and the 35 Ma Popigai impact events (Simonson and Glass 2004), but these layers are thinner than the Archean spherule layers. Compositional differences between the Archean and present-day continental crusts could have influenced the composition and preservation of the ejecta.

THE OLDEST IMPACT STRUCTURES PRESERVED ON EARTH

The earliest remnants on Earth of actual impact structures – excluding the more controversial and difficult-to-quantify evidence from the Early Archean spherule beds – date to about 2 billion years ago. Thus, for more than half of the 'life' of our planet – the first 2.5 billion years – we do not have any substantiated preserved remnants of the many impact structures that must have formed; the only evidence we have is indirect, for example by comparison with lunar impact structures of similar age. The oldest known terrestrial impact structures are the Vredefort and Sudbury structures with ages of 2023 ± 4 and 1850 ± 3 Ma, respectively (see Reimold and Gibson 1996) – these represent the complete, documented, pre-1.85 Ga terrestrial impact record.

The Vredefort Dome (South Africa) is the deeply eroded central uplift of a large (initial diameter about 200–300 km), complex impact structure. The rocks show the variety of impact-related features described at the beginning of this
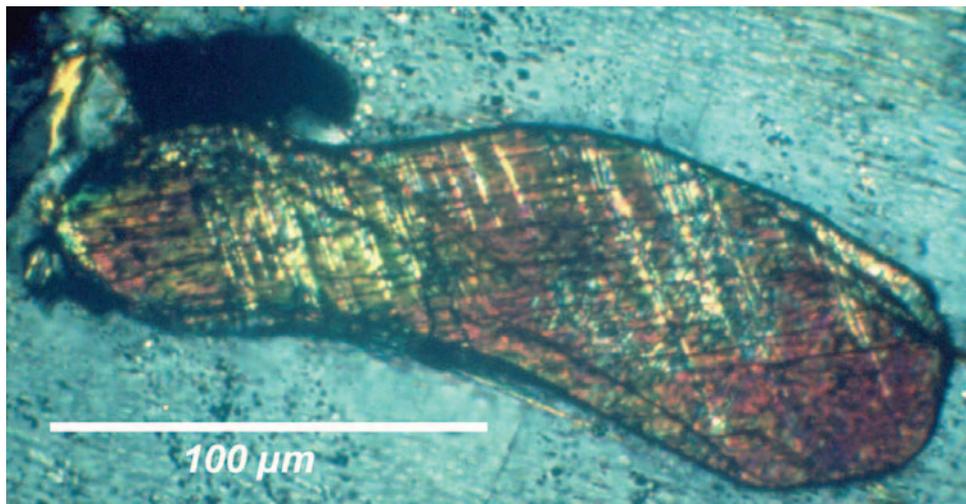
article, including shatter cones, coesite and stishovite (high-pressure polymorphs of SiO_2), shocked quartz and zircon (Figs. 3 AND 7), dykes of impact melt breccia, and abundant pseudotachylitic (melt) breccias. The absence of a definitive crater morphology, a coherent impact melt body, and fallback breccias indicate that considerable erosion has taken place since the impact event, removing the top 5–10 km of the post-impact surface. In contrast to the 1.85 Ga Sudbury structure, for which impact ejecta (including a spherule layer up to 10 cm thick) have recently been identified in Minnesota and western Ontario 650–875 km from the impact site (Addison et al. 2005), no confirmed ejecta related to the Vredefort impact have to date been discovered.

CONCLUSIONS

The early record of impacts on Earth is limited and mostly circumstantial. There is no record for the first one billion years and the later preserved rock record shows few events (just seven or eight documented impact layers) between 3.5 and 2.4 Ga. The oldest confirmed crater on Earth is 2 Ga old, and the impact record during the following one billion years is sparse in terms of both craters and ejecta layers. Three impact structures are known for the time period between 2.1 Ga and 700 Ma and the rest of the some 170 currently known impact structures are all younger than 700 Ma. Clearly the 'early' impact record on Earth, which spans more than half of the age of our planet, its most active period, is still a wide-open field of research. A more detailed discussion of this topic is given in the review by Koeberl (2006).

ACKNOWLEDGMENTS

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