EVIDENCE OF ARCHAEAN MEGA-IMPACTS: CONSEQUENCES FOR CRUSTAL EVOLUTION

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Abstract

The impact flux in the Earth-Moon system, combined with recent age determinations of Archaean spherule fallout units and lunar impact glass spherules, defines a major impact cataclysm about 3.2 +/-0.1 Ga. The tectonic and magmatic consequences of these events are explored, with implications for the nature and episodic evolution of the Archaean Earth. In the light of these events, new research is focussed on testing other potential correlations between mega-impacts and crustal tectonic and magmatic episodes during the Precambrian, with particular attention to the global c.2.71-2.67 Ga greenstone-granite forming mega-events defining the transition between Archaean and Proterozoic crustal environments.

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1. The Impact flux in the Earth-Moon system

Estimates of impact incidence rates and crater/size frequency distribution, combined with modelling of the tectonic and magmatic consequences of mega-impacts on thin thermally active oceanic crust (Glikson, 1996, 1999), suggest that impact-triggered faulting, rifting and associated igneous activity were of fundamental importance during the Archaean. Lunar mare crater counts, the terrestrial impact flux, and astronomical observations of asteroids and comets define a consistent impact rate of 4-6 * 10^-15 km^-2.yr^-1 within the inner solar system since the end of the Late Heavy Bombardment (LHB) ~3.8 Ga ago. Coupled with the observed crater size vs cumulative crater size frequency relationship of $N \propto D_c$^-1.8 (N = cumulative number of craters of diameter > D_c), these rates imply formation on Earth of more than 450 $D_c \geq 100$ km-diameter craters, more than 50 $D_c \geq 300$ km-diameter craters, and more than 20 $D_c \geq 500$ km-diameter craters.

The Late Heavy Bombardment (LHB) in the Earth-Moon system, broadly defined at 4.2-3.8 * 10^9 years (BVTP, 1981), may represent the tail-end of planetary accretion or, alternatively, include a distinct 3.95-3.80*10^9 years bombardment episode (Ryder, 1990). Combined evidence from terrestrial Archaean terrains and from the Moon militates for a major impact cataclysm in the Earth-Moon system about 3.2+/-0.1*10^9 years. Older less-well-defined impact events in the Earth-Moon system are also marked about 3.47-3.46*10^9 years - a time of maximum greenstone-granite terrain formation. The question is whether these events signify an extension of the LHB or represent temporally distinct episodes.

2. Evidence for a 3.2+/-0.1 lunar impact cataclysm

Some of the largest lunar maria basins contain low-Ti basalts which likely represent impact-triggered volcanic activity, including Mare Imbrium (3.86+/-0.02*10^9 year) and associated KREEP-basalts (K, REE, and P-rich) (3.85+/-0.03*10^9 year) (Apollo 15) (Ryder, 1997; Ryder and Dalrymple, 1997). Similar genetic impact-volcanic relationships may pertain in Oceanus Procellarum (Apollo 12) (low-Ti basalts - Rb-Sr and Ar-Ar ages - 3.29-3.08*10^9 year) and in Hadley Apennines (Apollo 15) (low-Ti basalts - Rb-Sr ages - 3.37-3.21*10^9 year; Ar-Ar ages - 3.35-3.10*10^9 year) (BVTP, 1981). The likelihood of impact-volcanic relationships on the Moon gains support from the recent laser 40Ar/39Ar analyses of lunar impact spherules from sample 11199 (Fra Mauro Formation - Apollo 14) by Muller (1993) and Culler et al. (2000) - showing a significant age spike at 3.18*10^9 year, ie. near the boundary between the Late Imbrian lunar era (3.9-3.2*10^9 year) and the post-mare Eratosthenian lunar era (3.2-1.2*10^9 year) as defined by the cratering record (Wilhelms, 1987). Some 34 lunar impact spherules yield a mean age of 3188+/-198 Ma and a median age at 3181 Ma, whereas 7 lunar spherule ages with error < 100 m.y. yield a mean age of 3178+/-80*10^6 years and a median at 3186*10^6 years.

3. Evidence for a c. 3.24 Ga impact cluster from spherulitic condensate fallout in the Barberton Mountain Land, Transvaal

Since 1986 Don Lowe and Gary Byerly perceptively recognised several impact fallout spherule horizons in the Barberton Mountain Land, Transvaal (Lowe and Byerly, 1986; Lowe et al., 1989; Kyte et al., 1992; Byerly et al., 1994). These are defined by U-Pb zircon age determinations of underlying and overlying pyroclastic volcanic units as: S1 - 3474-3445*10^6 years; S2 - 3243±4*10^6 years; S3, S4 - 3243-3227±4*10^6 years. They also detected a 3465-3458*10^6 years spherule units in the Warrawoona Group, Pilbara Craton, Western Australia (Lowe and Byerly, 1986). The extraterrestrial impact origin has been questioned on textural basis (Buick, 1987) and the PGE-rich composition of the spherules (Kyte et al., 1992) was re-interpreted in terms of secondary processes, with ensuing debate (Koeberl and Reimold, 1993; Glikson, 1994). However, these spherule horizons are now established as undoubted impact condensate fallout deposits, on the following basis:

(1) Occurrence within the spherules of quench-textured and octahedral Ni-chromites with extreme values of Ni (NiO<23%), Co, Zn and V, unknown in terrestrial chromites (Byerly and Lowe, 1994; Taylor and Glikson, in prep.) and which contain PGE nano-nuggets compositionally distinct from terrestrial PGE nuggets (Taylor and Glikson, in prep.);

(2) 53Cr/52Cr isotopic indices (E = - 0.32) corresponding to values of carbonaceous chondrites and values of K-T boundary impact fallout deposits, but distinct from terrestrial values (Shukolayukov et al., 1998);

(3) PGE chondrite-normalised patterns displaying marked depletion in the volatile species (Pd, Au) relative to refractory species (Ir, Pt), distinct from terrestrial PGE profiles (excepting depleted mantle harzburgites); (4) diagnostic textural features, including inward-radiating quench textures and offset vesicles, as defined by B.M. Simonson (Simonson, 1992).

4. Tectonic and magmatic implications of Archaean impacts

Mass balance calculations based on Ir and Cr levels and thermodynamic-based correlations of spherule sizes of up to 4 mm-diameter (Byerly and Lowe, 1994), suggest impact by asteroids on the order of 30-50 km-diameter, scaled to 400-800 km-diameter terrestrial impact basins. The Fe-Mg-rich spherule composition and the absence of shocked quartz in the units suggest the impact basins formed in simatic/oceanic regions of the Archaean Earth, which from geochemical and isotopic evidence (McCulloch and Bennett, 1996) occupied over 90 percent of the Earth surface before about 3.0*10^9 years. The occurrence of the Barberton S2-S4 spherule units immediately above the top of a >12 km thick mafic-ultramafic volcanic sequence (Onverwacht Group) and at the base of a partly granite-shed clastic sedimentary sequence (Fig Tree Group), hints at the onset of fundamentally different tectonic/magmatic regimes about c.3.24-3.227*10^9 years (Lowe et al., 1989).

An analogous lithological and tectonic break is observed in the Pilbara craton along the boundary between a 3.24*10^9 years volcanic sequence (Sulphur Springs Group) (Van Kranendonk and Morant, 1998) and an unconformably overlying clastic sandstone-siltstone (partly granite-shed) and banded ironstone sequence (Gorge Creek Group) - as yet of uncertain age. A search for impact spherules within these units is in progress.

It is suggested that the period 3.2+/-0.1*10^9 years represents a major cataclysm in the Earth-Moon system, resulting in extensive volcanic activity in lunar maria basins, with a possibility that some of the largest craters formed at that time. On Earth the bombardment resulted in formation of terrestrial maria on a scale of several hundred km-diameter, major volcanic activity, strong vertical movements, and formation of faulted trough/rift structures accumulating clastic sediments from uplifted terrains.

5. Outstanding questions

The original nature of the Archaean Earth remains little understood, including the structure and composition of the simatic crust which occupied well over 80 percent of the Earth surface. To date few impact signatures of Archaean age have been identified in Archaean terrains, an absence capable of alternative interpretations, including (1) low frequency of Archaean impacts; (2) removal and obliteration of impact signatures by erosion, metamorphism and partial melting; (3) common coverage of impact signatures by subsequent impact-triggered volcanic blankets, or some or all of these factors combined. The sharp outer boundaries which pertain to explosive impact structures, with limited structural effects on adjacent terrains (excepting ejecta rays), allow few clues on the proximity of impact structures from the surrounding regional geology. As shown by the relatively little scarred lunar maria surfaces, the density of post-LHB impacts was low relative to that of pre-3.8 Ga terrains. On the other hand, due to the Earth-Moon gravity section of 1.4 : 1, Earth can be expected to have been more heavily scarred than the moon. This is in apparent contrast with the lunar, terrestrial and asteroid impact fluxes, which requires that over 150 impact structures with D_c >= 100 km formed during the Archaean (3.8 - 2.6 Ga).

The episodicity of Precambrian igneous events may yield a clue for the potential effects of impacts. Compilations of Precambrian isotopic data have been alternatively interpreted in terms of continuous crustal accretion, distinct thermal and tectonic episodes (Condie, 1995; Glikson, 1993, 1996), or combined episodicity and accretion (Card, 1990). A global nature of these episodes is suggested by correlations between peak thermal events in separate Precambrian shields. However, the significance of age-distribution histograms is fraught with uncertainties arising from the likely selective preservation of crustal segments and from sampling bias due to economic and scientific priorities and terrain inaccessibility. The tentative episodic nature of mafic igneous activity suggested by age distribution diagrams may be interpreted in terms of purely endogenic factors, effects of mega-impacts, or a combination of both.

Whereas models of Archaean crustal evolution have rarely taken the effects of large impacts into account, extrapolations of the impact flux, which requires the formation post-LHB of at least 50 craters with diameters larger than 300 km, requires reconsideration of the effects of hitherto-obliterated mega-impacts on the Archaean oceanic crust, as modelled by Grieve (1980) and others. With an excavation depth exceeding its diameter, a projectile 10 km in diameter will penetrate the oceanic mantle, trigger catastrophic adiabatic melting and produce voluminous komatiite-basalt suites, covering and concealing the shock-deformed crust, as originally modelled by Green (1972, 1981). Long-term geothermal rises associated with cratered aureoles results in second-stage melting of the ultramafic-mafic crust, producing dacitic magmas. Propagation of radial lithospheric faults results in migrating loci of mantle and crust melting. Where such faults intersect older greenstone-granitoid nuclei, magmatically active rifted zones ensue. Such a model accounts for the multiple superposition of greenstone-granitoid cycles, as in the Pilbara, where magmatic episodes are identified at 3.51 Ga, 3.47-3.42 Ga, 3.3 Ga and 3.26-3.24 Ga (Nelson, 1997, 1998). Since the original impacted crust has been obliterated by burial, metamorphism and subduction, the only direct evidence may be provided by distal fallout deposits.

The positive identification of the 3.24 Ga impact cluster fallout deposits in the Barberton Mountain land, outlined above, yields the first well documented test case potentially allowing correlations between Archaean oceanic impact clusters and early crustal evolution. As further impact fallout deposits are identified, the role of extraterrestrial impacts in Archaean crustal evolution is bound to be progressively unravelled.

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