Extraterrestrial mega-impacts and continental growth on the early earth

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Solar system evolution chronicles how planets evolve through collisions of small and large asteroids and comets, and how even after completion of planet formation, around 4.56 Ga, these orbiting bodies continued their impacts through the entire Archaean and Phanerozoic eras, though progressively decreasing in size and number. On the moon, these impacts peaked around 3.95–3.85 Ga, a span known as the 'late heavy bombardment' (LHB), producing some of the well-preserved large craters, mares or basins. The earth also experienced these bombardments over the early formed crustal areas (cratons) and oceans, though today only a few of the craters produced have survived obliteration by geological processes like weathering, uplift, burial, crustal subduction or masked by later age magmatism, metamorphism and sedimentation.

Astrogeologists have found how galactic forces acting upon the solar system during its 250 million year orbit around the home galaxy, the Milky Way Galaxy, could have triggered intermittent biological, climatic and other changes on the earth. Cyclic occurrences of meteorite impacts with a 30–35 million year periodicity are found to coincide with successive passage of the solar system through each of the four spiral arms of the galaxy and these impacts were observed to be less pronounced during its interarm traverses[1,2]. According to the Earth Impact Data Base compiled in 2009 by the Canadian Planetary and Space Science Centre (PASSC), among the total 176 confirmed impact structures around the world, only five exceed 100 km diameter, 40 measure between 100 and 20 km and the rest < 20 km. A recent interpretative review[3] has summed up the observations made during the past few years by several groups on some of the impact generated crust–mantle effects (tectonic and magmatic consequences) on the early earth and has brought out how they are correlatable with specific impact episodes during the earth's evolution.

Collisions by large-sized extraterrestrial (ET) objects on the earth's surface at very high velocity (> 15 km/sec) liberate tremendous heat energy leading not only to the melting and vapourization of the impactor as well as the site-rocks but also to the shattering and brecciation of the site-rocks. Ejected out at immense force beyond the earth's atmosphere, this vapour cloud gets cooled and condenses into droplets and drops back either close to the impact site (proximal ejecta), or gets deposited thousands of kilometres away (distal ejecta)[4]. These ejecta or spherules, typically in spheroidal and near-spheroidal shapes may be entirely glass or glassy (microtectites) or partly crystalline (microkrystites). They retain signatures of their ET origin such as bubble cavities, quench devitrification textures, flow structures, streaks or schlieren besides mineralogical evidences like presence of platy magnetites, impact diamonds, shocked quartz and zircons, Ni-rich spinels, micrometre sized metallic nuggets of nickel and platinum group elements and chemical evidences such as high Ir, high Ir/Pd and greater $^{53}Cr/^{52}Cr$, $^{187}Os/^{188}Os$, $^{182}W/^{184}W$ isotopes, all in chondritic proportions[3].

Occurrences of several impacts during the Archaean and younger periods, missed either due to lack of expectation of their presence or mistakenly considered to be products of endogenic origin (e.g. ovoids of sedimentary origin and lapilli from terrestrial volcanism), are now getting recognized and reported increasingly from countries like South Africa, Australia, North and South America, Greenland, Europe and Russia. From India too spherule layers have been reported from the late Proterozoic Chaibasa shales in Eastern India[5], and spherules, glassy balls, magnetic dust and microbrecciated matrix from the late Cretaceous phosphorite beds in Barmer Basin, Rajasthan[6]. Environmental changes such as phosphate inundation in the sea leading to development of phosphorus bearing stromatolites in the Precambrian Aravalli Supergroup, Rajasthan are believed to be impact induced[7]. Discovery of Ir anomaly, impact-generated rare and exotic carbon form 'fullerene' are reported from Maharashtra and Gujarat, which are related to the late Cretaceous–Tertiary (K/T) impact[8].

The growing interest on studies about geological repercussions to the ET impacts on the earth owes much to the current developments in analytical techniques capable of providing geochemical, geochronological and isotopic data from minute mineral grains. Innovative procedures involving application of laser ablation microprobe coupled with an inductively coupled plasma mass spectrometer (LAM–ICPMS) have now made available several precise dates obtained on grains *in situ* and these have led to greater understanding of the potential of such dates in correlating incidences of ET impacts with geological, geodynamic events during the crustal evolution. Thus, it has now been possible to recognize impact relation to some of the events like, biological and atmospheric changes; development of unconformities; occurrences of tsunami boulder beds; compositional contrasts in beds that overlie and underlie the impact generated debris, lithostratigraphic changes; onset of iron-rich sedimentation; co-eval magmatic intrusives and enhanced heat flow; impact induced mantle rebound; tectonic and structural events, seismic activity, and rifting, breakup of continents.

Since oceanic coverage was greater during early earth times relative to the younger periods, there is a predominance of spherule layers over oceanic crustal sediments. Large 30–40 km sized impacts such as those that occurred between 3.20 and 3.24 Ga over the shallow Precambrian seas with their comparatively thin oceanic crust resulted in the creation of large crater basins, some > 1000 km diameter, depressing the crust at places to within 5 km of the Moho. Such violent impacts in the post-LHB period had forced volcanic eruptions (mantle plume magmatism or dyke swarms) leading to basalt flow flooding the basins, intrabasin sedimentation (volcanoclastic and reworked crustal materials), and finally subsidence of the basin floor due to loading[9,10]. Other geodynamic effects noted are mantle rebound, mantle diapirs, readjustment of mantle convection, higher geothermal gradient and seismic activity[3].

The post-impact regional and global changes in the environment have helped interpretations tracing secular changes in the nature of volcanism on earth, crustal makeup and variations in the nature of the incoming impactors. The observed disturbance and reworking of Precambrian marine formations in Western Australia (Hammersley Basin) and South Africa (Transvaal Group) are now linked to 3–5 oceanic impacts during the Neoarchaean[3], and likewise, perhaps, the late Proterozoic deep-sea Chaibasa shales and sandstones may be impact linked in view of their association with highly magnetic layers of platy magnetites found usually in impacts[5]. The controversial Shiva Crater (600 × 400 km) under the Arabian sea off the shores of Western India is thought to be produced by one of the multiple impactors that hit earth across Cretaceous–Tertiary boundary[11]. This collision is claimed to have triggered the Deccan eruptions as well as several geodynamic anomalies, deformation of the lithospheric mantle across western margin and initiated rifting of India and Seychelles besides precipitating a sudden, though brief, northward acceleration of the Indian plate during the Tertiary[11]. An earlier study in the same region has revealed higher heat flow and geothermal gradient, distortions within the asthenosphere and geodynamic events like crustal breakup, enhanced accumulation of hydrocarbons all possibly resulting from a bolide impact in the last ~130 Ma[12].

Spherule layers from impacts between 3.47 and 2.56 Ga are found overlying beds of Fe–Mg rich sediments (BIFs, jaspilite, ferruginous shales) from late Archaean to early Proterozoic marine formations in Pilbara Craton, Western Australia and Kaapvaal Craton, South Africa[3,13]. These Fe–Mg rich impact spherule layers are now supposed to have resulted from the melting of Fe–Mg rich crustal rocks beneath the impact site triggering mafic volcanism. Subsequent weathering of these uplifted and exposed Fe-rich rocks under the early-Archaean low-oxygen scenario is believed to have leached out the soluble iron (FeO) and enriched the anoxic seawater leading to their deposition as colloidal Fe-rich cherts and BIFs. Such associations of impact ejecta and iron-rich Archaean sediments could prove to be useful as stratigraphic links to impact episodes[13].

Evaluation of precise U–Pb ages obtained from over 5500 zircons has brought out 15 prominent age peaks between Palaeoarchaean and Permian (~ 3326 and ~ 290 Ma), which overlapped impact events and corresponded to thermal and tectonic events in the crust above impact sites implying the strong crust mantle connection[3]. Earlier studies have in fact brought out existence of punctuated thermodynamic evolution of the earth between early and late Proterozoic periods (1–2 Ga) like changes to mantle phase barriers, secular cooling related to mantle overturn events and subduction of plates[14]. Some of the changes that could be correlated with impact peaks are (a) those at the end of LHB at ~ 3.85 Ga, (b) impacts during 3.4 and 2.7 Ga records periods of maximum volcanic activity in the Archaean greenstone belts of Australia, South Africa, dyke swarms in Scotland, Finland, Russia, Antarctica, (c) ~3.34 Ga impact for the extensive volcanic activity in Pilbara Craton, (d) peaks between 3.26 and 3.24 Ga for the Barberton asteroid cluster, (e) at 2.03 Ga to Vredefort mega-impact, Kaapvaal and Glenburg orogeny in Western Australia, (f) the 1.85 peak with the Sudbury impact, actually this period coincides with worldwide intraplate and plate margin mafic magmatism in cratons, which would indicate global scale mantle upwelling and plume magmatism[15], and (g) the ~ 1.18 Ga peak with thermodynamic events in several Proterozoic mobile belts.

Mega-impacts > 100 km diameter could bring about a network of rifts, thermal disturbances and consequent volcanic activity. In the non-availability of precise isotopic ages for some of the distal ejecta observed at a few places, a clear correlation between impacts and these crustal effects has not been possible. However, some of the geological events having strong correlation potential are (a) the 65 Ma Cretaceous–Tertiary impact for the onset of Carlsberg Ridge spreading, Deccan volcanism and Hawaii-Emperor mantle plume, (b) the 145 Ma Jurassic–Cretaceous boundary impact for the Gondwana breakup, East African Rift structure, (c) the 250 Ma Permian–Triassic boundary impact for the Siberian Traps and early Triassic rifting[9]. In India, unproven but having strong possibilities for impact connections are the 1.89-Ga-old occurrence of the newly recognized Large Igneous Province in South Bastar Craton and the mafic sills in the nearby Cuddapah basin including the impact induced crustal fracturing[3,15], creation of the Arabian Sea bottom Shiva Crater, the triggering of temporary northward speeding up of the Indian Plate and rifting of Seychelles and India all ascribed to the 65 Ma K/T impact[11].

Except for the K/T impact correlation of the Indian occurrence of fullerene in the Ir-rich Cretaceous–Tertiary beds from Anjar in Gujarat[8] , and the hypothesized correlation of the spherule beds in the late Proterozoic marine sediments – the Chaibasa shales in Eastern India[5] and Cretaceous marine beds in the Aravalli Supergroup in Rajasthan in Northwestern India to the impacts of the respective periods[6], a greater part of the Indian Precambrians has not been examined for distinctive fingerprints such as geological, mineralogical or geochemical features pointing to direct impacts. Further, the role of mega-impacts in the claimed triggering of some of the continental breakup and initiation of rifting to open up oceans or for the onset of plate tectonism or intense magmatic and volcanic episodes leading to flood basalts are still much debated issues. In this category can be listed Indian examples of Deccan Volcanism; Kerguelen Large Igneous Province, Rajmahal Basalts and the older age dyke swarms in parts of Southern and Eastern India besides rifting of Seychelles from India.

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