The geochemistry of ecopoesis

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Liquid water is the dominant prerequisite for the origin, development, and sustainability of life as we know it. Earth has retained a significant hydrosphere since soon after its formation, which sets it apart from the other planets of the inner solar system. The presence of an extensive, early hydrosphere infers that the necessary environments for the emergence of life (i.e. ecopoesis) were in place prior to *c.* 3900 Ma. Once established, life has had a profound influence on elemental cycling on the surface of the Earth. The activity of life promotes disequilibrium fractionations between the terrestrial reservoirs of the bioessential elements C, N, O, S and P on the planetary scale, which can be evaluated by geochemical investigations, in this case, of the oldest rocks. The nature of the earliest environments for life remains poorly understood, but certain avenues of research are currently broaching the subject.

The lost record of the origin of life on Earth

The geological record is the only source of information about ecopoesis. Life has been traced to the oldest known rocks of sedimentary origin (Mojzsis *et al.*, 1996; Nutman *et al.*, 1997) but due to the recycling effects of plate tectonics and weathering, clues to conditions for its origin on this planet prior to 3900 Ma appear to be lost.

The search for pre-3600 Ma evidence of life on Earth has focused on water-lain sediments contained in the oldest crustal remnants preserved in metamorphic terranes of the North American craton. The >3000 km^2 Itsaq Gneiss Complex of the Ameralikfjord area in southern West Greenland has the largest, best-preserved, and most extensively studied occurrences of >3600 Ma crust. This and all other slightly younger 3600–3700 Ma gneissic terranes with associated supracrustal rock units found in southern Africa, Western Australia, north-eastern China and elsewhere, experienced intensive (amphibolite to local granulite facies) metamorphism by the late Archaean. The metamorphic histories of such terranes apparently preclude the possibility of finding preserved, and 'interpretable' fragile micro-fossil forms in any known rock units older than ~3600.

Isotopic *vs* morphologic fossils of life

Carbon isotope measurements have long been used to evaluate the contribution of bioorganic matter to sedimentary rocks, with or without the indicative presence of recognizable microfossils. No abiotic means for fractionating the isotopes of carbon have been identified that can mimic the characteristic fractionation of $^{13}C/^{12}C$ resulting from metabolic processing via enzymatically-driven reaction pathways that convert inorganic carbon to bioorganic matter. The sensitivity, during thermal alteration, of this bioorganic carbon isotopic signature to drift toward isotopically heavier values (not the reverse) requires that the system be isolated from isotopic exchange with a dominant reservoir of inorganic (e.g. carbonate) carbon after formation. The armouring of reduced carbon, e.g. in stable mineral phases resistant to metamorphism, has been demonstrated to improve the preservation of the bioorganic signature against progressive erasure, and thus provides an indicator of life in sediments of all ages and extending into the earliest known rocks on Earth.

Ecopoesis and the late heavy bombardment

Although it yet remains unknown how or when life first appeared on Earth, the window for this event is limited to the roughly 600 million years between the formation of the planet at 4550 Ma and the deposition of the oldest known sediments *c.* 3900 Ma. The presence of life on Earth before 3,850 Ma appears to occur in the context of the late heavy bombardment of the Moon; a constraint on the survivability of an emerging ecology can be argued by invoking impact frustrations deleterious to the origin, or continuous evolution, of life. Ironically, this early infall of extraterrestrial debris is also postulated to have been an important contributor to the inventory of organic matter, and other reducing compounds, to the surface of the pre-3900 Ma Earth at the time of life's

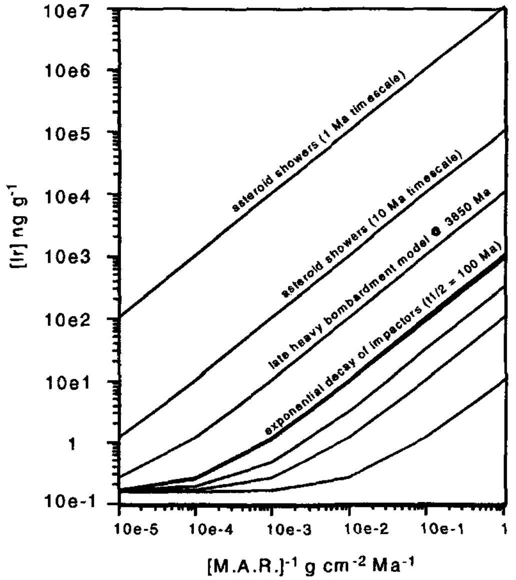

FIG. 1.

emergence (e.g. Chyba and Sagan, 1992).

However, incomplete sampling of the lunar crust has created uncertainties in the timing of bombardment of the Moon between 3700 and 3900 Ma. Some model calculations based on statistical analyses of known lunar crater ages, and applied to Earth, suggest that the meteoritic influx could have been about 10^4 greater at ~3900 Ma than at present, which translates to ~4 μg m^{-2} a^{-1} of meteoritic material reaching the Earth's surface at that time. Since decoupling of the core and mantle before 4500 Ma (Halliday *et al.*, 1996), the PGE content of accumulating sediments may be used as a sensitive indicator of meteoritic influence, and places an upper limit e.g. on the contribution of exogenous carbonaceous material reaching the surface of the Earth.

To test this hypothesis, investigations by instrumental neutron activation analysis of the trace element and Ir geochemistry of BIFs from the early Archaean have been initiated. Pre-3700 Ma terrestrial sediments would be expected to preserve an Ir (and other PGEs) signal of higher incident fluxes of extraterrestrial debris, such as dusts from airbursts, interplanetary dust particles (IDPs, which contain upwards of 10 mass % C) and/or local impacts, impact breccias, and melt sheets. Early Archaean chemical sedimentary precipitates such as BIF, are desirable for evaluating potential contamination from meteoritic infall, because during deposition they sampled the chemistry of their overlying water column and contain negligible contributions from the weathering detritus of igneous rocks which could blur or severely dilute the PGE signal.

None of the BIFs thus far investigated contain Ir above the detection level of individual samples. Upper limits for the Greenland rocks averaged <0.4 ppb Ir (Ir chondrite equivalent, IrCE = 0.08%), which is comparable to present-day pelagic clays, bituminous shales and Fe-rich marine hydrothermal sediments, which contain <1 ppb Ir (*vs* 480 ppb in CI meteorites). The oldest sediments yet documented have Ir abundances as low as the 2100 Ma Proterozoic analyte Gunflint chert, and are less than would be expected both from theoretical calculations of exogenous delivery of material at ~3850 Ma (~10 ng Ir $m^{-2}a^{-1}$) and assumptions of the sedimentation rate of BIF (using ~1 mm a^{-1}; Fig. 1). This might mean that the decline in meteoritic infall from the time period 3850 Ma (the age of Imbrium) to 3800 Ma using the cataclysm model was even more rapid than that inferred from lunar samples, or that it describes a record of impacts parochial to the Moon that also occurred over different timescales from the Earth.

Conclusions

The observation that life was present at the time of the deposition of the oldest rocks, and of an apparent absence of a significant meteoritic signal in these sediments is used to make a case for an extension of the window of life's emergence on Earth back in time to a period hitherto forbidden by model arguments for an uninhabitable and intensely bombarded surface near 3900 Ma. This raises the question of the relative ease for an origin of life, and the possibilities for it to arise elsewhere in the early solar system (e.g. Mars, Europa) when liquid water was stable (Mojzsis and Arrhenius, 1998).

References

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