PERSPECTIVE

EARTH SCIENCES

On the biospheric effects of geomagnetic reversals

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Unlike its neighbor planets Mars and Venus, Earth has a global magnetic field. The geomagnetic field effectively protects life from the solar wind and cosmic radiation, prevents atmospheric erosion and water loss, and thus make for a habitable planet [1]. The geomagnetic field also provides useful clues to orientation and navigation for a diverse group of organisms, from bacteria to vertebrates. Ground station and satellite measurements indicate that the strength of the-present-day magnetic field is decreasing, and the South Atlantic Anomaly, a huge area spanning South Africa to Patagonia of low field strength, is continuously growing in size. These raise concerns and discussion both among specialists and the public if a geomagnetic field reversal, a flipping with the pole reversing sign, may be imminent; if happened, life on Earth including our humans may face high irradiation and other environmental risks.

Paleomagnetic studies have indicated that the geomagnetic field has reversed its polarity at least several hundred times during the Phanerozoic Eon. The strength of dipole field can decrease by as much as 90% at Earth's surface during a reversal or an excursion (also called a failed/aborted reversal) (Fig. 1a, b). Recently, Channell and Vigliotti found that the timing of geomagnetic field strength minima across Quaternary geomagnetic excursions appears to correspond to events in mammalian evolution [2]. Ueno and coworkers proposed that an increase in galactic cosmic rays during the Matumaya-Brunhes transition (the last geomagnetic polarity reversal at ~780 ka ago) produced an "umbrella effect" of low-cloud cover which led to high atmospheric pressure in Siberia, possibly causing the East Asian winter monsoon to become stronger [3]. In more deep time, a good opportunity to uncover the impacts of geomagnetic field variation on the biosphere is the intervals of high-frequency geomagnetic reversal (Fig. 1b). Meert and coworkers further suggested that the high-frequency geomagnetic reversals during the Ediacaran-Cambrian transition might be responsible for a major replacement of biotas that led to the appearance of Phanerozoic higher-level taxa and ecological communities in the marine realm [4]. Recenly, Tarduno's group contributed single crystal paleointensity data and found the Ediacaran time-averaged field strength extraordinary low [5], followed by a significantly increase in strength in Cambrian. Nevertheless, Lingam argued that the dynamic and heterogeneous Edicarian geochemical environment, rather than the nucleation of inner core or an increase in the magnetic field strength, appears more plausible driving the Cambrian radiation [6].

Indeed, as one of the important prerequisites, the geomagnetic field is a constructive factor enabling life on Earth: adding protection against atmospheric escape, and diminishing doses of ultra-violet radiation (UVR), galactic cosmic rays, and other energetic particles reaching the surface. Moreover, as a factor in environmental change on an enormous scale, geomagnetic reversals could impact many elements of the biosphere. Specifically, in this scenario, geomagnetic field reversals can have a positive evolutionary effect by stimulating the emergence of new function and new organisms via associated environmental changes. Paleomagnetic records indicated that the geomagnetic field might exist since the late Hadean, prior to the development of the first microbial life (Fig. 1c) [1]. Although the radiative effects of energetic charged particles of solar or cosmic ray may not directly negatively impact the biosphere because of shielding by the atmosphere, their increasing entry into the atmosphere during geomagnetic field transitions can lead to an increase of ozone loss, and an increasing penetration of solar UVR to the Earth's surface [7]. On one hand, solar UVR can produce a multitude of harmful effects on cells including alteration in the structures of DNA and other biologically relevant molecules, chronic depression of key physiological processes, and acute physiological stress. These can act as a kill mechanism for terrestrial life. On the other hand, UVR stress might have been one of the major ambient selective pressures that led life to develop a wide range of evolutionary adaptations to defend against harmful UVR. These include behavioral mechanisms (e.g., migrations, burrowing, nocturnal activity), screening or absorption (i.e., pigments like mycosporine-like amino acids, carotenoids or melanin), and cellular mechanisms (i.e., DNA-repair, anti-oxidants, and biomineralization). UVR stress would bring about increases in mutation rate within populations as a barometer of speciation, which is the foundation of biodiversity and evolution. Thus, aperiodic yet frequent geomagnetic field reversals, rather than merely a killing mechanism, could be an evolutionary force speeding up mutation rate, speciation, and biological innovation through environmental UVR stress.

Life on Earth is the result of a continuous, yet variable, selection since its onset. Evolution is composed of many events of mass extinctions, recoveries and radiations which were often interactively coupled with significant environmental perturbations (Fig. 1a,b,c). Many organisms have developed evolutionary adaptations to coevolve with Earth's environmental disturbance that includes changes in the geomagnetic field (e.g., geomagnetic reversals, superchrons) and associated UVR flux. Thus, the geomagnetic field is a natural component of environmental forcing important for organisms. Interestingly, from the very beginning of their existence, organisms functioned and evolved in the presence of the geomagnetic field. By using the geomagnetic field as a source of spatial information, many organisms, from magnetotactic bacteria (MTB) to plants and animals, could better adapt to environmental and climate changes. Examples include long-distance animal migration/navigation and up-and-down MTB magnetotaxis shuttle [8,9]. We recently found that long-term exposure of mice to hypomagnetic fields exhibit significant impairments of adult hippocampal neurogenesis and hippocampus-dependent learning, implying that the geomagnetic field is essential for mammals [10]. In light of ever accumulating evidence, we conclude that geomagnetic field effects on the biosphere have always existed, and that these directly and indirectly, have influenced biotic evolution. These have acted together with other global environmental processes such as sea-level fluctuation, paleoclimate change, plate tectonics, volcanic eruptions, oxygenation, asteroid impact, and other processes. But the effects of the geomagnetic field have been non-negligible through the history of life on the planet.

Therefore, it is necessary to gauge biospheric effects of geomagnetic field variations in the space-time dimension. So far, our understanding of the fundamental mechanisms between geomagnetic field and biological effects is incomplete due to the complexity of the linkages and shortage of data. Multidisciplinary studies on the geomagnetic field-UVR-life interplay are crucial for a better understanding of cause-effect relationships. A combination of behavioral, physiological, and molecular studies could provide insights into the fundamental mechanisms. Simulation and experimental studies on the geomagnetic field-atmosphere and climate interplay are also needed to assess if changes in the geomagnetic field could trigger the changes in cloud cover and precipitations, topics which are currently intensively debated. Future studies recovering records of the paleomagnetic field and ancient life in rocks (integrated paleoenvironmental, paleomagnetic and paleontological studies, including big data analyses), and in particular, studies of specific polarity transitions and/or high frequency geomagnetic reversal intervals are needed to decipher deep-time truth. Such investigations could provide unprecedented insights into understanding the linkage between the geomagnetic field and biosphere, the co-evolution of life with environments, and, ultimately, planetary habitability.

Acknowledgements

We are grateful to Rixiang Zhu, Chenglong Deng, and Wei Lin for discussions, and Jiawei Liu, Min Zhang, Yan Liu, and Peiyu Liu for assistance in figure preparation. We weould like to thank three anonymous reviewers for their valuable and constructive suggestions, which led to significant improvement of the quality of our manuscript.

Funding

This study was supported by the NSFC grants 41621004 and 42225402.

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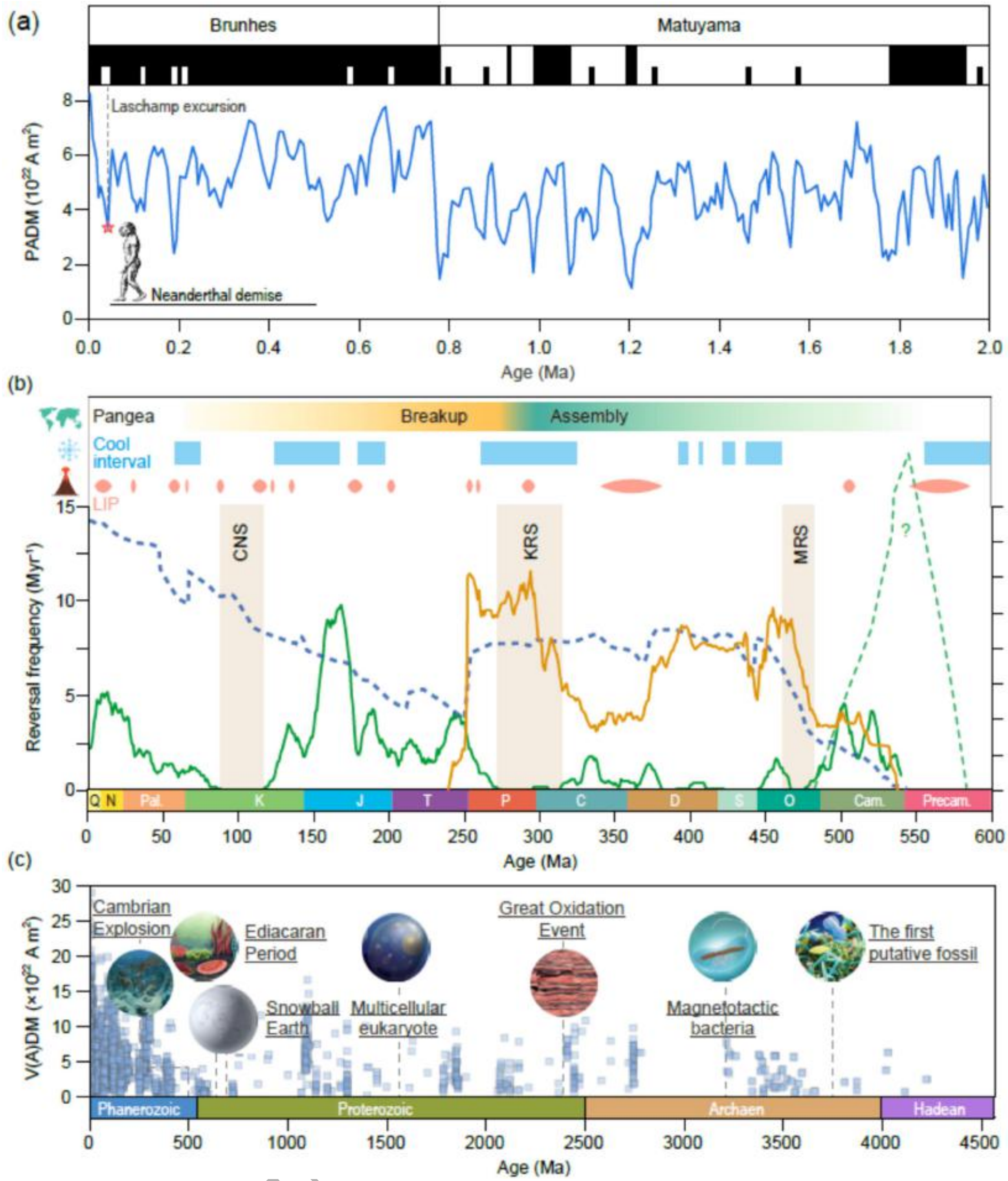

Figure 1. Polarity, reversal frequency, and strength of the geomagnetic field correlate with the major geological and biological events (see the Supplementary Materials online for detailed description).