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Earth Matters: A tempo to our planet's evolution

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Earth is our home and we, along with all life, are dependent on it for our future. There is no more fundamental issue, from either a philosophical or a practical viewpoint, than to understand Earth history and how it has evolved to form the environment we live in and the resources on which we depend. The origin of Earth, and our role within it, has fascinated humanity from time immemorial, yet we know remarkably little of Earth's long-term temporal and spatial evolution. Apart from the last few thousand years, most of our 4.55 billion years of history is preserved in the rock archive, but that record is incomplete, and our knowledge of it decreases with increasing age and depth. Furthermore, the long-term record is restricted to relatively buoyant continental lithosphere (crust and upper mantle). Thus, continents provide the only long-term record of development and evolution of our planet's atmosphere, oceans, crust and underlying mantle from the time of their formation to the present day. Over the past quarter century, our ability to interrogate the continental record has dramatically improved through developments in microanalysis and in computing. This has enabled ever-increasing documentation of spatial and temporal variations in rock units and events, including the composition and pressure-temperature-time conditions to which specific rocks and regions were subjected, and from this data an increased ability to develop high-fidelity numerical models of the processes involved. These expanding data sets and models highlight the dynamic nature of our planet's feedbacks between its solid and surficial reservoirs, and their response to evolving internal and external forces.

Although the archive is incomplete, it is clear that Earth's reservoirs record a pulsed and episodic history across a range of spatial and temporal scales (Fig. 1). However, long-term trends are superimposed on short-term atmosphere and ocean cycles (Fig. 1), leading to speculations on feedbacks between the surficial and solid reservoirs and potential links to changing geodynamics (e.g., decreasing mantle potential temperature, the onset of plate tectonics) and/or paleogeography (e.g., supercontinent cycle; Shields, 2007; Cawood and Hawkesworth, 2014; Lyons et al., 2014; Knoll and Nowak, 2017).

Brown et al. (2020, p. 488 in this issue of Geology) proposes temporal links between whole Earth spatial and temporal data sets and possible geodynamic drivers. They present a time-series analysis of thermobaric ratios (temperature/pressure [*T*/*P*]) of metamorphic rocks ranging in age from ca. 3700 Ma to 15 Ma (Eoarchean to Cenozoic). This analysis identifies shifts in mean *T*/*P* that they suggest correspond to inferred secular change in Earth geodynamics, including the onset of plate tectonics in the Archean and supercontinent assembly and breakup in the Proterozoic and Phanerozoic. Thermobaric ratios record significant drops in mean *T*/*P* at 1910, 902, 540, and 515 Ma, and rises at 1830, 604, and 525 Ma. Changes in *T*/*P* also correspond with changes in hafnium (Hf) and oxygen (O) isotope compositions in zircon but with a reversal in the correlation changes at ca. 500 Ma, corresponding with a change in the overall trend of seawater ^{87}Sr/^{86}Sr ratio (Fig. 1). Prior to 500 Ma, Hf shows a negative correlation with *T*/*P*, and O shows a positive correlation with *T*/*P*, while post-500 Ma, Hf is positively correlated with *T*/*P*, and O is negatively correlated with *T*/*P*. Brown et al. note that changes in the thermobaric record are concentrated in the late Paleoproterozoic (ca. 1900–1800 Ma) and late Neoproterozoic to early Phanerozoic (ca. 600–500 Ma), corresponding to the assembly phases of the Nuna (Columbia) and Gondwana supercontinents, respectively. The paucity of changes in the intervening time period, as well as through the remainder of the Phanerozoic, could be linked to larger-scale continental cycles (Fig. 1). In the case of the Nuna-Rodinia association (Nudinia), this provides a stable paleogeographic setting for the environmental, evolutionary, and lithospheric stability that extended from ca. 1.8 to 0.8 Ga (middle age in Fig. 1). The cessation of this phase corresponds with the breakup of Rodinia, as well as the preservation in the rock record on blueschist and ultra-high pressure assemblages (Ernst, 1972; Brown, 2006), which corresponds with the overall drop in the thermobaric record noted by Brown et al.

The development of global data sets, such as those presented by Brown et al., documenting temporal trends in atmosphere, ocean, biosphere, and crustal evolution has led to much discussion of both intra- and inter-reservoir controls (Fig. 1; Shields, 2007; Cawood et al., 2013; Lyons et al., 2014; Hawkesworth et al., 2017; Knoll and Nowak, 2017). Trends in these long-timescale reservoirs correspond with continental evolution, supercontinent cycles, and changes from non-plate to plate tectonic geodynamic regimes (Fig. 1). Proposed correlations range from tightly time-constrained (e.g., Brown et al.) to time-lags of tens to hundreds of millions of years between proposed cause and effect (e.g., Campbell and Davies, 2017; Doucet et al., 2019). The growing data sets and proposed correlations within and between them are stimulating research into Earth as a system and, in particular, the importance of mantle and solid Earth controls on surficial elements (atmosphere, oceans, biosphere). However, there is also a tendency to draw correlations simply on the basis of time, when it may be difficult to evaluate the links. Thus, it is topical to relate any and all changes in late Archean data sets to the onset of plate tectonics, with or without an understanding of how such compositional changes relate to, or are controlled by, the geodynamic regime. This is especially significant because the timing at which plate tectonics started is debated, and it likely occurred not at a single point in time but as a transition phase over hundreds of millions of years (Fig. 1; Cawood et al., 2018). Changes in the Proterozoic are often linked to the supercontinent cycle. Irrespective of whether invoked links are close or offset in time, methods to quantitatively evaluate the causes and drivers of such links are lacking. Drawing temporal correlations is important, but it is not an end in itself, and the potential exists that doing so becomes a self-fulfilling justification that they are significant.

With any data analysis it is important to know what is being measured and whether it is representative. This is particularly relevant to the

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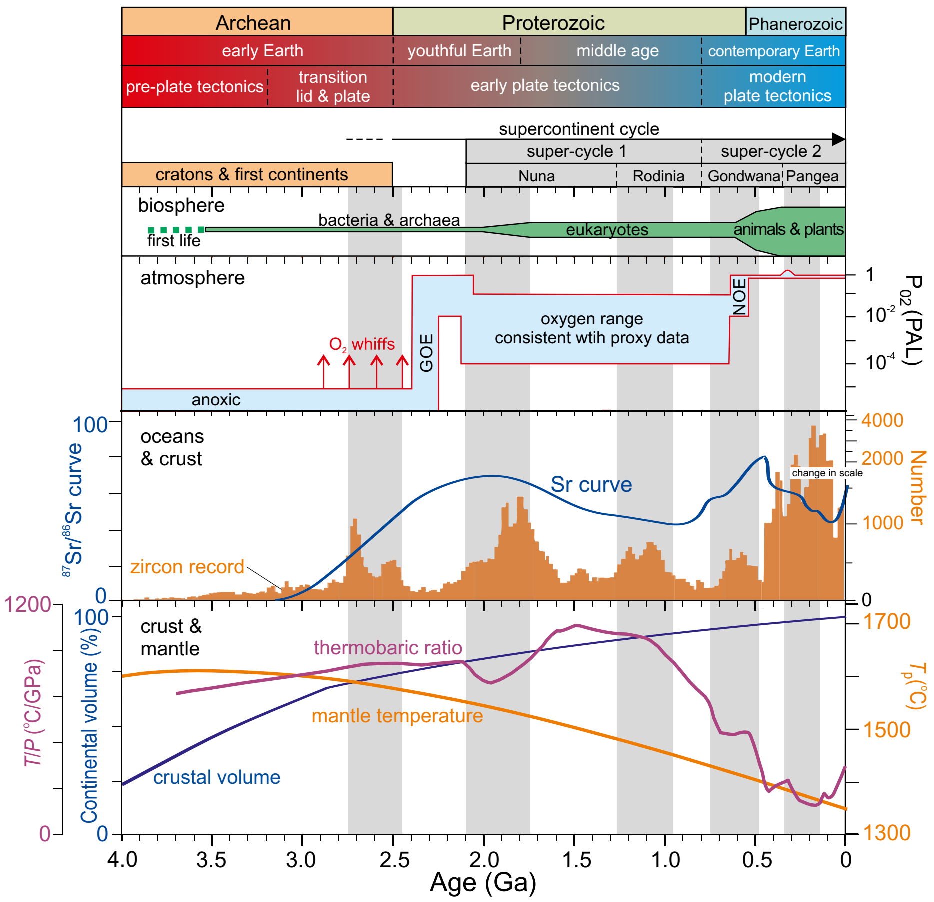

Figure 1. Potential stages of Earth evolution and geodynamic regimes with respect to the formation and stabilization of cratons and first continents; the development of the supercontinent cycle; the evolution of life within the biosphere (Knoll and Nowak, 2017); changing oxygen levels within the atmosphere relative to present atmospheric level (PAL; Lyons et al., 2014); normalized seawater ^{87}Sr/^{86}Sr curve (Shields, 2007); U-Pb crystallization ages of over 100,000 detrital zircons (Voice et al., 2011); locally weighted scatter-plot smoothing thermobaric ratio curve (Brown et al., 2020); an estimate of crustal volume (Dhuime et al., 2012); and inferred mantle potential temperature (Herzberg et al., 2010). Gray shaded bars correspond to the assembly phase of the Kenor supercraton, and the Nuna, Rodinia, Gondwana, and Pangea supercontinents.

study of Earth in deep time due to the fragmentary nature of the preserved record. For example, Hawkesworth et al. (2009) have argued that the episodic character of the zircon age population record (Fig. 1) is not a primary record of their generation but reflects a secondary preservation bias related to the supercontinent cycle. Thus, if specific *T*/*P* data (e.g., high dt/dP versus intermediate dt/dP) analyzed by Brown et al. are biased by selective preservation, rather than representing the tectonic setting for their generation, this will impact interpretations of the significance of any temporal changes. Therefore, we, as a discipline, need to move beyond simple temporal correlations and undertake a critical evaluation of the reasons for such links. A potential way forward is to couple observational data sets with numerical modeling. For example, Sizova et al. (2014) revealed how falling mantle temperatures on modern Earth (post-800 Ma) enabled deeper levels of slab breakoff at collision zones, resulting in greater depths of underthrusting of continental lithosphere, and thus accounting for the development of the ultrahigh-pressure metamorphic assemblages. Thermomechanical models by Capitanio et al. (2019) of mantle convection and melting under inferred early Earth (pre-2500 Ma) conditions replicated the pressure-temperature regimes recorded in the rock record within a non-plate, rather than a plate, tectonic setting and demonstrated the synchronous development of two stable long-lasting tectonic domains (stagnant lid and proto-plate).

The coupling of observations with modeling provides a method to critically assess the Earth system under the myriad of conditions, and range of temporal and spatial scales, that it has operated in over its 4.5-billion-year history, and provides an exciting future for the Earth Sciences.

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