Earth Evolution, Emergence, and Uniformitarianism

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Emergent phenomenon describes the propensity for any high-energy, far-from-equilibrium system to self-organize in ways that cannot be predicted from knowing its individual components (Ablowitz, 1939; Pines, 2014). Emergence is closely related to self-organization, complexity, and evolution. Animals, ecosystems, spiral galaxies, hydrothermal systems, hurricanes, and civilizations are some of the many examples of emergent phenomena, where low-level rules give rise to higher-level complexity. Entirely new properties and behaviors "emerge," without direction and with characteristics that cannot be predicted from knowledge of the constituents alone. The whole is truly greater than the sum of its parts. Yes, the second law of thermodynamics is real, but it can take a long time for the system to stop dissipating energy. In the case of long-lived, high-energy systems like convecting silicate planets with a significant fraction of primordial heat trapped inside and with slowly diminishing contributions from radioactive decay, entropy may have to wait billions of years to shut down the party.

Morowitz (2002) outlines the emergence of 28 things, beginning with the Big Bang and ending with civilization. The self-organization of organic molecules to make life may be the most spectacular example of emergence. Earth's climate, hydrosphere, and nutrient cycle all are emergent phenomena. These are in fact co-emergent systems, evolving together in ways that presently cannot be predicted. Those who have tried to predict the stock market or the course of the COVID-19 pandemic know the futility of trying to foresee what will happen next in these emergent systems. The tectonic styles of convecting silicate bodies in our Solar System are also examples of emergent behavior. Such behavior is expected for these high-energy, far-from-equilibrium systems as their interiors cool and their lithospheres respond by becoming thicker, denser, and stronger. Strong temperature gradients between the cold, rigid exterior and the hot, convecting interior cause density inversions coupled to large nonlinear variations of rock strength and viscosity that together drive emergent behavior, manifested in the lithosphere as tectonics.

Although emergent behavior is today impossible to predict, it can leave evidence that allows the history of an emergent system to be reconstructed and quantitatively understood. This is as true for planets as it is for civilization. Is it possible to discern emergent behavior in the tectonic behavior of active bodies in the Solar System? Yes, but it is easier for smaller, dying planets than for more vigorous, larger ones (Earth, Venus), where evidence for earlier tectonic styles is often obliterated by newly emergent ones. Mars is a good example of a slowly dying planet, because its small size has enhanced cooling of its interior over its 4.56 Ga lifetime. Mars' crustal dichotomy preserves evidence of three successive emergent tectonic styles: (1) creation of the primitive crust now preserved in the southern hemisphere; (2) crustal rejuvenation (best exposed in the northern lowlands) by widespread volcanism possibly related to giant impact and subsequent mantle convection (e.g., Golabek et al., 2011); and (3) strongly focused long-term magmatism and tectonics caused by localized mantle plumes, manifested by large volcanoes in the Tharsis and Valles Marineris regions.

Plate tectonics—Earth's unique lithospheric manifestation of mantle convection—is almost certainly an example of emergent behavior of a still-vigorous convecting planet. This conclusion was recently highlighted by Brown et al. (2020), who compiled and analyzed thermobaric ratios (temperature/pressure, *T/P*) for Paleoarchean to Cenozoic metamorphic rocks and used this to identify times when significant shifts in mean *T/P* occurred. The variations in Earth's thermobarometric ratio must reflect changes in Earth's convective and tectonic style that can usefully be called emergent. Consistent with this conclusion, numerical modeling investigation even of very simplified mantle convection systems with Earth-like rheology shows emergent behavior, such as spontaneous appearance and self-organization of various tectonic plate boundaries; growth, aging, and subduction of oceanic plates; and generation of a global plate mosaic (e.g., Tackley, 2000). Lenardic (2018) explored this point further, arguing that any convecting Earth-like silicate body would experience multiple emergent transitions between different planetary tectonic regimes, reflecting changes in lithosphere strength and planetary internal energy with time. Indeed, numerical models reveal that several different global geodynamic regimes in Precambrian time likely preceded modern plate tectonics (e.g., Gerya, 2019). Multi-stable behavior allows, in particular, for the possibility that plate tectonics could emerge, transition to another mode, and re-emerge along a planet's cooling path.

Because the emerging tectonic regime will obliterate much of the evidence for earlier regimes, we will have to be clever to figure out how plate tectonics evolved on Earth and even more clever to figure out what other tectonic styles emerged before this. We have argued elsewhere that the modern episode of plate tectonics emerged when a very strong mantle plume ruptured all-encompassing but gravitationally unstable lithosphere (Gerya et al., 2015), and one of us has repeatedly argued on different lines of evidence that this happened in Neoproterozoic time (Stern, 2018). These ideas are controversial but beg the question: why hasn't the conceptual framework of emergent tectonics gained more currency in our science?

GSA Today, v. 31, https://doi.org/10.1130/GSATG479GW.1.

One problem may be our (mostly implicit but still pervasive) attachment to the principle of uniformitarianism,"The present is the key to the past" and its offspring, actualism "The present, punctuated by occasional catastrophes, like bolide impacts and snowball Earth, is the key to the past" (Windley, 1993). Uniformitarianism was very useful when eighteenth- and nineteenth-century geologists were debating the age of the Earth with clergy claiming it was 6,000 years old, but that was then, and this is now. Does our allegiance to the old philosophy stop us from addressing questions that need to be asked?

Gould (1965) distinguished substantive and methodological uniformitarianism. Substantive uniformitarianism considers that ancient Earth processes (e.g., orogeny, sedimentation, erosion) were the same as now operating. In contrast, methodological uniformitarianism states the obvious: that the laws of physics and chemistry pertain to all of Earth's history. Gould (1965) concluded that substantive uniformitarianism was "…false and stifling to hypothesis formation…" and is "…an incorrect theory [that] should be abandoned" (p. 223). There is still an important role for substantive uniformitarianism in our efforts to reach and teach students and the public. Perhaps in 1965 it appeared that the battle with creation pseudoscience was over, but not in 2020, at least in the United States. Substantive uniformitarianism is still useful for teaching lower-division undergraduates and in battles with creationists, for example, to show why and how the Grand Canyon was carved in a few million years by the Colorado River flowing through a plateau lifted up by mantle convection, not in a few days by Noah's flood. But within the scientific community, substantive uniformitarianism poisons scientific discussions about how plate tectonics came to be Earth's dominant convective mode.

Modern earth sciences use methodological uniformitarianistic approaches for both discovering and understanding emergence based on numerical modeling that uses fundamental physical laws for investigating behavior of complex geological systems. This emergent trend in earth sciences reflects the maturing of the discipline from a descriptive qualitative to a predictive quantitative science and opens the door to clearer thinking about emergent phenomena on Earth. In this respect, modeling combined with observations offer a good way to better calibrate our intuition for emergence, as well as to test if a geological system of interest is prone to emergent behavior and what are the main physical parameters controlling it.

We think that encouraging thinking about the role of emergence in all earth systems should be part of the way for the geosciences to advance in the twenty-first century. The field of emergence is much broader than the earth sciences, with entire institutes studying a wide range of emergent phenomena; for example, the Santa Fe Institute, https://www.santafe.edu/about. At present, the emergence of planetary tectonic styles is not being considered by these researchers, and it should be. How can we help make this happen? A good first step would be for more geoscientists to learn about emergence; the Wikipedia entry "emergence" is a good place to start. Second steps include teaching about emergence in our classes and considering it in our research.

Embracing emergence for understanding Earth's history not only can inject excitement into our science, the philosophy can pay psychic benefits. We are facing a very uncertain future, but thinking about emergence can perhaps reassure us that all futures are uncertain except for low-energy systems (e.g., dead planets and dead people). Which would you rather be part of, a low-energy system with a certain future or a high-energy system with an unpredictable future but with the promise that something will emerge, some time in the future? We know which planet we want to be on!

ACKNOWLEDGMENTS

Thanks to Pete DeCelles and an anonymous referee for constructive comments and suggestions. This is University of Texas at Dallas geosciences contribution #1373.

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Manuscript received 23 July 2020
Revised manuscript received 20 Aug. 2020
Manuscript accepted 6 Sept. 2020