



Commentary

Did Earth drive itself to a snowball?

Chunan Tang ^{a,b,*}^a State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China^b State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan), Wuhan 430074, China

The icehouse model, in terms of low CO₂ effect, elegantly accounted for the global cooling events on Earth's surface, which has occurred at least several times in the history of Earth evolution. However, it does not appear to explain the great cooling events such as the Late Ordovician glaciation with an unusually high CO₂ level of 4,000 ppmv [1], more than ten times higher than the CO₂ level of today. Previous published records shows a CO₂ increase during some glaciations [2], conflicting with the mainstream theory. Although Pagani et al. [3] later suggested that the evidences available support a drop in CO₂ as a critical condition for global cooling, whether CO₂ played a dominant role alone to cause the greenhouse-icehouse transition or whether a threshold level of CO₂ ultimately induced global cooling cannot be determined from their results.

Donnadieu et al. [4] believed that the extensive cooling event during the Sturtian episode may have been resulted in due to a high obliquity (750 Ma). However, it is impossible to produce large glaciations in the case of mid to high latitude paleogeographies such as the Varangian-Vendian episodes (620–580 Ma). In addition, if we accept the idea that high obliquity is a possible trigger for glacial events such as the Sturtian glaciation, we have to found a mechanism to recover from the high obliquity. Seeking primarily to explain the paleomagnetic data, Williams (1975) proposed that Earth's axial tilt (the obliquity of the ecliptic) exceeded 54° until the end of the Proterozoic [5,6]. This implies that Earth's climatic zonation would accordingly have been reversed in the Proterozoic, meaning lower insolation at low latitudes than at the poles. However, the seasonal cycle would have been greatly amplified, resulting in hot biannual summers, which do not favor glaciation. The Williams's hypothesis of high-obliquity is not consistent with the observed glacial deposits with carbonates including inorganic sea-floor aragonite precipitates [5].

Despite the early skepticisms about the extent of CO₂ effect or the high-obliquity effect on global cooling, these hypothesis were subsequently used to account for almost all anomalous cooling events. However, the causal relationship between the decrease of CO₂ and global cooling from the original predictions of the hypothesis have not been confirmed.

Donnadieu et al. [7] try to explain the mechanism of Proterozoic snowball Earth by connecting it with the increase in runoff as a

consequence of Rodinia breakup 800–700 Ma ago. They assume that the precipitation increase and runoff over the continents causes large quantity of carbon dioxide to consume. However, Brune et al. [8] show that supercontinent breakup could also produce massive, long-term CO₂ emissions. A clear geological link between continental rifting or breakup and CO₂ degassing has been found on Earth, and more and more evidence of CO₂ flux measurements have been documented in many types of rift systems, such as the Basin and Range Rift, the Rio Grande Rift, the Eger Rift, the East African Rift System, and its western branch. All of these data indicate that the continental rifting system provides important pathway to connect the vast carbon reservoir in Earth's mantle to Earth's surface [8].

Hence, precise quantitative evaluation of the effect of atmospheric CO₂ fall in terms of runoff on the global cooling or the effect of atmospheric CO₂ rise in terms of rift emission on the global warming requires a sophisticated approach in considering their heat balance.

The history of Earth's evolution exhibits geologically active and quiescent periods, including magmatism, metamorphism, mineralization and tectonism. In the meantime, alternative cooling and warming have also occurred many times in the geological history of Earth. However, there is no consensus about the fundamental relationship between the thermal cycles and the episodic processes. Scientists generally ascribe the cause of cooling and warming either to bias in the effect of CO₂ cycles or astronomical effect. In a recent paper in *Nature Geoscience* [9], Spencer et al.'s discovery of a prominent magmatic gap seems challenge this geological belief. After a comprehensive evaluation of the geologic record from 2.4 to 2.0 Ga, they found a tectono-magmatic lull around 2.3–2.2 Ga. During this long geological quiescent period, global-scale continental magmatism and orogenic activity decreased greatly. The data also shows a lack of sedimentation activity on passive margin and rate of plate motions were relatively subdued. In fact, a period between 2.4 and 2.0 Ga called tectonic shutdown has previously been defined to interpret this tectono-magmatic lull [9].

The global cooling between 0.8 and 0.6 Ga, the second snowball Earth, also coincide with a prominent magmatic gap (the prominence of the zircon age lull) [1].

Spencer et al. [9] also posit that the geological quiescence ended about 2.2 billion years ago by a flare-up of juvenile magmatism, released significant thermal energy that had accumulated during the geological quiescence of the snowball Earth. This flux of

* Corresponding author.

E-mail address: tca@mail.neu.edu.cn

mantle-derived energy could have provided a mechanism for Earth warming and cooling as a consequence of heat accumulation and loss underneath the crust. These events must be linked to the thermal cycle of the Earth's interior rather than the surface external causes. The correspondence of a prominent magmatic lull with the extensive 0.1 Ga duration of snowball Earth suggests that it is not convincing to correlate the snowball Earth climate with an enhanced consumption of atmosphere CO₂ through changes in runoff due to the dispersal of the supercontinent. This mechanism clearly ignores the fact that widespread continental rifting will result in huge heat loss, both through rifting induced de-compressive melting and lava eruption.

Although no unifying model explains all of the observed thermal fluctuations of Earth [1], we now know that there are many ways for Earth to trigger global cooling events by losing its interior heat. Moore and Webb [10] proposed a heat-pipe Earth model to provide an explanation of early Earth cooling through volcanism [10]. Sporadic processes such as enhanced plume activity and mountain building have been invoked as drivers of specific warming or cooling intervals. Lourenço et al. [11] even find that heat loss due to intrusive magmatism can be particularly efficient compared to volcanic eruptions. Recently, Stern and Miller [12] recognized that the Neoproterozoic Snowball Earth climate crisis may reflect the transition of Earth's tectonic style from stagnant lid (single lithosphere) to the modern episode of plate tectonics, and only extraterrestrial triggers cannot be reconciled with the hypothesis that the Neoproterozoic climate crisis was caused by a prolonged (200–250 Ma) transition to plate tectonics. This implies that it must be caused by some reasons from interior of the Earth, which exactly support my idea: Earth drive itself to a snowball.

The idea of Earth's thermal cycles is akin to heat and pressure fluctuation within a heating pressure cooker, with lithosphere playing the role of lid and rifting or breakup playing the role of valve [13,14] (Fig. 1). Continuous interior heating warms up the

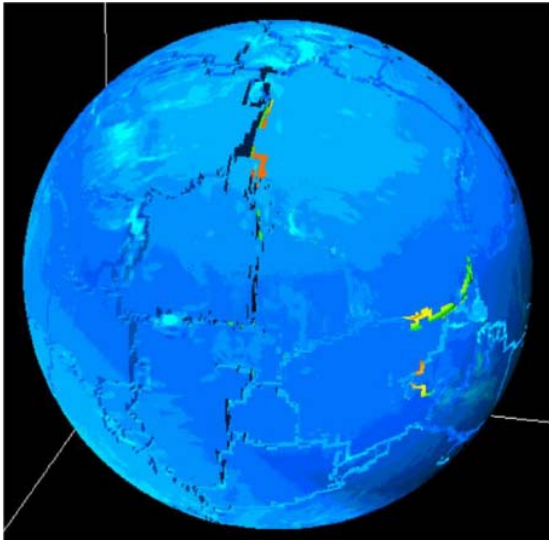


Fig. 1. The numerically obtained spherical shell failure due to interior expansion provided a heat fluctuation mechanism to explain thermal cycle of Earth, which is akin to a heating pressure cooker, with lithosphere playing the role of lid and breakup playing the role of valve [13,14].

Earth until catastrophic global-scale magmatism abruptly releases substantial heat, terminating the warming cycle and initiating a new cooling cycle, causing ice ages [14]. Given that the period of magmatic lull does exactly match the period of the snowball Earth, it is perhaps no surprise to infer that the surface climate change should then be the result rather than the cause of Earth's interior thermal cycles, with CO₂ effect, in terms of icehouse or greenhouse, acting as the catalyst for the irreversible transition from climate warming to cooling, or vice versa.

Conflict of interest

The author declares that he has no conflict of interest.

Acknowledgments

This work was supported by the project from the State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) (183120).

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Chunan Tang is a Chair Professor in Rock Mechanics, Dalian University of Technology, and Chief Professor in Structural Geology, China University of Geosciences (Wuhan). He is also the principal investigator of an open funding project from the State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences. He is a Vice President of the Chinese Society of Rock Mechanics and Engineering CSRME.