

The Balanced Billion

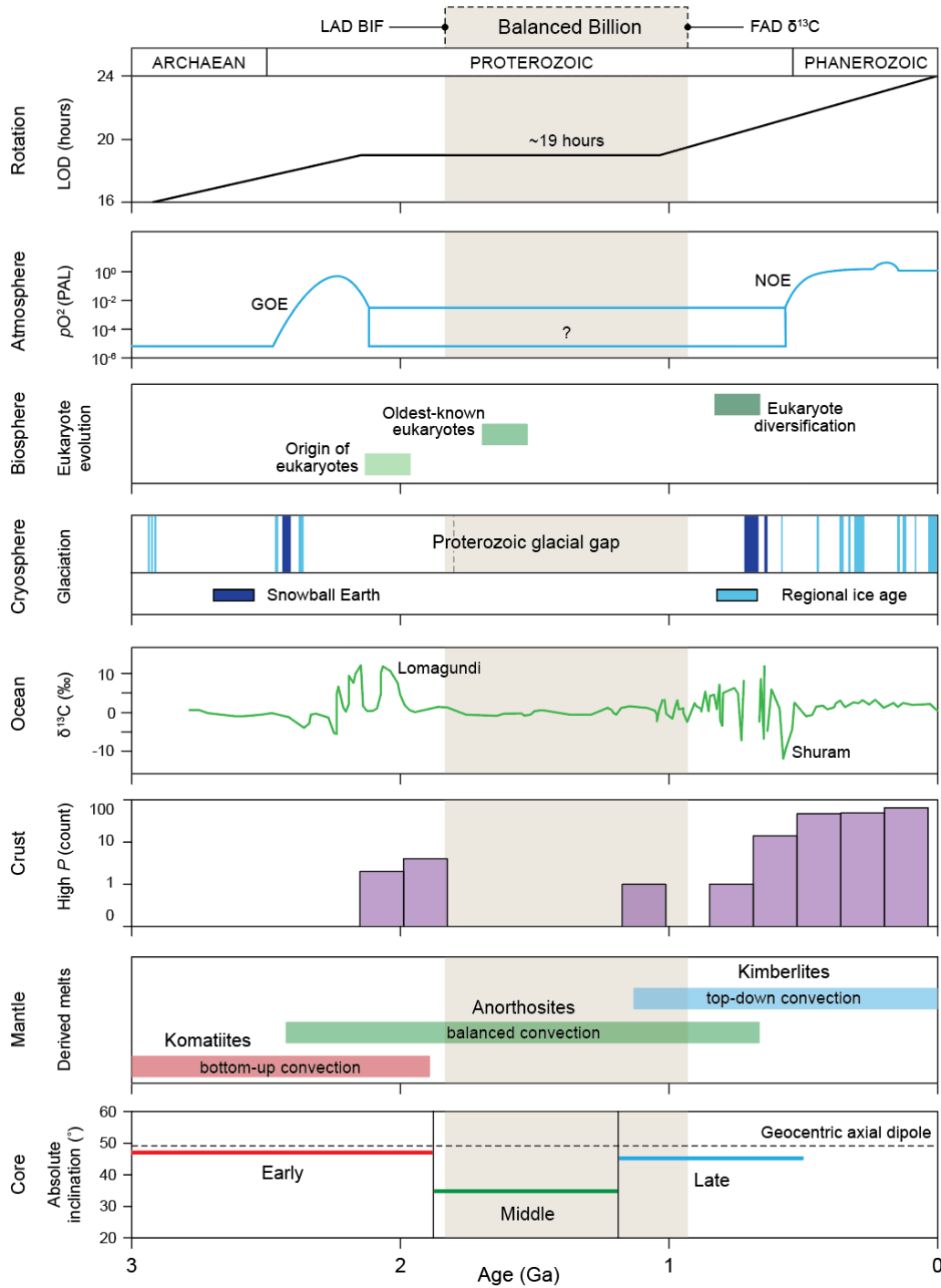
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There is a mid-Proterozoic stretch of Earth's history (roughly 1.9–0.9 Ga) called, non-affectionately, the “boring billion”. The moniker was first inspired several decades ago by the apparent absence of any significant carbon isotope anomalies and was linked to the relatively “boring” interval in between Earth's broadly two-step pattern in atmospheric oxygenation^{1,2}. Not only does this observation continue to hold true today, but other datasets from many facets of Earth dynamics during this time have been shown to be equally peculiar. Just a few examples include: the disappearance of iron formation, notable absences (of any large oxygenation events, phosphorites, or glacial and manganese deposits)²⁻⁴, and a billion year lag between the oldest known eukaryotes and the increasing eukaryotic diversity and their ecological importance taking hold⁵.

But the oddities of this billion years come not only from records of surface evolution and palaeoenvironment, but even solid Earth records including metamorphic style (a lack of high-pressure conditions)⁶ and either absences (ophiolites) or abundances (anorthosites) of igneous geologic records⁷. Another clue, still ambiguous at the moment, will be understanding the kinematic and geodynamic transition between the two Proterozoic supercontinents between its proposed “introversion” and “extroversion” endmember styles⁸. Most recently, the mid-Proterozoic has even been suggested to be expressed as deep as mantle convection and as far flung as the Earth–Moon system: with the billion years suggested to respectively represent the transition between bottom-up to top-down mantle convection⁹ as well as a remarkable flat-lining of Earth's rotational history at a constant ~19 hours per day^{10,11}. And oddities even seem to occur as deep as Earth's core, where measured palaeomagnetic inclinations (which convert to palaeolatitude assuming a geomagnetic field model) appear to generally follow the expectation of a geocentric axial dipole for early and later periods, but during the middle interval deviate strongly¹².

In light of (i) the original evidence coming from a relatively stable carbon cycles, (ii) the souring over time of the non-flattering term “boring billion” and (iii) the more recent additional clues coming from solid and deep Earth too, we suggest a rebranding to the term the “Balanced Billion”. The first benefit of this change is that it circumvents the subjectivity of what is “boring” as well as the strawman argument used repeatedly in the literature and news media that a new discovery overturns what had previously been thought to be a boring interval. The second, more important benefit of this renaming is that it is not only better marketing but also potentially a more accurate reflection of Earth system processes during the peculiar time—not only the balanced carbon cycle, but also balanced mantle convection and a constant daylength. Whether and (if so) why these variegated processes are related is a frontier for understanding the interconnectedness of the Earth system. Furthermore, understanding Earth's mid-Proterozoic balancing act will lead to a better understanding of the long delayed fuse in the rise of animals. Finally, as modern climate change trends toward ever increasingly extreme extremes (hotter/colder and drier/wetter), unlocking the secrets to the balanced billion may help society devise geoengineering solutions that mimic a time when Earth was more measured in its global change.



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Fig. 1 | The Balanced Billion. Proxy records from Earth's layers—from bottom to top—that exhibit important idiosyncrasies during the mid-Proterozoic. LAD BIF, last appearance datum banded iron formation; FAD $\delta^{13}C$, first appearance datum carbon isotope excursion; proposed lower/upper boundaries of the Balanced Billion. See text for data sources.

- 52 1 Brasier, M. D. & Lindsay, J. F. A billion years of environmental stability and the emergence of
53 eukaryotes: New data from northern Australia. *Geology* **26**, 555-558 (1998).
- 54 2 Holland, H. D. The oxygenation of the atmosphere and oceans. *Philosophical Transactions of the*
55 *Royal Society B* **361**, 903-915 (2006).
- 56 3 Hoffman, P. F. *et al.* Snowball Earth climate dynamics and Cryogenian geology-geobiology.
57 *Science Advances* **3**, e1600983 (2017).
- 58 4 Planavsky, N. J. The elements of marine life. *Nature Geoscience* **7**, 855-856 (2014).
59 <https://doi.org:10.1038/ngeo2307>
- 60 5 Knoll, A. H. & Nowak, M. A. The timetable of evolution. *Science Advances* **3**, e1603076 (2017).
- 61 6 Brown, M. & Johnson, T. E. Time's arrow, time's cycle: granulite metamorphism and
62 geodynamics. *Mineralogical Magazine* **83**, 323-338 (2019).
- 63 7 Roberts, N. M. W. *et al.* On the enigmatic mid-Proterozoic: Single-lid versus plate tectonics.
64 *Earth and Planetary Science Letters* **594**, 117749 (2022).
65 <https://doi.org:https://doi.org/10.1016/j.epsl.2022.117749>
- 66 8 Evans, D. A. D. in *Ancient Supercontinents and the Paleogeography of Earth* (eds Lauri J.
67 Pesonen, Johanna Salminen, Sten-Åke Elming, David A. D. Evans, & Toni Veikkolainen) 549-
68 576 (Elsevier, 2021).
- 69 9 Mitchell, R. N., Brown, M., Gernon, T. M. & Spencer, C. J. Evolving mantle convection from
70 bottom up to top down. *The Innovation* **3** (2022). <https://doi.org:10.1016/j.xinn.2022.100309>
- 71 10 Mitchell, R. N. & Kirscher, U. Mid-Proterozoic day length stalled by tidal resonance. *Nature*
72 *Geoscience* **16**, 567-569 (2023). <https://doi.org:10.1038/s41561-023-01202-6>
- 73 11 Wu, H., Murray, N., Menou, K., Lee, C. & Leconte, J. Why the day is 24 hours long: The history
74 of Earth's atmospheric thermal tide, composition, and mean temperature. *Science Advances* **9**,
75 eadd2499 (2023). <https://doi.org:doi:10.1126/sciadv.add2499>
- 76 12 Veikkolainen, T. & Pesonen, L. J. in *Ancient Supercontinents and the Paleogeography of Earth*
77 (eds Lauri J. Pesonen, Johanna Salminen, Sten-Åke Elming, David A. D. Evans, & Toni
78 Veikkolainen) 81-108 (Elsevier, 2021).
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