

## SUPPLEMENTARY NOTE 1: SUMMARY OF THE EARTH SYSTEM STATE IN GEOLOGIC TIME

Earth's modern environment differs fundamentally from its hot, anoxic and lifeless state over 3 billion years ago. Among the many changes that occurred along the way, the most pivotal developments are: (1) the broadly two-stage rise in the flux of elements and bioactive nutrients to the oceans, (2) at least two major oxidation events – the Global Oxidation Event (GOE; 2.4-2.2 Ga) and Neoproterozoic Oxidation Event (NOE; 0.8-0.6 Ga) – (3) two “Snowball Earth” icehouse episodes that occurred in the wake of these oxidative events, and (4) the origin and diversification of complex life, and the broadly two-stage growth of global biomass (Fig. 1). Broad temporal consistencies have inspired multi-disciplinary research into the complex feedback mechanisms among the cycles of O<sub>2</sub>, CO<sub>2</sub> and CH<sub>4</sub>, which may have caused these staggering changes. Likewise, a multitude of external forcing mechanisms for these changes, as well as other changes in element and nutrient cycles, including increased runoff due to supercontinent breakup, enhanced weathering of basaltic rocks at low latitude, and a dwindling CO<sub>2</sub> flux from arc volcanism<sup>59,62-68</sup>. In this supplementary note, we summarize a few key records of secular change.

The rise of oxygen levels in the global oceans and atmosphere is a complex stepwise process, with many intervals of local and global change. Of these various events, the two most substantial and impactful changes occurred in the wake of the Archean and in the Proterozoic. From c. 3.0 Ga onward, oceanic oxygen levels started to rise. This pivotal change is recorded in various natural archives, including biomarkers, sedimentary records, and the isotope compositions and elemental concentrations of redox-sensitive elements, such as S, Cr, Mo, Re, and U<sup>59,60,69-75</sup>. Steady oxygenation during the Meso- and Neoproterozoic culminated in the Great Oxidation Event (GOE; 2.4-2.2 Ga<sup>55</sup>), when atmospheric oxygen concentrations (*p*O<sub>2</sub>) rose rapidly and the mass-independent S isotope fractionation and Xe isotope fractionation signatures of global anoxia disappeared indefinitely<sup>76,77</sup>. Global oxygenation during the Neoproterozoic and Paleoproterozoic was fundamentally driven by the start of oxygenic photosynthesis, with facilitation by many other factors. The GOE may have been propelled by increased submarine volcanism and changing composition of volcanic gases, the escape of H<sub>2</sub> to space, shifts in the composition of the exposed crust<sup>42,67,78-81</sup>. The second stage of global oxygenation – the Neoproterozoic Oxidation Event (NOE; 0.8-0.5 Ga) – has been identified through distinct changes in the total organic content and the concentration of redox-sensitive elements (e.g., V, Mo and U) of black shales, and the S isotope compositions and of marine sulfides and sulfates<sup>60</sup>. The NOE has been ascribed to changes in global plate configuration and the development and diversification of algae and other micro-organisms<sup>55,60</sup>.

The resonance of the global oxidative events across the terrestrial environment and marine water column is reflected in the S isotope record, which is coupled to the O cycle via sulfate-sulfide reactions. For instance, the S isotope composition of marine pyrite shows increasingly higher variability, with more negative and positive values, from c. 3.0 Ga onward<sup>57</sup>. These signatures are undoubtedly influenced by differences in sedimentation rate, the concentration of dissolved C, S and Fe, and the degree of Fe and S remobilization within the sediment that hosts the pyrite<sup>82</sup>. An overwhelming effect on pyrite δ<sup>34</sup>S values – defined as the permille deviation in <sup>34</sup>S/<sup>32</sup>S relative to a standard – is caused by biological S metabolism, which can cause positive or negative isotope excursions depending on the exact microbial pathway and process<sup>83</sup>. The range in δ<sup>34</sup>S values (Δ<sup>34</sup>S) shows two distinct increases, the first occurring over a protracted period from c. 3.0 Ga culminating in the GOE and the second broadly during the NOE (Fig. 1). Both stages resulted in significant increases in global biomass and biodiversity, showing the limiting role of O<sub>2</sub> on the evolution of life<sup>56</sup>.

Enhanced oxidative weathering in the wake of the GOE drove the burial of large amounts of organic carbon<sup>55,84</sup>. Drastic positive excursions in δ<sup>14</sup>C recorded in global carbonate deposits formed between 2.31 and 2.06 Ga (the Lomagundi-Jatuli Excursion) reflect this carbon, which is characterized by

low  $\delta^{14}\text{C}$  due to photosynthetic fixation<sup>85-87</sup>. Rapid carbon burial during this time was likely aided by an increasing abundance of shallow basins<sup>88</sup> following the c. 3.0-Ga emergence of the continents<sup>11,45</sup> and a flood of bio-limiting nutrients to these basins and the global ocean<sup>55,59</sup>. Further impacting greenhouse gas levels, rising oxygen levels drove atmospheric methane dissociation and suppressed methanogenesis of organic matter by microbes—the latter adding to curtailing of biogenic methanogenesis due to a drastic decline in the supply of bioactive Ni to the oceans<sup>89</sup>. These processes, together with a  $\text{CO}_2$  drawdown driven by enhanced weathering of flood basalts formed at low latitude<sup>59</sup>, plunged the world into a global icehouse, with widespread glaciation occurring episodically in between pulses of rising  $p\text{O}_2$  (Huronian Glaciation<sup>55,59,78,90,91</sup>). A similar scenario unfolded in the wake of the NOE, when enhanced continental runoff due to supercontinent breakup and flood basalt eruption at low latitude, and a dwindling  $\text{CO}_2$  flux from global arc volcanism led to a catastrophic  $\text{CO}_2$  drawdown that ultimately triggered two distinct “Snowball Earth” glaciations – the Sturtian (717-659 Ma) and Marinoan (650-635 Ma) Glaciations<sup>59,61-63,68</sup>. Barring the clear difference of no pre-existing methane greenhouse in the Neoproterozoic, similarities between the GOE and NOE could indicate that both changes share climatic feedback mechanisms<sup>59</sup>. Although yet to be fully characterized, it is likely that these mechanisms that are the reason why the two most severe icehouse episodes occurred in the wake of the two most substantial oxidative events in Earth’s history.

The drastic changes summarized above are set against the backdrop of the evolving solid Earth, with its cooling mantle, differentiating crust, and evolving geodynamic regime and plate configuration. The proto-continental crust was relatively mafic, still retained  $^{142}\text{Nd}$  and  $^{182}\text{W}$  excesses from early differentiation, and mostly developed through the volcanic resurfacing of high-U/Pb basalts, internal differentiation, and delamination<sup>92</sup>. This changed from 3.2 Ga onward, with the widespread development of juvenile crust of largely tonalite-trondhjemite-granodiorite (TTG) composition<sup>93</sup> and the steady development of a more andesitic upper crust<sup>41,42,89</sup>. This change likely links to a shift from the stagnant-lid regime with temporal “squishy-lid” or mobile-lid geodynamics to a mode more akin to modern-day plate tectonics<sup>28,92,94-100</sup>. Although Archaean TTGs likely reflect melting of crustal roots, rather than actual arc magmatism<sup>35,101-103</sup>, the hallmarks of subduction emerged in the geological record of this time<sup>100,104-106</sup>. Global plate tectonics set in motion the supercontinent cycle, which involved the assembly and breakup of pan-continental landmasses between 2.7-2.4 Ga (Superia and Vaalbara, Ur, or Kenorland), 2.1-1.8 Ga (Columbia or proto-Nuna), 1.6-1.4 Ga (Nuna proper), 1.1-0.8 Ga (Rodinia), 0.6-0.4 Ga (Gondwana), and 0.3-0.2 Ga (Pangaea)<sup>90,107-110</sup>.

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