

A TERRESTRIAL PERSPECTIVE ON ARCHEAN AND PROTEROZOIC HABITABILITY ON EARTH.

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Introduction: Most of our understanding of the long-term changes in habitability on Earth comes from marine records. This is both because the terrestrial rock record is relatively sparse for the Archean and Proterozoic, but also because until recently, there have not been good tools to study terrestrial environments. However, identification and study of Precambrian paleosols parented by both bedrock [1] and floodplain sediments [2], and more intense study of lacustrine deposits [3-4] have given new insights into both the environmental conditions at the time of deposition and to questions about whether a terrestrial biosphere was present and what it was doing. Here, new geochemical results on Earth's surface conditions in the Archean and Proterozoic will be presented and compared with climate model results from both 1-D photochemical models and 3-D coupled atmosphere-ocean general circulation models (AOGCM), as well as to marine records of paleoenvironmental change.

Paleosols as Recorders of pCO₂: In addition to providing insights into surface weathering environments and potential signatures of a terrestrial biosphere [5], paleosols have also been used to reconstruct atmospheric pCO₂ levels [2, 5-6], giving results that are both internally consistent (i.e., multiple paleosols of the same age indicated the same pCO₂ level; [2]), as well as being consistent with independent estimates based on microfossils [7-8]. Using the model of Sheldon [6], the geochemical compositions of recently identified paleosols are used to extend the pCO₂ record to cover 3.0-0.5 Ga. Paleosol-based pCO₂ estimates are consistently relatively low, less than 0.05 bars or ~150 times pre-industrial levels with all sources of uncertainty included, and with a "best guess" of less than 0.016 bars (~50x PIL). The paleosol-based estimates also suggest three broad conclusions: (1) pCO₂ was high and relatively uniform from 3.0 Ga to at least 1.8 Ga, (2) pCO₂ fell dramatically to less than 0.0016 bars (5x PIL) at some time between 1.8 and 1.1 Ga, and (3) pCO₂ rose again in the Neoproterozoic and Cambrian, regardless of how "snowball Earth" events were triggered. Comparison of paleosol-based pCO₂ estimates with independent measures of weathering intensity from shales (e.g., CIA; compilation of [9]) show a strong correlation between elevated pCO₂ and highly weathered marine sediments, as well as corresponding more weakly weathered sediments during times of relatively low pCO₂ as indicated by the paleosol record.

Recorders of the Terrestrial Biosphere: A number of recent studies have looked at both elemental [5] and isotopic [10] composition of paleosols and have found evidence for changes in metal biogeochemistry [5], nutrient biogeochemistry [11], and complex carbon cycle processes [10]. In addition, lacustrine [3-4] and terrestrial-marine transitional zones record both physical and chemical evidence for a terrestrial biosphere. Taken together, these various data indicate the presence of a terrestrial biosphere back to at least 3 Ga, consistent with marine records that indicate long-term habitability. However, the early biosphere was likely limited to a small range of environmental conditions and primarily interacted with the atmosphere. By 1.8 Ga, there is evidence for microbial activity below the surface [11], and by 1.1 Ga, some paleosols record carbon cycling similar to modern soils [10]. Given the relative paucity of appropriate rocks and relatively recent development of the tools to study paleosols, it is likely that all of those time constraints may be pushed back in the future or become more tightly constrained.

Climate Model Results: If the paleosol-derived pCO₂ estimates are used to drive both 1-D photochemical and 3-D AOGCM models of surface climatic conditions, long-term equability at most latitudes is indicated for at least 3.0-1.1 Ga. However, if the lack of evidence for either polar or lower latitude glaciation is used as an additional constraint, then ppm levels of CH₄ are also required throughout the same time interval. Given the low reconstructed pCO₂ in the late Mesoproterozoic, pCH₄ needed to be ca. 20 ppm (>25x PIL). This result is consistent with recent marine results [12] that have indicated relatively low atmospheric pO₂ throughout the Proterozoic.

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