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Continent ruggedness drives long term Earth surface climate and environmental change

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Glaciation and atmospheric oxygenation are among Earth's most transformative events, significantly shaping its habitability and biosphere evolution. Despite extensive studies, the drivers behind these events remain debated. Intriguingly, glaciation and oxygenation correlate temporally, yet this relationship has been rarely explored. Here, we introduce continent ruggedness, defined as the variability in elevation across continental crust, and present a novel approach to quantitatively assess Earth's ancient ruggedness and its impact on climate and environmental changes. Our results suggest that increased ruggedness promotes sedimentation, erosion, chemical weathering, and organic carbon burial, thereby enhancing CO_2 sequestration and O_2 accumulation and creating conditions conducive to glaciation and oxidation events. Specifically, our reconstructions reveal that the early Paleoproterozoic and late Neoproterozoic were characterized by greater continent ruggedness than other geological periods, helping to explain the occurrences of Snowball Earth events, the Great Oxygenation Event, and the Neoproterozoic Oxygenation Event. In the Phanerozoic, continent ruggedness remains generally high, peaking in the late Paleozoic, which may have triggered late Paleozoic glaciation and oxygenation events. Conversely, the Mesoproterozoic generally exhibits low continent ruggedness, with a notable peak in the middle of this period, providing new insights into the 'boring billion' and the Mesoproterozoic Oxidation Event. These findings suggest that continent ruggedness is a crucial driver of Earth's surface climate and environmental changes over the course of its history.