PNAS LETTER

# Existing thermochronologic data do not constrain Snowball glacial erosion below the Great Unconformities

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The Great Unconformity is an iconic geologic feature, commonly defined by a substantial time gap between Cambrian and Precambrian units. Recent studies propose sub-Great Unconformity erosion was due to multiple tectonic and geodynamic drivers over a protracted period (1) or to synchronous glacial erosion from Snowball Earth (2, 3). This debate also highlights conflicting views on the value of incorporating geologic knowledge into thermal history reconstructions.

McDannell et al. (2) forego geologic evidence and use inversion modeling of "the thermochronologic data alone" from four locations to argue for "rock cooling and multiple kilometers of exhumation in the Cryogenian Period in support of a glacial origin for erosion" and state that glacial erosion is "the only plausible mechanism that satisfies the required timing, magnitude, and broad spatial pattern of continental erosion." However, their model outcomes are artifacts of their converging algorithm, thermal history priors, and output representation scheme. They attribute end-Tonian to Cambrian (850 Ma to 541 Ma) rock cooling to glacial erosion, although Snowball Earth was limited to ∼25% of this interval (717 Ma to 635 Ma); they show no data or metric to assess how well their preferred time–temperature (*t*–*T*) paths replicate the observations or to illustrate that they outperform alternative *t*–*T* paths; and many of their favored histories are not at surface temperatures in Cambrian time, thus violating the very geologic feature that the paths supposedly reproduce.

In reality, no data examined by McDannell et al. (2) limit substantial erosion to the 717- to 635-Ma span of Snowball glaciation. We show that thermal histories corresponding to pre-Snowball (pre-717 Ma) and/or post-Snowball (post-635 Ma) exhumation of Precambrian basement, with no rock cooling/erosion during Snowball, also reasonably reproduce the data (Fig. 1). Different scenarios fit some results better at the expense of others, with data scatter stemming from imperfect knowledge of diffusion and annealing kinetics, and likely other factors influencing the results (4).

Contrary to what is asserted by McDannell et al. (2), "the thermochronologic data alone" currently lack the resolving power to uniquely determine the timing of sub-Great Unconformity erosion. It is a mistake to trust statistics and algorithms in isolation without careful consideration of sample context. Reducing the vast parameter space (Fig. 1, *Right*) requires integrating critical geologic data in targeted localities (1, 4) to discern the timing, magnitude, spatial extent, and mechanistic drivers of the Great Unconformities.

**Data, Materials, and Software Availability.** Forward thermal history models and predictions are available in the Open Science Framework (10).

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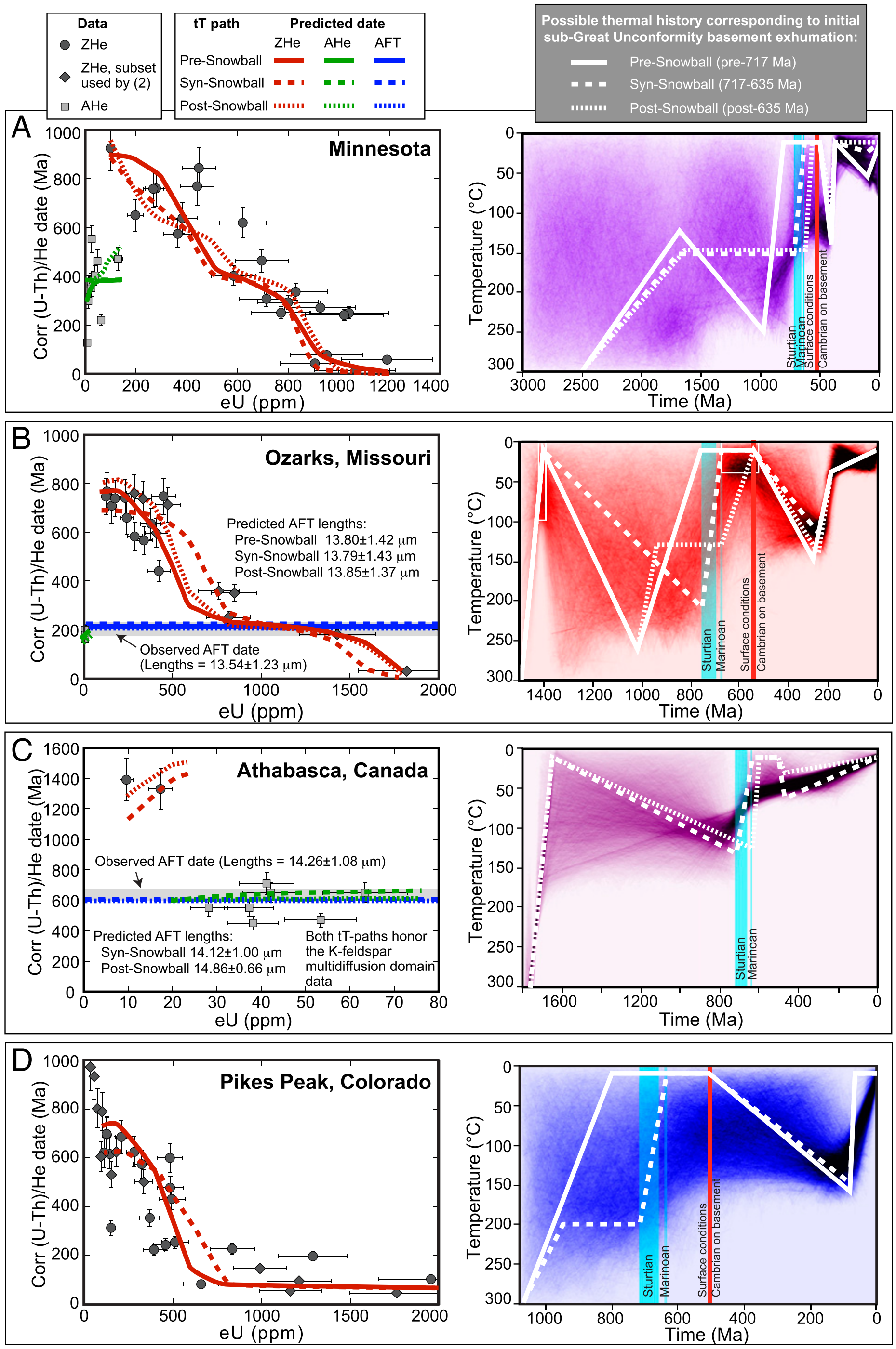


**Fig. 1.** The thermochronologic data (*Left*) for the four locations modeled by McDannell et al. (2) do not require rock cooling/erosion during Snowball Earth (*Right*). No new data are published by ref. 2; these data were mined by ref. 2 from an undergraduate honors thesis (5) and from publications that previously reported, modeled, and interpreted the data within their geologic context (1, 6–8). Data are shown as plots of corrected (U-Th)/He date vs. eU for (*A*) Minnesota (5); (*B*) Ozarks, Missouri (6), one outlier excluded; (*C*) Athabasca, Canada (7, 8); and (*D*) Pikes Peak, Colorado (1), one outlier excluded. (U-Th)/He dates and eU values are shown with 10% and 15% uncertainties, respectively. Gray bands in *B* and *C* represent the central apatite fission track (AFT) date with 2σ asymmetric uncertainty. *Right* are *t*–*T* diagrams, with colored shading taken directly from ref. 2, representing their *t*–*T* path densities. Denser regions are where algorithmically generated paths more frequently intersect in *t*–*T* space (irrespective of goodness of fit of any one path to data). Vertical blue bands are Sturtian and Marinoan Snowball events; Gaskiers glaciation is omitted because it is not recorded on North America. We superimpose possible pre-, syn-, and post-Snowball exhumation *t*–*T* paths in *Right* for *A* and *B*. For *C* and *D*, we show only a post-Snowball and pre-Snowball *t*–*T* path, respectively, for comparison with a syn-Snowball scenario as favored by ref. 2, because, for Athabasca, ref. 9 provides strong evidence for post-650 Ma (likely post-Snowball) basement exhumation in the central Canadian shield with a footprint likely encompassing the Athabasca region and, for Pikes Peak, we consider the Tavakaiv injectite relationships to indicate pre-Snowball exhumation (1). *Left* shows thermochronologic dates predicted by these *t*–*T* paths with the HeFTy software program using the same kinetic models as in ref. 2 for comparison with observed data. We do not favor the specific pre- or post-Snowball *t*–*T* paths displayed; these are for illustrative purposes only. Forward thermal history models and predictions are available in the Open Science Framework (10).