GEOLOGY

Orogenic quiescence in Earth's middle age

Ming Tang[1]*, Xu Chu[2], Jihua Hao[3,4], Bing Shen[1]

Mountain belts modulate denudation flux and hydrologic processes and are thus fundamental to nutrient cycling on Earth's surface. We used europium anomalies in detrital zircons to track mountain-building processes over Earth's history. We show that the average thickness of active continental crust varied on billion-year time scales, with the thickest crust formed in the Archean and Phanerozoic. By contrast, the Proterozoic witnessed continuously decreasing crustal thickness, leaving the continents devoid of high mountains until the end of the eon. We link this gradually diminished orogenesis to the long-lived Nuna-Rodinia supercontinent, which altered the mantle thermal structure and weakened the continental lithosphere. This prolonged orogenic quiescence may have resulted in a persistent famine in the oceans and stalled life's evolution in Earth's middle age.

Earth's continents have a highly skewed elevation distribution. Most of the continental areas lie close to sea level because of the balance between erosion and deposition (*1*). However, at convergent plate boundaries, an active mountain-building process known as orogenesis generates substantial uplift. These mountainous terrains, though minor by area, profoundly influence global denudation and hydrologic processes on land (*2*–*5*).

Mountain belts owe their high elevations to crustal thickening, which in turn is driven by tectonic compression and magmatic inflation (*6*). Meanwhile, uplift increases erosion efficiency and induces gravitational spreading (*7*), which counters crustal thickening. After magmatism and tectonic compression terminate, erosion and collapse of the orogen prevail, and the crust quickly loses its thickness and elevation as it ages. Thereby, mountains are ephemeral, and the history of mountain building has been constantly erased and overprinted. The thickness of the remnant is not representative of the crust when it formed. This preservation issue poses great challenges to tracking orogenesis in deep time.

Here, we reconstructed mountain-building history using a recently calibrated zircon-based crustal thickness proxy (*8*). Detrital zircons are derived from a variety of crustal rocks and naturally sample large tracts of the continental crust exposed to erosion. Because of their refractory nature, zircons survive most erosion and weathering processes, remain chemically intact, and thus provide a continuous record of magmatic history where fragmented rock records fail (*9*). The zircon-based crustal thickness proxy uses the pressure-sensitive Eu systematics during magmatic differentiation, which is recorded as Eu anomalies (Eu/Eu*, chondrite normalized Eu/$\sqrt{\text{Sm} \times \text{Gd}}$) in crystallizing zircons. We filtered out metamorphic zircons and zircons derived from S-type granites based on zircon Th/U ratios and P contents, respectively (*10*).

Our approach calculates the thickness of all magmatically active crust, which we call the active continental crust. Most of this crust forms at convergent plate margins because of oceanic plate subduction and continent-continent collision. The overriding continental plate in which orogenic magmatisms develop could be either reworked preexisting crust or juvenile crust. In both cases, the resulting mountain belts interact with the surface environment in essentially the same way. Thus, we did not filter our compilation with zircon Hf or O isotope data. The scope of this study and our approach thus differ from a previous study by Dhuime *et al.* (*11*), who used Sr isotopes and Nd model ages to specifically constrain the thickness of juvenile crust.

The reconstructed thickness of active continental crust averaged 50 to 60 km in the Phanerozoic and showed a thickening trend toward the present (Fig. 1A). The thick active continental crust in the Phanerozoic is consistent with the observation that most of the

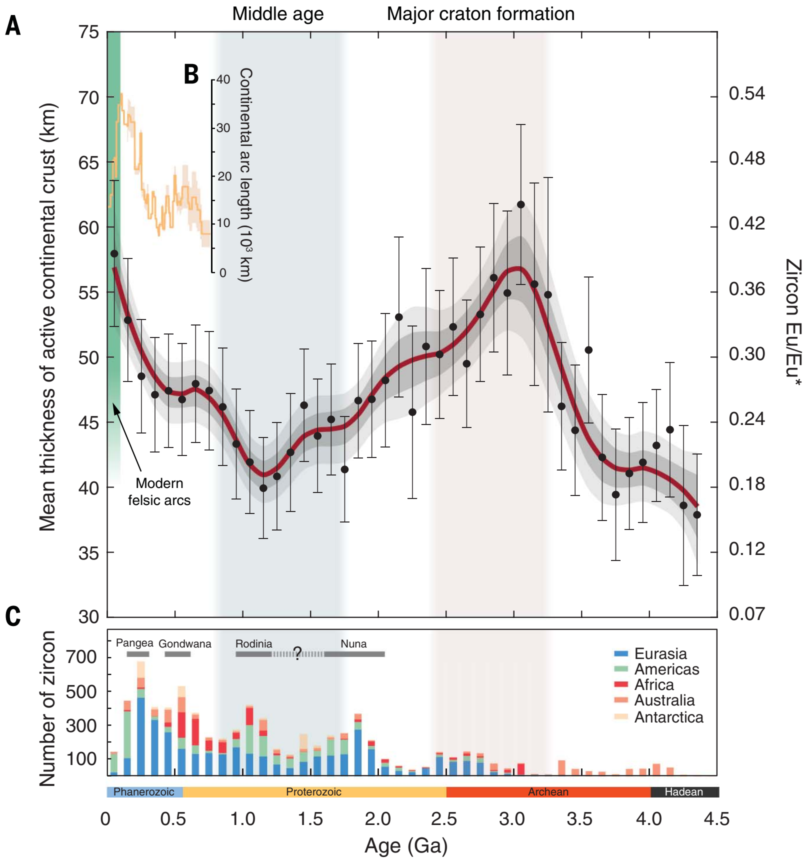

Fig. 1. Reconstructed thickness of active continental crust over Earth's history. (**A**) Reconstruction based on >14,000 analyses of detrital zircons from around the globe (*10*). Data are plotted as binned averages (bin size, 100 million years), with error bars indicating ± 2 SEM. A smoothed trend bracketed by 68 and 95% confidence intervals is shown by the red curve with shaded envelopes. We take zircon crystallization ages as the ages of synmagmatic orogenesis. The time window of major craton formation (pink band) is from (*13*). (**B**) Length of continental arcs in the last 750 million years (means enveloped by uncertainty intervals) is from (*49*). (**C**) Number of detrital zircons from each continent within each 100-million-year bin.

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[1] Key Laboratory of Orogenic Belt and Crustal Evolution, MOE; School of Earth and Space Science, Peking University, Beijing 100871, China. [2] Department of Earth Sciences, University of Toronto, Toronto, Ontario M5S 3B1, Canada. [3] Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08901, USA. [4] CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China.
***Corresponding author. Email: mingtang@pku.edu.cn**

modern felsic arcs are built on crust >40 km (*12*). We also found that the pattern of reconstructed crustal thickness mimics the trend of continental arc length in the last 750 million years (Fig. 1B). Because continental arcs represent the thick end member of active crust, this pattern similarity affirms that the crustal thickness reconstructed from detrital zircons faithfully tracks the overall mountain-building activity in the past.

The Precambrian active continental crust varied substantially in thickness over time (Fig. 1). The active crust became progressively thicker from the Hadean to the Archean and reached a maximum average thickness of 55 to 65 km in the Mesoarchean to Neoarchean [3.2 to 2.5 billion years ago (Ga)]. The emergence of thick felsic crust in the Mesoarchean to Neoarchean coincided with the peak of craton formation (*13*), which may also result from compressive tectonics (*14*, *15*). The lack of thick active crust and thus orogenesis in the Paleoarchean and Hadean (Fig. 1) suggests that lateral plate convergence may have been weak in the first billion years of Earth's history. We note that this speculation is based on a limited number of detrital zircons from this time period and may be tested when additional detrital zircon data become available.

In the Proterozoic, the thickness of active continental crust exhibited a "V"-shaped temporal pattern. Crustal thickness declined continuously from the Paleoproterozoic through the end of the Mesoproterozoic. At 1.3 to 1.0 Ga, the average thickness of active crust may have been as low as 40 km, close to the crustal thickness of the heavily eroded continental interior. This would imply that, on 100-million-year time scales, the continents at that time were far less mountainous than today.

This long-term quiescence in mountain building coincides with a substantial reduction of subduction flux in the Proterozoic (*16*) inferred from Nb/Th of the depleted mantle (*17*) and ^{4}He/^{3}He of ocean island basalts (*18*). Reduced orogenesis and subduction flux may be linked to the unusual supercontinent cycles in the Proterozoic. Supercontinents insulate the underlying mantle, and this "blanketing" effect can profoundly alter mantle thermal structure (*19*–*21*). As a consequence, the mantle beneath a supercontinent becomes hotter, whereas the mantle beneath an oceanic domain cools down for a thermal balance (*21*). Cooling increases suboceanic mantle viscosity and thus decreases oceanic plate velocity.

The Proterozoic witnessed two supercontinents, Nuna (Columbia) and Rodinia. Nuna was assembled between 2.1 and 1.8 Ga (*22*) and then broke up between 1.6 and 1.2 Ga, followed by the amalgamation of Rodinia at 1.2 to 0.9 Ga (*22*). However, a growing body of evidence suggests that the breakup of Nuna was limited, and it transitioned to Rodinia with only minor reconfiguration (*23*, *24*). This unconventional transition is also supported by the paucity of passive margins in the Mesoproterozoic (*25*). Therefore, Nuna and Rodinia may be viewed as one largely coherent supercontinent cycle [also known as Nudinia (*26*)] spanning from the late Paleoproterozoic to the early Neoproterozoic (*27*). The mantle thermal structure, altered by the long-lived supercontinent lid, may have led to substantial cooling of the suboceanic mantle to the point that plate tectonics operated intermittently until the breakup of Rodinia.

Prolonged heating of the continental lithosphere may prompt widespread low-pressure–ultra-high-temperature metamorphism and intraplate anhydrous magmatism within the continents (*19*), which are distinctive in the mid-Proterozoic metamorphic (*28*) and igneous (*29*) records. The Grenville orogen, formed between 1250 and 980 million years ago (Ma), has long been regarded as a prototype of the Himalaya-Tibet orogen (*30*). However, the massive anorthosite massifs, dike swarms, peralkaline shoshonite, and ubiquitous A-type granite suites that characterize the Grenville orogen (and the Sveconorwegian orogen) have been rare in Phanerozoic orogens (*27*, *31*). Intense heating could thermally weaken the lithosphere, causing thickened crust to relax rapidly. Detrital zircons of broadly defined Grenvillian ages (1250 to 980 Ma) from North America further show that the Grenville orogen differs from its Phanerozoic counterparts. In southern Tibet and the North American Cordillera, most detrital zircons record 50- to 70-km crustal thicknesses, whereas in the Grenville, crustal thickness peaked at 40 km (Fig. 2).

Long-term quiescence in mountain building may have a profound influence on the hypsography of Earth's surface. The elevation of continent freeboard is determined by a number of factors, including the thickness of the continental crust and oceanic crust, densities of the crust and mantle, and seafloor depth (*32*, *33*). For simplicity, we extrapolate the conditions of isostasy on modern Earth to the past. We found that if the sea level was not substantially different, most of the active continental crust in the mid-Proterozoic would have elevations of no more than 1 to 2 km, in contrast to 3 to 5 km in the succeeding Phanerozoic era (Fig. 3A).

The loss of elevation contrasts between the active continental crust and oceans would substantially reduce erosion rate (*2*) and the intensity of the hydrologic cycle (*34*) on the continents, leading to a subdued weathering flux in this time period. This effect is shown by the similar active continent elevation and seawater Sr isotope curves in the Proterozoic (Fig. 3, A and B).

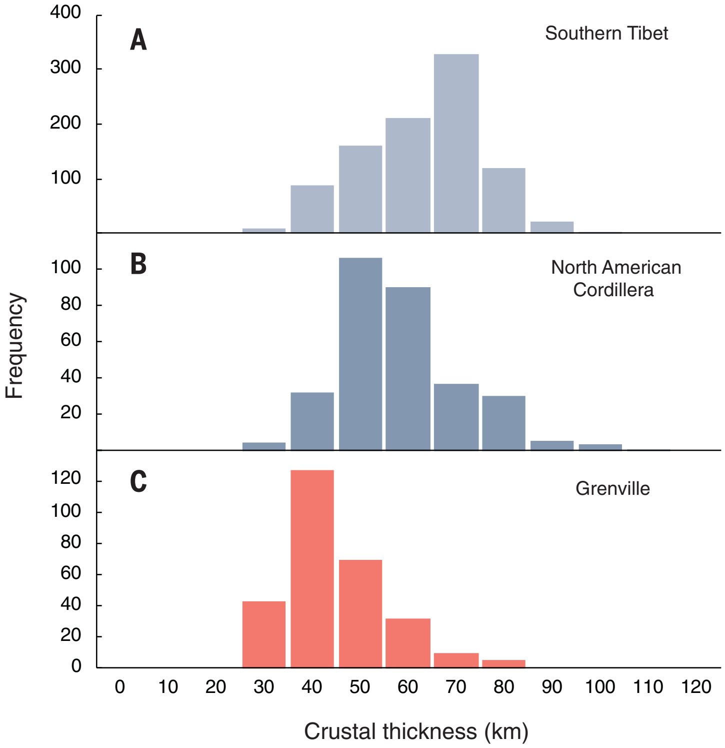

Fig. 2. Reconstructed crustal thicknesses for southern Tibet, North American Cordillera, and North American Grenville. (**A**) Southern Tibet detrital zircon data (100 Ma to present) are from (*8*). (**B** and **C**) We assumed that North American detrital zircon populations at 230 to 50 Ma and 1250 to 980 Ma were primarily sourced from the North American Cordillera (B) and Grenville (C) orogens, respectively.

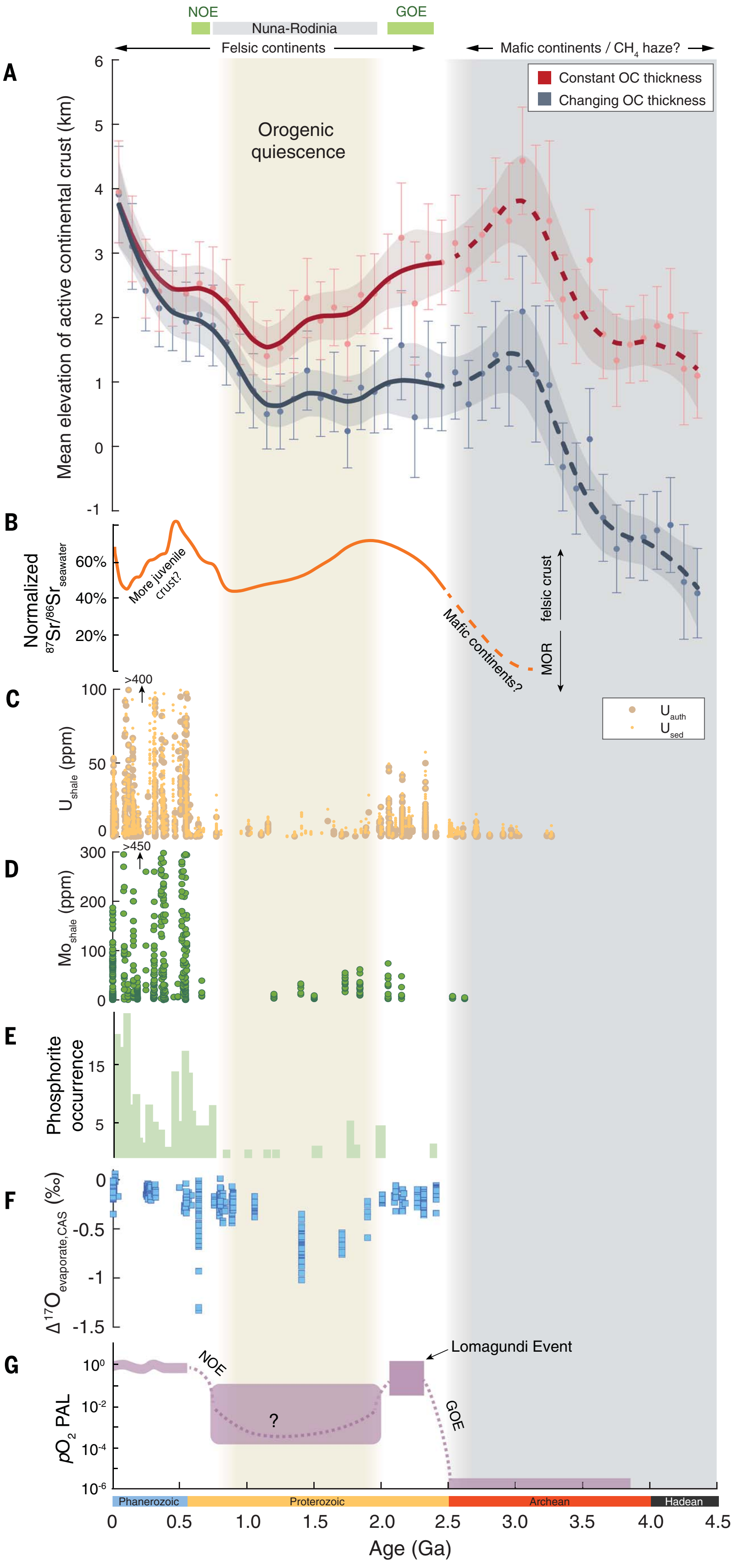

Fig. 3. Elevation of the active continental crust over Earth's history and evolution of Earth's surface environment. (**A**) Elevation plotted as binned averages (bin size, 100 million years), with error bars indicating ± 2 SEM. Also shown are the smoothed trends bracketed by 95% confidence intervals. The elevation of active continental crust can be calculated from our reconstructed crustal thickness using an isostasy model (*10*). We consider two end-member scenarios of oceanic crust thickness, one with constant thickness over time and the other decreasing thickness from the Hadean to the present day (*10*). (**B**) The normalized seawater Sr isotope curve is from (*50*), which removes the radiogenic decay effect and thus reflects the contributions from the midocean ridge (MOR) and the felsic continental crust. The Sr isotope curve has decoupled from that of the elevation since ~450 Ma, which was probably caused by an increasing contribution from juvenile crust with MOR-like Sr isotopes (*51*). (**C**) Sediment U contents and authigenic U concentrations in black shales (*42*). (**D**) Mo concentrations in black shales (*36*). (**E**) Sedimentary phosphorite occurrence (*39*). (**F**) $\Delta^{17}O$ in evaporate and carbonate-associated sulfate (*41*). (**G**) Atmospheric O_2 partial pressure relative to present atmospheric level (PAL). The purple fields are from (*52*) and (*53*). The dashed curve in the Proterozoic field is our proposed path (schematic). NOE, Neoproterozoic Oxidation Event; GOE, Great Oxidation Event.

With muted continental weathering, nutrient supply to the oceans declines. The scarcity of P, Mo, and other trace metals would dampen primary productivity and reduce O_2 production (*35*), which would in turn further decrease the Mo flux from the continents (*36*) and enhance Mo and P removal from the Proterozoic oceans (*36*–*38*).

Eventually, a widespread famine followed by a collapse of primary productivity may have occurred in the Proterozoic oceans. This is reflected by the extremely low Mo in black shales, disappearance of sedimentary phosphorite, and strongly negative $\Delta^{17}O$ evaporates and carbonate-associated sulfate between 1.8 and 0.8 Ga (*36*, *39*–*41*) (Fig. 3, D to F). The systematic decline in atmospheric O_2 into the mid-Proterozoic is corroborated by the decreasing U concentrations in black shales (*42*) (Fig. 3C) and the fall of seawater sulfate level (*43*, *44*) after the initial rise of atmospheric O_2 between 2.5 and 2.0 Ga, the Great Oxidation Event. Biological evolution may have been largely stalled during this 1-billion-year orogenic quiescence, a time period often referred to as the "boring billion" (*45*, *46*).

The middle-age orogenic quiescence came to an end in the Neoproterozoic (Fig. 1A), a time corresponding to the termination of the long-lived Nuna-Rodinia supercontinent. The breakup of Nuna-Rodinia may have relaxed the thermal contrast between the suboceanic and subcontinental mantle and established modern-style plate tectonics. As mountains reappeared on the continents, nutrient supply to the oceans was enhanced, which catalyzed surges in biological productivity and resumed surface oxidation. Efficient orogenesis appears to have been maintained ever since (Fig. 1). The sustained high erosion and weathering rates promoted organic C burial, as evidenced by a systematic ^{13}C enrichment in Phanerozoic carbonates (*47*). With the emergence of a fully oxidized atmosphere-ocean system, the planet was eventually primed for the arrival of metazoans in the Cambrian (*48*).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 and S2
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Database 1
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Ming Tang, Xu Chu, Jihua Hao and Bing Shen

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A boring billion for mountains

Earth's crust has changed over time as supercontinents formed and broke apart. Tied into this cycle are the building and erosion of high mountains, which are tied to collisions between tectonic plates. Tang *et al.* use europium anomalies in zircons to estimate the mean thickness of crust over Earth's history. This proxy shows that mountain building has not always been as active as it is today or as it was very early in Earth's history. Mountain building, and the subsequent erosion, was less intense for about a billion years, roughly correlated with a so-called ''boring billion'' period of biological evolution.

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