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Raising mountains for a habitable Earth

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Abstract

The formation of mountain belts (orogens) raises rocks above sea level and makes them available for chemical weathering, altering the composition of the atmosphere and oceans, which in turn control habitability. The typical elevation of mountain belts through time depends on their crustal thickness, which depends on crustal strength and tectonic style, which both changed during secular cooling of Earth's interior. Here we show that the thickness of orogenic crust has increased, in two pulses, around 2.2 and 0.8 billion years ago, adding c. 30 km to the orogenic crust each time. To this end, we used pressure estimates from metamorphic rocks that tectonically or magmatically rose up from the base of orogenic belts. We postulate that these changes resulted from geological responses to subduction and collision processes in a cooling Earth. The two orogenic growth spurts correspond to coeval major increases in terrigenous element and nutrient fluxes, changes in biological sulfur metabolism, and oxygenation, which can be explained by the enhanced weathering of taller mountains. This suggests first-order mechanistic links between secular geodynamic change, changes in Earth system state and habitability, which shaped the conditions for the evolution of complex life.

Introduction

Continental silicate weathering controls the oceanward flux of carbon and bioactive nutrients that limit marine primary productivity, thus exerting a control atmospheric chemistry, climate, and marine biomass and biodiversity[1,2]. The majority of the global terrigenous runoff derives from mountainous regions[3]. On regional scale and in the short term, the mass flux from such regions is a function of mean surface temperature, humidity, relief-runoff relationships, rates of topographic decay, weatherability and other orogen-specific factors[4,5]. On a global scale and in the long-term, the time-integrated mass flux of sediment from the continents to the oceans is coupled to the prevalence and maximum elevation of mountain ranges. This sedimental yield is controlled by erosion above 3 km altitude[3,6]and scales exponentially with mean drainage-basin elevation[4]. Terrain elevation in mountain belts is controlled by the shear stress on plate contacts, and relates to the thickness and density of the orogenic crust across tectonic settings[7,8]. Both factors have changed considerably with time. The surface area of the continental crust increased and the crust has emerged more prominently above sea level since 3.5 Ga[9,10,11] and significant amounts of seawater have been increasingly lost to the mantle through the subduction-driven recycling of hydrated oceanic lithosphere[12]. These changes form the backdrop to the many changes that have affected the Earth system state during and since then (Supplementary Note 1). Nevertheless, causal links are still largely unknown.

Answers to pertinent questions in this context require time-resolved, (semi-)quantitative record of crustal thickness in mountainous regions. However, two main issues complicate obtaining such record. Firstly, the geological record is intrinsically discontinuous due to the cyclical nature of tectonic processes, resulting in uncertainty about the presence and state of mountain belts during certain time periods. Secondly, there is significant difficulty in reconstructing the paleo-depth of the crust-mantle boundary

(Mohorovičić discontinuity or Moho). Bulk-rock chemical indices for Moho depth in igneous rocks (e.g., Sr/Y, La/Yb) may work well in modern arcs[13], but may not be reliable in non-arc settings, and alternative approaches, such as zircon Eu anomalies and other rare earth element-based indices, depend too strongly on case-specific parameters to enable their use in the investigation of global phenomena and secular change[14]. However, the metamorphic rock record is a largely untapped resource in this regard. Within the borders set by its characteristics, limitations and caveats (Supplementary Note 2), this record may provide key information on the conditions and depths of the basal parts of orogenic systems, and changes in these parameters with time. Here, we use *P* estimates from the metamorphic record (Fig. 1) to investigate the secular evolution of orogenic thickness.

Metamorphic Mohometry

Orogenic crustal thickness is related to the tectonic process by which orogenic systems develop. On the one hand, orogens can develop 'intraplate', where the entire lithosphere is shortened and thickened, and crustal thickening and horizontal shortening are directly linked. Such intraplate orogenic processes typically occur often above subduction zones (Andes, Rocky Mountains, Tibetan Plateau) and within plates (Tien Shan, Atlas), and are related to far-field stresses acting at plate boundaries or at the base of the lithosphere[15,16]. The thickness of the ensuing crust depends on its strength and, in present-day setting, is regionally up to c. 60 km. On the other hand, orogens may develop in an accretionary fashion, by which tectonic slices of up to several kilometers thick are scraped off the subducting lithosphere and stacked up to form thick orogenic wedges[16]. If subducting lithosphere is oceanic, such wedges reach 30-40 km (e.g., Japan[17]), but if continental margins subduct, the thickness of the accreted upper crust increases rapidly (e.g., Himalaya). Moreover, the subducting continental crust may horizontally underthrust the already thickened upper plate, leading to orogenic crust as thick as 85 km (e.g., Tibet[18]).

The metamorphic record in these different types of orogens can be fundamentally different, the main difference being that in intraplate orogeny all rocks remain part of the orogenic pile, whereas during accretionary orogeny, much of the lower-plate lithosphere may become subducted into the mantle. In the latter, accreted rock slices of oceanic and continental margin provenance may be particularly deeply subducted and are either lost to the mantle or become exhumed as small (<1,000 km^2) ultrahigh-pressure (*UHP*) terranes that record fast burial (<5 Myr) and rapid, buoyancy-driven exhumation (3-6 cm yr^{-1}; e.g., *UHP* terranes in Ladakh, Western Alps, Papua New Guinea[19]). Continental lithosphere behaves fundamentally differently due to its strength and buoyancy. Continental crust can be buried into the mantle, but – unlike with oceanic or transitional lithosphere – deep continental subduction only represents a transient state that occurs during the first few million years during which a continental margin may get dragged down into the mantle by a still-attached subducting oceanic slab[20]. This process is reflected by low-*T*/*P* (<250 °C GPa^{-1}) or exceedingly high-*P* (>3.3 GPa) outliers in the *P*-*T* record of quintessential continental (*U*)*HP* terranes, such as the Western Gneiss Complex in Western Norway[22]. Overwhelmingly more common in the metamorphic record of deeply buried continental

terranes are the regional high-*T* (*U*)*HP* conditions[22] (>700 °C, *T*/*P* of 250-400 °C GPa^{-1}; Fig. 2), which are imparted when the buried crust bounced back up, stalls at the base of the orogenic wedge following slab breakoff, and is heated up and pervasively overprinted[21]. Upon this stalling, parts of the continental crust may be thrust further beneath the orogenic hinterland[23], as occurred in Cenozoic time in the Zagros Mountains[24], Taiwan[25], Anatolia[23] and the Tibetan Plateau[18]. Other parts detach and exhume over 15-30 Myr as large (*U*)*HP* complexes (>2,000 km^2) within foreland-directed thrust belts[19]. These complexes are unique witnesses to the deep processing of continental crust at the base of orogenic wedges. Relics of this deep processing manifest as “hot eclogites” – mafic (*U*)*HP* rocks of continental provenance enclosed in felsic migmatites, granulites, and orthogneisses. Such rocks occur in the rock record since at least 1.9 Ga (Supplementary Note 2), providing an archive for investigating the dynamics and depths of ancient orogenic root zones.

The metamorphic record that was investigated in this study includes existing and new thermobarometric and chronometric data obtained for global metamorphic rocks of continental provenance (Supplementary Notes 2, 3). For chronometric data, we focus on high-precision Lu-Hf and Sm-Nd garnet ages where available, given that these may more unequivocally date metamorphism (Supplementary Note 2). Key, in this regard, are the maximum regional pressures in each time slice, which provide a record of depth and crustal thickness. Eclogites in Phanerozoic continental (*U*)*HP* terranes record consistent peak-*P* conditions of 2.8-3.3 GPa, exceeded only by local occurrences of rocks reflecting early transient passage into the mantle. These conditions indicate a relatively common processing depth at the base of accretionary orogens, which—assuming lithostatic conditions—would be c. 90 km. This estimate matches closely the maximum crustal thickness estimated for the Pamir and Himalaya, which comprise the largest and thickest accretionary orogen that is still active (c. 85 km[26,27]). Such *P* conditions are not recorded by continental rocks buried in the large, hot orogens of the Proterozoic. Instead, these record a relatively consistent maximum *P* of c. 2 GPa. With deep burial of continental crust into the mantle likely impeded in these orogens due to lithospheric unzipping and shallow slab break-off[23,28,29] , this *P* likely represents the maximum depth of Proterozoic root zones and would correspond to a depth of 55-60 km (Figs. 1,2), which is consistent with the maximum crustal thickness estimated for the Grenville (1.2-0.9 Ga), Picuris (1.47-1.37 Ga), Yavapai (1.72-1.69 Ga) and the Trans-Hudson (2.1-1.8 Ga) orogens using seismic restoration and chemical proxies[30,31,32,33]. These observations signify internal consistency among these various estimates and validate the geological interpretation of regionally peak conditions recorded by continental (*U*)*HP* terranes. Deep (>40 km) burial-exhumation cycles are not reflected in the rock record prior to the Neoarchean (Figs. 1,2), where consistent peak *P* estimates would indicate maximum burial depths of c. 35 km in the Neoarchean and 30 km before this time. Pre-Neoarchean TTGs reflect melting of garnet- and rutile-bearing lower-crustal residues[34,35], which could indicate that the crust was locally thicker. This apparent discrepancy may signify that such deep would have comprised dense residual eclogite that was gravitationally unstable and thus was more prone to be lost to the mantle via delamination than to exhumed to the surface. This loss would have been exacerbated by the relatively high mantle potential temperatures and higher

crustal densities in the Archean, which would further favour the development of gravitational instabilities at the Moho[36,37] and thus maintain delamination as an effective means of crustal recycling during this time[35,38].

Crustal thickness and elevation correlate as a function of mean crustal density across geological settings, and with crustal compositions and age[7]. Using this empirical correlation, the crustal thicknesses indicated by *P* estimates can be recast into first-order estimates of paleo-elevation. Assuming an average density of 2.83 g cm^{-3} for modern andesitic continental crust[39], we compute paleo-elevations. To illustrate, a maximum Moho depth of c. 85 km estimated for the modern Pamir and Himalaya based on geophysical observations[26,40] indicates an elevation of $8.8_{-0.7}^{+0.7}$ km above sea-level, which is indistinguishable from the elevation of the world's three highest peaks Mt. Everest (8,848 m), K2 (8,661 m) and Kangchenjunga (8,586 m). The same calculations would yield a consistent elevation of $5.0_{-0.6}^{+0.6}$ km for the large hot orogens of the Proterozoic. A theoretical elevation of $1.4_{-0.5}^{+0.4}$ km would be estimated for the Neoarchean, whereas an estimate of $-0.1_{-0.4}^{+0.4}$ km c would be obtained for the Eoarchean, assuming an a more mafic average Archean (proto-)crust before 3.0 Ga with an average density[37] of 2.87 g cm^{-3} and a gradual transition to an andesitic average crust between 3.0-2.5 Ga[40,41]. Whether these estimates are to be considered quantitatively depends on whether mean sea level can reasonably be assumed to be constant. This assumption is valid for the Phanerozoic, when mean sea level likely did not differ by more than 300 m from that of present-day[43] (van der Meer et al., 2022). A case could be made that this also applies to the Proterozoic, given that the factors that determine mean sea level – ocean volume, continental lithosphere volume and density relative to that of oceanic lithosphere, thickness of oceanic crust and relative height of spreading centers – are controlled by the geodynamic regime, which has been kept at steady state by plate tectonics. For the Archean, however, mean sea level likely was vastly different, because (1) the crustal portion of the oceanic lithosphere was much thicker[44], (2) the oceans were more voluminous (c. 1.5 times) due to sea water not yet having been recycled back significantly into the mantle[12], and (3) the Archean (proto-)continental crust was more mafic, thus causing lower crustal elevation through density inversion from widespread lower-crustal eclogitization[10]. It is thus remarkable or perhaps coincidental that the onset of crustal thickening capable of sustaining widespread emergence, as indicated by the metamorphic record, was broadly synchronous with emergence as indicated by O isotopes in shales, and Sr isotopes in of marine carbonates and stratiform barite deposits (3.5-3.0 Ga[11,45].

Orogenic growth spurts - causes and consequences

The evolution of metamorphic processes and conditions has long been recognized as being discontinuous, with two major revolutions ultimately driven by the secular cooling of the mantle[29,44]. The first of these revolutions (*R1*) occurred in the Meso- or Neoarchean, when the global geodynamic regime shifted from being dominated by stagnant-lid behavior and delamination to one characterized by horizontal plate motion involving subduction and crustal thickening[28,46]. Widespread "paired

metamorphism"—with intermediate-*T*/*P* metamorphism (c. 300 °C GPa^{-1}) in lower plates and high-*T*/*P* metamorphism (>600 °C GPa^{-1}) in upper plates of active margins—is a clear manifestations of this tectonic change[46,47], as are the widespread formation of passive margins[48], the assembly and reorganization of large continental landmasses, and the production of large, long-lived orogens formed by accretion and intraplate thickening[49]. Towards the end of the Proterozoic, steady cooling of the mantle resulted in a myriad of geodynamic changes as part of the second revolution (*R2*), including (1) deeper slab break-off and increased slab pull, (2) a thicker oceanic lithosphere capable of coherent, long-term subduction, and (3) a departure from default lithospheric unzipping in orogens, leaving in its place the downward force needed to subduct buoyant crust into the mantle in accretionary orogens[23,28,29]. These changes marked the terminus of the "hot orogens" of the Proterozoic, with their characteristic ultrahigh-temperature metamorphism and massif-type anorthosites, and the establishment of the modern geodynamic regime, expressed in the metamorphic record as the emergence of continental (*U*)*HP* rocks, and low-*T*/*P* (<300 °C GPa^{-1}) oceanic blueschists and eclogites[29]. The deep underthrusting of continental margins that has been prevalent since *R2* invited the formation of large accretionary orogens that were built from off-scraped slivers of continental margin material and represent the thickest orogens ever made. Evaluation of the metamorphic record shows that revolutions 1 and 2 each represented an irreversible "growth spurt" after which the crust in orogenic belts became up to twice as thick and supported c. 4 km of additional elevation. The growth spurt associated with *R1* resulted in emergence and the formation of the first mountainous regions, whereas the *R2* growth spurt caused a shift from orogens with intermediate-altitude (c. 4 km) terrain to high-altitude mountain ranges akin to the present-day Pamir-Himalaya-Tibet orogen.

Causes for environmental upheaval culminating into the Great Oxygenation Event (GOE) and the Neoproterozoic Oxygenation Event (NOE; Fig. 1) have been sought in various external forcing mechanisms, such as increased runoff due to supercontinent breakup, enhanced weathering of basaltic rocks at low latitude, and a dwindling CO_2 flux from arc volcanism (Supplementary Note 1). Although each a valid hypothesis, these processes are largely transient, which does not match the irreversible nature of global oxygenation. Their role as fundamental external forcing on the environment can be further called into question, because they are not restricted to the periods leading up to the GOE and NOE; similar processes have occurred throughout Earth's history seeming without any major environmental consequence. The apparent absence of time-consistent external-forcing mechanism in the geologic record inspired the development of models that can explain global oxygenation through internal biochemical feedbacks[50]. In contrast to all of these processes, the orogenic growth spurts that occurred as part of tectonic revolutions R1 and R2 match—in their timing, duration, pace, paucity and irreversibility—the major events of environment upheaval, including both global oxygenation events and rapid increases in biological S metabolism, with the two most intense icehouse episodes in Earth's history occurring in their wake (Fig. 1; Supplementary Note 1).

Coevolution of orogenic processes and the Earth system state can be expected for several reasons. First and foremost, the growth spurts would have raised global terrigenous runoff and nutrient fluxes. For the

first growth spurt, this effect would be compounded by continental emergence and crustal growth, which would both have raised continental weatherability. The sediment flux increases are clearly reflected in seawater Sr records, which show drastic increases in the proportion of terrigenous strontium (Sr) relative to the total Sr delivered to the oceans during the growth spurts – c. 70% during the first and 40% during the second (Fig. 1). Similar changes would apply to phosphorous (P), because P and Sr are similarly incompatible and enriched in the upper crust and are both sequestered in relatively weatherable carbonate and phosphate minerals. The enhanced terrigenous element flux would have directly raised primary productivity, given that the P supply is rate-limiting and terrigenous runoff contains many other bioactive (micro-)nutrients such as Ba, Zn, Fe, and Si. This effect would be amplified by an increase in the SO_4^{2-} supply available for the release of bioactive P from re-mineralizing marine biomass[51]. Consequences of an enhanced flux of P would have been particularly impactful in Archean surface waters, where P concentrations were particularly low as a result of anoxic and ferrigenious conditions favoring Fe-P trapping and P exhaustion through photoferrotrophy[51,52]. Major biological innovation in response to these flux increments is demonstrated by the S isotope record of marine pyrite, which reflects concomitant increases in S metabolism, each followed by an increase in global biomass and biodiversity (Fig. 1). Other effects of raising mountains would have been: 1) oxygenation from increased burial of organic carbon[53], 2) an increased CO_2 flux to the atmosphere from accelerated oxidative weathering of rock-bound organic carbon (Zondervan et al., 2023), and 3) increased pH and salinity of ocean waters from an enhanced terrigenous supply of alkali metals. These many feedbacks show that the orogenic growth spurts identified through the metamorphic record should be considered as a possible endogenic driver for the development of a habitable environment during the past 3 billion years.

Declarations

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Figures

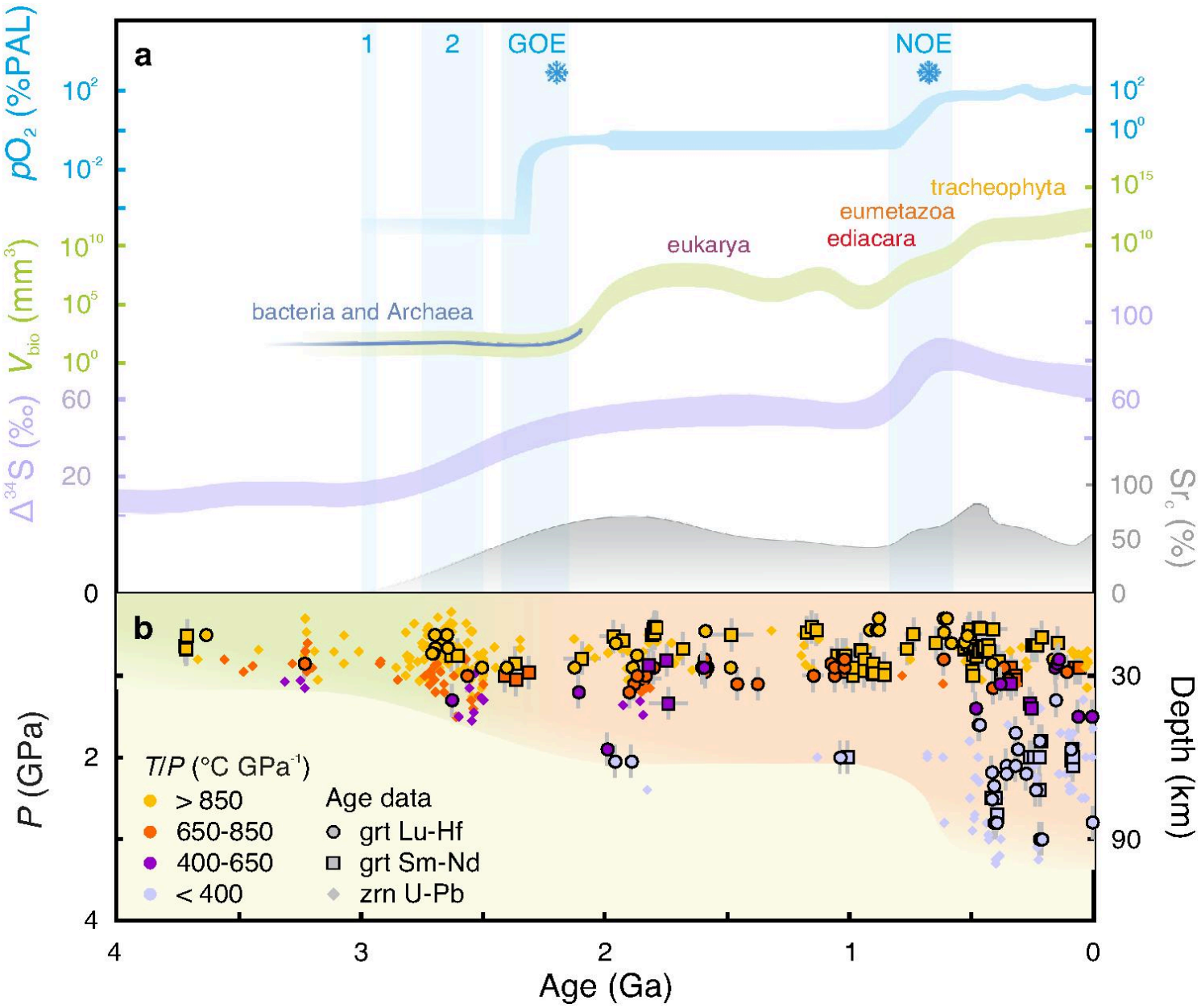


Figure 1

The metamorphic record in the context of Earth system change. (a) Evolution of atmospheric pO_2[55], the biovolume[56], S isotope diversity in marine pyrite as measure of S metabolism ($\Delta^{34}S$ is the difference between the highest and the lowest $\delta^{34}S$ value observed for pyrite of a given age; determined from $\delta^{34}S$ records[57], the percentage of oceanic Sr that is continent-derived[58] (Sr_c). (b) Peak-*P* conditions of continental metamorphic rocks through time. Colours indicate episodes during which the continental crust was andesitic (orange) or more mafic[41,42] (green). Oxygenation stages are shown for reference, marking early oxidative weathering (1), early "whiffs" of oxygenation and the rise of organisms capable of oxygenic photosynthesis[55] (2), the Great Oxidation Event[59] and the Neoproterozoic Oxidation Event[60]

in partial O_2 pressure relative to the present atmospheric levels (PAL). Snowflake symbols indicate main icehouse stages (Huronian Glaciation at c. 2.2 Ga, and the Sturtian and Marinoan Glaciations at 717-659 Ma and 650-635 Ma, respectively[59,61].

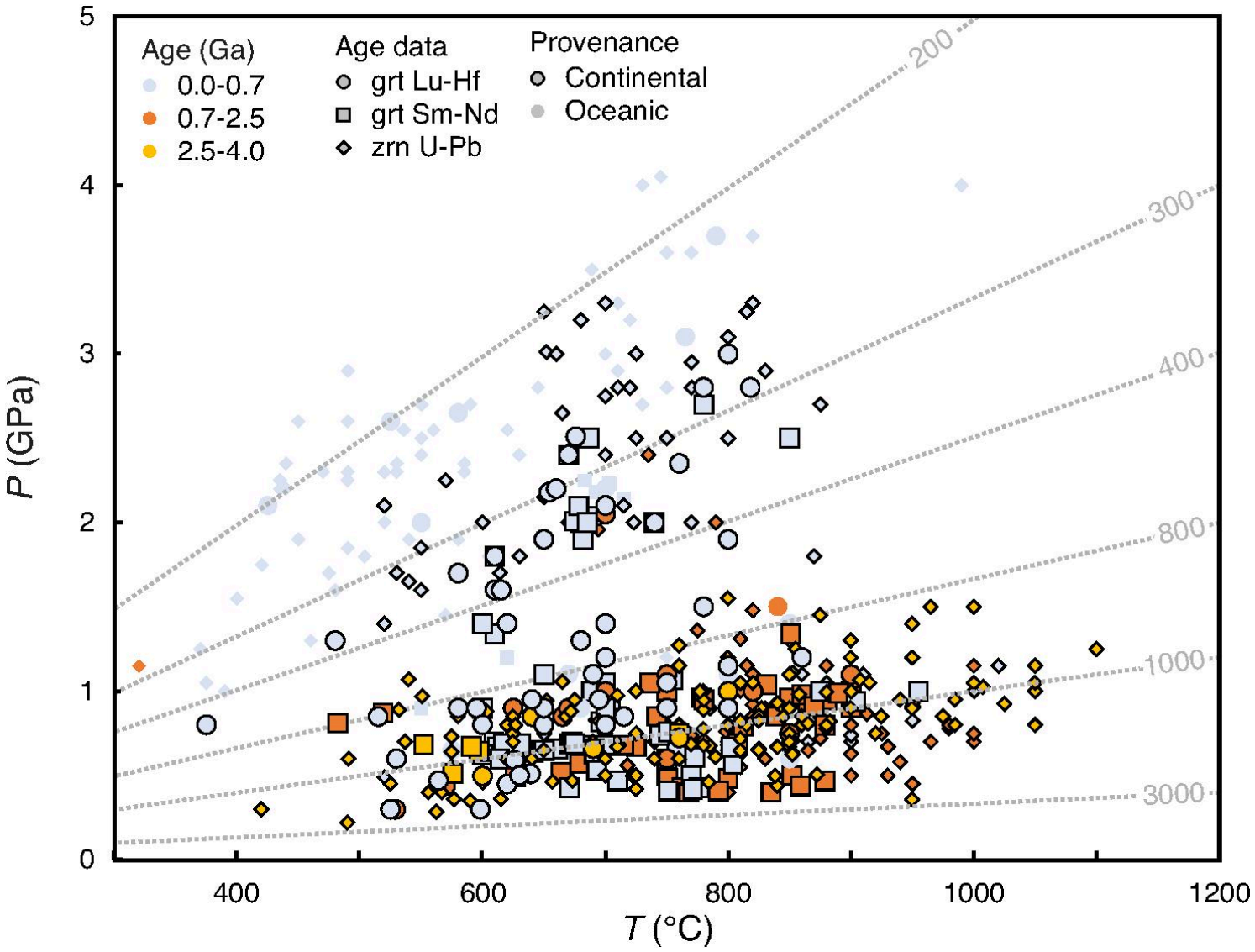


Figure 2

*P-T*estimates for metamorphic rocks. Symbols with outline represent continental and marginal rocks, whereas symbols without outline represent oceanic rocks.

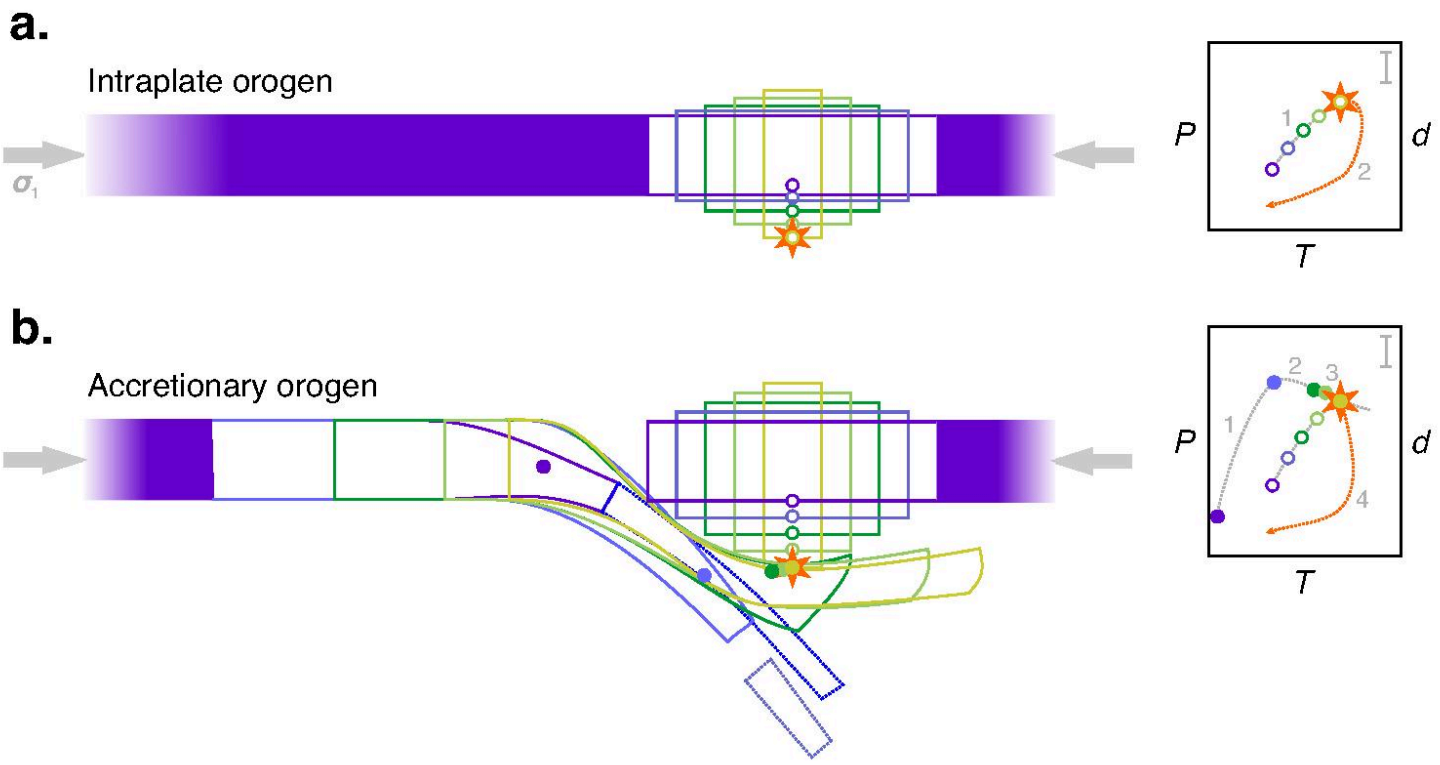


Figure 3

Schematic representation of metamorphic pressure (*P*), temperature (*T*) and depth (*d*) evolutions of (a) intraplate and (b) accretionary orogens developing as a result of far-field stress σ_1. Markers track the evolution of the deepest crustal rocks that can ultimately be exhumed to the surface, with the orange star marking the deepest conditions recorded by these rocks. Typical uncertainties on *P* estimates are shown for reference. (a) Intraplate orogens thicken relatively homogeneously, with rocks exhumed from its deepest sections best capturing the thickness of the mature orogenic column. Stages in the *P-T* diagram are (1) thickening and (2) exhumation of the marker rock. (b) In accretionary orogens, the lower plate is buried into the mantle due to slab from the still-attached oceanic lithosphere (1). Upon detachment from this lithosphere (2), the lower plate will bounce back and stall pond at the base of the developing accretionary orogen (3), where it will be pervasively overprinted and lose most if not all of the record of earlier, colder and deeper burial. The marker indicates those parts of the ponded lower plate that will detach and exhume (4) as a large (*U*)*HP* terrane in the frontal part of the orogen.

Supplementary Files

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- SupplementaryTableS1.xlsx
- SupplementaryNote1.pdf
- SupplementaryNote2.pdf

- SupplementaryNote3.pdf