SUPPLEMENTARY NOTE 2: THE METAMORPHIC RECORD

Building the metamorphic record – approach and caveats

Establishing the metamorphic record requires accurate constraints on the timing of metamorphism. So far, this has mostly been done using age data from zircon, which is the most widely used chronometric technique. Although zircon provides by far the richest resource of age constraints, there are potential limitations due to possible lithological bias, age misattribution in cases of poly-metamorphism, and general difficulty of linking zircon (re-)crystallization to *P-T* conditions. Garnet provides a useful alternative resource in this regard. Like with zircon, precise and accurate age data can be obtained from garnet using chronometers that are relatively robust against thermal re-equilibration (^{176}Lu-^{176}Hf and ^{147}Sm-^{143}Nd[111-113]. Unlike with zircon, garnet is typically metamorphic and directly provides *P-T* estimates, thus limiting the risk of misattributing ages to metamorphic events[114-117]. Using garnet-based data for time-series analysis of the metamorphic record thus provides additional constraints, as well as an independent check for possible age misattribution. Bulk-grain Lu-Hf and Sm-Nd geochronology enables high-precision age constraints (typically <0.5% 2 s.d.), which permit extreme age resolution for time series analysis. These data were used in conjunction with robust peak *P-T* estimates obtained from the same sample or similar samples from the same tectonic terrane or unit. At a first-order, the garnet-based record is broadly similar and complementary to that obtained using U-Pb zircon ages (Fig. 1). Where both zircon U-Pb and high-precision garnet Lu-Hf or Sm-Nd are available, both broadly date the same orogenic stage, with some notable exceptions for several Proterozoic *HP* rocks, where metamorphism was misattributed to the Archean on the basis of zircon. These and other details of the garnet-based metamorphic record are discussed below.

Consideration was given whether to expand the garnet-based record with results obtained using new methods of in-situ Lu-Hf and U-Pb garnet dating[118,119]. Although growing fast, the technique is still in its infancy and the amount of data from these techniques is at this stage still small. Additional factors to consider are that in-situ age results are inherently less precise (typically ≥3% 2 s.d.) and are typically obtained from subsets of data selected on the basis of interpretive or statistical arguments. Causes for dispersion and general accuracy are difficult to verify given the still-limited number of available garnet reference materials for either method. For the analysis done in this study, we deem the advantages of unilaterally including in-situ garnet age data – slightly increased number of data and coverage – to not yet outweigh the uncertainty associated with some of the results. Instead, we highlight specific results obtained recently for Archean terranes where high-precision garnet age data are not yet available. With rapid development and applications of in situ techniques, it is expected that testing and refinement of garnet-based time series analysis using in-situ data will be valuable in the future.

Using garnet- and zircon-based metamorphic data, a basic approach to building a time resolved-record of metamorphic processes and possible burial depths would be to survey the maximum *P* conditions and to take these as proxies for burial depth. This approach faces several inherent limitations and caveats that are intrinsic to the metamorphic record[29]: 1) metamorphism is punctuated, with recrystallization processes typically occurring only when active tectonic processes are still ongoing; 2) the metamorphic record is inherently discontinuous; active mountain building and associated metamorphism are not ubiquitous, and preservation bias, overprinting or poor coverage may cause signals from specific orogens to be obscured, overlooked or even entirely erased; 3) Rayleigh-Taylor instabilities at the base of the orogenic crust may cause rocks to transiently reside at depths that exceed regional Moho depth[120,121]; 4) *P-T* estimates may be problematic; thermobarometric estimates may be significantly less reliable than indicated by analytical uncertainties alone and may be in error when based on questionable mineral modes and activity estimates, or the composition of minerals that may not have reached equilibrium; 5) records of active orogens may be biased, because the deepest domains of the orogenic crust may not (yet) be entirely exhumed and exposed (e.g., Himalaya-Tibet orogen). Crustal xenoliths in magmatic rocks may be used instead to gain insight into the still-buried parts of orogens, but these are rare, even in modern orogenic settings, and their *P*-*T* and petrological record may be affected by melt-rock interaction.

A more fundamental issue pertains to the use of *P* estimates as proxy for depth. Generally, lithostatic pressure is assumed where *P* equals the product of the thickness and average density of the overburden, and the gravitational acceleration. This generally amounts to 0.3 GPa km^{-1} for most of the crust and uppermost mantle, which is widely used to convert *P* to burial depth. This assumption, however, is likely not to hold in many parts of the lithosphere. Contributions from deviatoric stresses to the overall stress state of rocks may cause large differences between the apparent depths that would be estimated from thermobarometric *P* estimates assuming lithostatic conditions and the actual depth where the rock resided[122-124]. Being case-specific, such differences are expected to manifest as scatter in the *P* record of metamorphic terranes and the metamorphic record in general. Given these various limitations, the metamorphic record, as obtained from continental rocks exhumed or erupted from the depths of mountain belts, is to be approached conservatively as an incomplete series of imprecise snapshots of the long-term evolution of orogens and orogenic processes. Its examination is a matter of extrapolating across time gaps and distinguishing consistency from anomaly to determine the general trends that are geologically meaningful and relevant. Acknowledging the above, we developed a time-resolved record of metamorphism using garnet-based data (Supplementary Table 1) complemented with zircon-based data from existing compilations[47,125]. The latter compilations were screened and filtered for data that represented mantle rather than crustal rocks and data based on *P*-*T* conditions that could not be verified in publications. Details of this record and the characteristics for each eon are provided below.

Metamorphic conditions through time

The Archean: Constraints for the Archean are few, yet crucial for the characterization of early metamorphism. The earliest examples of this are therefore discussed individually and in detail, followed by a more general survey. The age record from metamorphic garnet starts in the Eoarchean with the results obtained for the Isua Supracrustal Belt (ISB) and Itsaq Gneiss Complex (IGC) in W. Greenland. The earliest results for the ISB (Sm-Nd ages of 3.72 ± 0.02 Ga[126]), however, have garnered significant scrutiny, given their relatively complex nature. New Lu-Hf results from the ISB cast doubt on the interpretability of these results and instead indicate a Neoarchean age of metamorphism and shearing of the ISB (2.6-2.4 Ga[127]). Eoarchean ages were also obtained for garnet within amphibolites (peak *P*-*T* conditions: c. 0.9 GPa and 780 °C) from the adjacent IGC[128]. The in-situ Lu-Hf ages (3.65-3.58 Ma) are uncertain and may reflect partial disturbance, which motivated independent verification. High-precision Lu-Hf geochronology was performed on a similar type of garnet-bearing amphibolite to verify these (Supplementary Note 3). The Lu-Hf age of 3,635 ± 5 Ma validates the interpretation of Alfing et al.[128] of Eoarchean garnet-grade metamorphism in the IGC. The results establish the precise age of the oldest-known garnet growth in crustal rocks and provide the first reliable garnet-based datum on the time line, constraining the age of the low-*P*, high-*T*/*P* (840-950 °C GPa^{-1}) metamorphism that is common for much of the Archean.

The second oldest known occurrence of garnet-grade metamorphism is in the Acasta Gneiss Complex (AGC; Northwest Territories, Canada). The AGC is widely recognized as a polymetamorphic terrane with a range of Archean metamorphic imprints recorded from 3.75 Ga onward, as well as Paleoproterozoic overprinting relating to the Wopmay Orogeny. In-situ Lu-Hf analysis of garnet from tonalite gneisses within a low-strain enclave of the AGC provided ages between 3.28-3.21 Ga, as well as

1.86 ± 0.04 Ga[129], showing that the terrane was metamorphosed (c. 750 °C and 0.5 GPa) during the Paleoarchean and was reworked in the Paleoproterozoic and possibly in between. The Paleoarchean age resembles that obtained for garnet in the Stolzburg terrane of the Barberton Granite-Greenstone Belt (3.23 ± 0.02 Ga), which reflects metamorphism at slightly higher *P* (c. 640 °C and 0.9 GPa[130]). The dispersion in the AGC in-situ data could reflect the c. 1.86-Ga overprint, but could also signify additional Archean reworking. To test this, we performed high-precision Lu-Hf garnet dating on a different AGC lithology: a garnet-bearing amphibolite (Supplementary Note 3). The result (2,629 ± 4 Ma) is younger than the ages interpreted for garnet growth in the low-strain enclave, but broadly matches the ages of regional deformation, metamorphism (c. 650 °C and 0.6 GPa), and syn-tectonic plutonism associated with the amalgamation of the Slave Craton (2.63-2.60 Ga[131-133]. This event thus likely represents an additional, much younger occurrence of Archean garnet-grade metamorphism in the AGC and is thus included in our evaluation.

The search for early high-*P* metamorphism in the rock record has been ongoing for a long time. Eclogitic rocks of oceanic and continental provenance in the Belomorian Province (Kola Peninsula, Russian Federation) have yielded c. 2.87 Ga U-Pb zircon ages and have hence been argued to represent a very early occurrence of high-*P* metamorphism[134]. One of these occurrences ("Gridino-type eclogite") is argued to derive from mafic dykes of continental provenance, thus suggesting Archean deep continental subduction to peak conditions of c. 700°C and >1.3 GPa. Garnet Lu-Hf dating of the oceanic ("Salma-type eclogite") and continental eclogites, however, consistently yielded Paleoproterozoic ages 1,901 – 1,878 Ma[114,135], as did further U-Pb dating and REE analysis of zircon (1.91 – 1.88 Ga[135,136] and recent in-situ Lu-Hf garnet dating (1.88 ± 0.09 Ga[137]), indicating a case of age misattribution by Mints et al.[134].

A case for Archean high-*P* metamorphism may be provided by metasedimentary rocks from the Lewisian Gneiss Complex (LGC), NW Scotland. The metamorphic assemblages in these rocks reflect *T*/*P* < 440 °C GPa^{-1}, which is lower than the values reflect by most Archean metamorphic rocks (>675 °C GPa^{-1}). In-situ Lu-Hf garnet dating indicates an age of 2.81 ± 0.04 Ga for the formation of these assemblages[138]. The *P*-*T* estimates for these rocks (580-660 °C and 1.5-2.5 GPa) are different from those obtained so far for Lewisian crustal rocks, all of which indicate peak-*P* conditions below 1.5 GPa[139-142]. Evaluating the cause of this difference is at this point difficult. On the one hand, the rocks may represent an occurrence of *HP* metamorphism. On the other hand, *HP* conditions may need further validation, because (1) they are based on empirical phengite barometry, which is inherently uncertain; the Si contents seen in LGC white mica (3.2-3.5 a.p.f.u.) are more prevalent at *HP* conditions, but also occur below 1.5 GPa[143], and (2) omphacite, which thermodynamic modelling predicts to occur in the rocks, was not observed. Due to the above and the large uncertainty in *P* estimates, the LGC datum at this stage does not provide the necessary resolution for time series analysis and was hence not included in Fig. X. Other than the above, the metamorphism recorded before the Neoarchean is typified by high *T*/*P* (>675 °C GPa^{-1}) and peak-*P* conditions at or below 1.0 GPa, with a few exceptions from the Pilbara and Barberton granite-greenstone belts, which reached 1.1-1.2 GPa in the Mesoarchean. This changed going into the Neoarchean, when occurrences of metamorphism at c. 1.0 GPa became more common and several continental terranes reworked in large tectonic zones record *P* conditions of up to c. 1.5 GPa.

The Proterozoic and Phanerozoic: A new steady state in the peak-*P* conditions of metamorphosed continental crust appears to have been reached in the Paleoproterozoic, with the occurrence of high-grade metamorphism of the former eclogites of the Belomorian Province (see above), the Usagaran Belt in Central Tanzania[144] and the Ungava Orogen in North Québec, Canada[145]. Most of these rocks reflect peak *P* conditions of c. 2.0 GPa, with the exception of the mafic rocks from the Ungava Orogen, for which an estimate of 2.5 ± 0.2 GPa has been proposed. As burial of crust into the mantle is unlikely during this time (see main text), such relatively high *P* could instead be taken to indicate relatively extensive crustal thickening or transient overthickening, or could represent a local pressure anomaly[46]. Alternatively, the estimate itself may be less certain than indicated. The mafic rocks in question are reported to contain relict omphacite and much of the matrix is argued to have comprised this *HP* phase[145]. Nevertheless, due to the strong retrogression, a peak assemblage could not be fully established. The *P* of c. 2.5 GPa was estimated on the basis of garnet modal abundance as determined by point counting on a section of rock. There are two potential issues with this: (1) this approach could yield biased results given the coarse grain size and heterogeneous distribution of garnet in the rock, and (2) close scrutiny of the point-counting results shows that many domains were counted as garnet, even though they are not and may not have been. Possible *P* overestimation would be consistent with the jadeite component of omphacite, which is too low for this rock at 2.5 GPa and instead indicates c. 2.0 GPa. We thus conclude at this point that Paleoproterozoic *HP* rocks reflect a relatively common peak *P* of c. 2.0 GPa and that the estimates obtained so far for the retro-eclogites of the Ungava Orogen are not constrained well enough to disprove this hypothesis.

The Mesoproterozoic Grenville Orogen provides several occurrences of *HP* rocks of continental origin, all of which show peak *P* conditions similar to those recorded by the Paleoproterozoic *HP* rocks described above (c. 2.0 GPa)[146-149]. The eclogitic rocks that record these *P* conditions underwent relatively high temperatures (740-870 °C) and are typically migmatitic or restitic. Exhumation of these rocks can often be ascribed to ductile extrusion, by which a part of the hot, and partially molten and eclogitized lower crust was transported towards and through the orogenic wedge, exhuming as a large, intensely deformed nappe[150]. Most of these rocks exhibit a pervasive granulite-facies overprint associated with the latter stage of their history, clearly reflecting the relatively extreme thermal state that typifies the large hot orogens of the Proterozoic. High-*P* rocks recording similar 2.0 GPa peak-*P* conditions occurred into the Neoproterozoic – notably in the Egéré-Aleksod Terrane in southern Algeria (c. 685 Ma) and the Richarddalen Complex in northwest Spitsbergen (c. 620 Ma) – but peak-*T* conditions reflected by these rocks are generally lower (<700 °C).

The first signs of a major break in the style of orogeny are provided by the eclogites of the Ceará Group in the Brasiliano Orogen, northeast Brazil. These rocks underwent peak-*P* conditions of c. 2.8 GPa, which is far higher than any *P* recorded until then by continental rocks. The rocks appear to chime in the modern age of continental (*U*)*HP* metamorphism. Continental terranes that have since become formed the lower plates of accretionary orogens reflect similar or even higher pressures. Although single eclogite or diamond-bearing gneiss occurrences among these terranes may indicate much higher *P* conditions (>3.7 GPa), most eclogites in these terranes reflect a common 2.8-3.3 GPa imprint. These prevalent *P* conditions can be ascribed to the widespread reworking of these terranes at the base of orogenic wedge[21] and are observed in all continental *UHP* terranes of the Phanerozoic, including those in the Northern Qaidam Orogen, northern China (c. 435 Ma), the Western Gneiss Region, western Norway (c. 410 Ma), the Sulu Belt, southeast China (c. 230 Ma), and the youngest-known *UHP* rocks exposed on the d'Entrecasteaux Islands, eastern Papua New Guinea (c. 7 Ma). While not yet exhumed from the Pamir-Himalaya-Tibet Orogen, continental rocks of predominantly felsic composition appear reside at depths consistent with such pressures within orogenic root zone[151].

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