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Establishing the Timing of UHP Metamorphism and Exhumation from Long-Lived and Complex Zircon Growth

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Major advancements in understanding the timing of continental subduction to ultrahighpressure (UHP) conditions and subsequent exhumation have come from studies of zircon, which can grow at almost any stage on the pressure–temperature (*P–T*) path. This is in part due to the fact that many UHP terranes experience partial melting during exhumation (Zheng et al. 2011), allowing for multiple zircon growth events (e.g. Hermann et al. 2001). Meeting the challenge of determining the metamorphic evolution of UHP terranes relies on the ability to link ages obtained from wellcharacterized zircon domains to the pressure–temperature (*P–T*) path. This is not always a straightforward task because zircon from some UHP terranes defines a 10-50 m.y. range of U-Pb ages. The common approach to extracting segments of the *P–T* history from a large age spread is to use cathodoluminescence (CL) images, inclusion suites and trace element chemistry to define smaller age domains that correspond to growth or recrystallization events. A further complication is that the "events" themselves may be continuous or episodic.

A number of UHP terranes—Dabie-Sulu and North Qaidam, China, the Western Gneiss Region, Norway and North-East Greenland—show long-lived (>10 million years) and complex zircon growth during UHP metamorphism followed by exhumation to crustal conditions, which takes another 10-20 m.y. Zircon from the North-East Greenland UHP terrane formed over at least a 45 million year period, recording peak UHP metamorphism to the end of amphibolite facies ductile deformation. Our study employs the USGS-Stanford University sensitive high resolution ion microprobe – reverse geometry (SHRIMP_RG) to determine U/Pb ages and trace element concentrations in zircon separated from 17 samples chosen to capture the formation and exhumation history of the area (Gilotti et al. 2013). The resulting data set illustrates common approaches and pitfalls of employing complex zircon to establish the timing of UHP metamorphism and exhumation. The Carboniferous history of UHP metamorphism and exhumation in North-East Greenland is the youngest event known in the Caledonian collision between Baltica and Laurentia. UHP metamorphism in the overriding plate of Laurentia (i.e. Greenland) requires that plate convergence continued for at least 50 million years beyond the culmination of the Scandian collision at ≈400 Ma (Gee et al., 2008). Plate divergence is first possible at the beginning of exhumation of the North-East Greenland UHP terrane—hence the importance of this data set.

CL images are useful for identifying similar domains in a zircon population that reflect their growth in the protolith or later metamorphic, melting or deforming (dynamically recrystallized) environments; however, the CL domains may or may not correlate with age. Inclusion suites tied to distinct CL domains are key to linking ages to segments of the *P–T* paths. Zircon domains with coesite and diamond inclusions are critical for dating UHP metamorphism (McClelland and Lapen 2013). Trace element signatures in zircon, though not unique, can also aid in the interpretation of CL domains. For example, trace element patterns with flat HREE that lack a Eu anomaly are characteristic of eclogite facies zircon (Rubatto, 2002); however, Liu and Liou (2011) found this same trace element signature in zircon domains with quartz and plagioclase inclusions—demonstrating that this pattern can persist into the amphibolite facies. The eclogite facies trace element pattern also lingers in the amphibolite facies for some Greenland samples. Ti-in-zircon thermometry is another tool to assess the cooling history during exhumation of UHP terranes.

Fig. 1 shows that zircon records long-lived UHP metamorphism and subsequent exhumation from ≈ 365 Ma to 315 Ma. Coesite-bearing eclogites tend to best record the UHP metamorphism from 365-350 Ma, while

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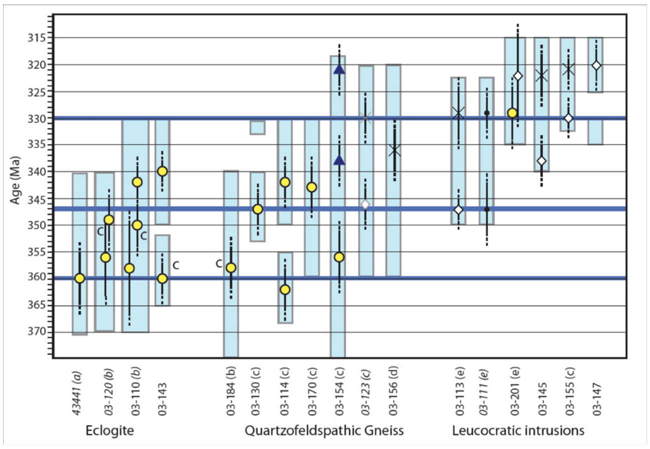

Fig. 1. Summary of U/Pb ages from the North-East Greenland UHP terrane for eclogites, quartzofeldspathic gneisses and leucocratic intrusions (from Gilotti et al. 2013).
Additional data is from (a) Gilotti et al. (2004); b) McClelland et al. (2006); c) McClelland et al. (2009); d) Gilotti and McClelland (2011); e) Gilotti and McClelland (2007). C indicates coesite. Symbols refer to distinct trace element patterns: 1.) yellow circles are flat HREE, no Eu anamoly, high T with garnet signature; 2.) blue triangles are flat HREE, variable Eu, low T with garnet signature; 3.) white diamonds are steep HREE with a magmatic signature; and 4.) x's are very steep HREE, metamorphic without garnet.

variably retrogressed host gneisses and late-stage, leucocratic melts emplaced into the gneisses track exhumation. All stages of exhumation involved melting, beginning with H_2O-absent dehydration melting of phengite during the initial stages of decompression. A garnet-bearing leucosome associated with a coesite-eclogite boudin gives an age of 347 Ma, which is interpreted as the beginning of phengite melting. Hornblende-bearing leucosomes formed in HP granulite to amphibolite facies gneisses between 350-340 Ma. Fluid assisted melting continued until 320 Ma in the form of pegmatites that cross cut all the ductile deformation fabrics in the gneisses. Changes in the zircon trace element patterns are tied to decreasing temperature. Inherited cores recording protolith ages typically preserve magmatic temperatures (700 ºC) and igneous REE patterns (Yb/Gd = 10). UHP/HP eclogite-facies zircon records higher T (900 ºC) and flat HREE patterns (Yb/Gd = 1). Granulite to amphibolite facies zircon in quartzofeldspathic gneisses records both flat (Yb/Gd = 1) and steep (Yb/Gd = 100) HREE patterns at ca 700 ºC, suggesting a range of garnet behavior during decompression. Amphibolite facies pegmatites and leucosomes document a transition from moderate HREE (Yb/Gd = 10) at 700 ºC to steep HREE (Yb/Gd = 100-1000) patterns at 600 ^{o}C. The pronounced steepening of the HREE is ascribed to garnet breakdown during amphibolite-facies metamorphism. The 30-50 million year spread of ages observed in individual samples records numerous periods of zircon growth, and are construed as a characteristic signature of slowly exhumed UHP terranes. The data show that zircon ages combined with trace element and textural characterization of zircon from a broad range of lithologies can successfully define the exhumation history of UHP terranes.

Key words: eclogite, geochronology, trace element geochemistry, UHP metamorphism, zircon

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