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Sensitive high-resolution ion microprobe U-Pb dating of prograde and retrograde ultrahigh-temperature metamorphism as exemplified by Sri Lankan granulites

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ABSTRACT

Ultrahigh-temperature (UHT) granulites of the central Highland Complex, Sri Lanka, underwent some of the highest known peak temperatures of crustal metamorphism. Zircon and monazite U-Pb systems in granulites near Kandy, the highest grade region (~1050 °C; 0.9 GPa), preserve both a record of the timing of prograde and retrograde phases of UHT metamorphism and evidence for the ages of older protolith components. Zircon grains from a quartz-saturated granulite containing relics of the peak UHT assemblage have remnant detrital cores with dates of ca. 2.5–0.83 Ga. Date clusters of ca. 1.7 and 1.04–0.83 Ga record episodes of zircon growth in the source region of the protolith sediment. Two generations of overgrowths with contrasting Th/U record metamorphic zircon growth at 569 ± 5 and 551 ± 7 Ma, probably in the absence and presence of monazite, respectively. The age of coexisting metamorphic monazite (547 ± 7 Ma) is indistinguishable from that of the younger, low-Th/U zircon overgrowths. Zircon from a quartz-undersaturated monazite-absent UHT granulite with a mainly retrograde assemblage is mostly metamorphic (551 ± 5 Ma). The ca. 570 Ma zircon overgrowths in the quartz-saturated granulite probably record partial melting just before or at the metamorphic peak. The ca. 550 Ma zircon in both rocks, and the ca. 550 Ma monazite in the quartz-saturated sample, record post-peak isothermal decompression. A possible model for this pressure-temperature-time evolution is ultrahot collisional orogeny during the assembly of Gondwana, locally superheated by basaltic underplating, followed by fast extensional exhumation.

INTRODUCTION

Zircon, with its low reactivity and high closure temperature for U-Th-Pb diffusion, is the mineral of choice for dating high-temperature metamorphism. However, the specific conditions under which zircon grows or recrystallizes, and therefore the stages of metamorphism it records, remain incompletely defined (Harley et al., 2007); the same applies to monazite. Interpretation is even more complicated if the high-temperature metamorphism is imposed on rocks already metamorphosed by previous events. The ultrahigh-temperature (UHT) granulites of the central Highland Complex, Sri Lanka (Kriegsman and Schumacher, 1999), part of the dismembered Pan African (ca. 650–500 Ma) granulite terrane exposed in remnants of East Gondwana, record some of the highest known temperatures of crustal metamorphism (~1150 °C: Sajeev and Osanai, 2004). Rocks metamorphosed under such extreme conditions provide a rare opportunity to study zircon and monazite growth, and date the stages of UHT metamorphism, with minimal textural or isotopic memory of earlier events.

GEOLOGICAL SETTING

The basement of Sri Lanka consists mostly of Mesoarchean to Neoproterozoic orthogneiss and paragneiss complexes (Milisenda et al., 1988; Kröner et al., 1991). The oldest rocks are in the Highland Complex (Sajeev and Osanai, 2004), a belt of mostly charnockites and metasediments in the center of the island (Fig. 1). Younger granites and orthogneisses on either side are dominantly of Mesoproterozoic to Neoproterozoic age.

The basement was metamorphosed to amphibolite and/or granulite grade in the Neoproterozoic, each complex having a discrete metamorphic history. Metamorphic grade in the Highland Complex changes systematically on a regional scale (Fig. 1). Pressure grades from ~0.5–0.9 GPa west to east (Faulhaber and Raith, 1991), but the temperature maximum of >1100 °C is near the center of the complex (Sajeev and Osanai, 2005). Most of the terrane evolved along a clockwise pressure-temperature (*P-T*) path (Hiroi et al., 1994; Raase and Schenk, 1994).

Early estimates of the age of metamorphism (500–450 Ma) were mostly based on K-Ar and U-Pb analyses of pegmatite minerals (Holmes, 1955; Vitanage, 1959; Cooray, 1969). Higher ages, mostly from Rb-Sr whole-rock analyses, also were interpreted as metamorphic ages. Crawford (1969) proposed high-grade metamorphism of the Highland Complex ca. 2.0 Ga, followed by events ca. 650 and 450 Ma. De Maesschalck et al. (1990) proposed that the southwestern Highland Complex was metamorphosed ca. 1.93 Ga. Their age of ca. 800 Ma measured in the same area was interpreted as dating Vijayan metamorphism. Cordani and Cooray (1989) dated that metamorphism at ca. 1.0 Ga. Hölzl et al. (1991)

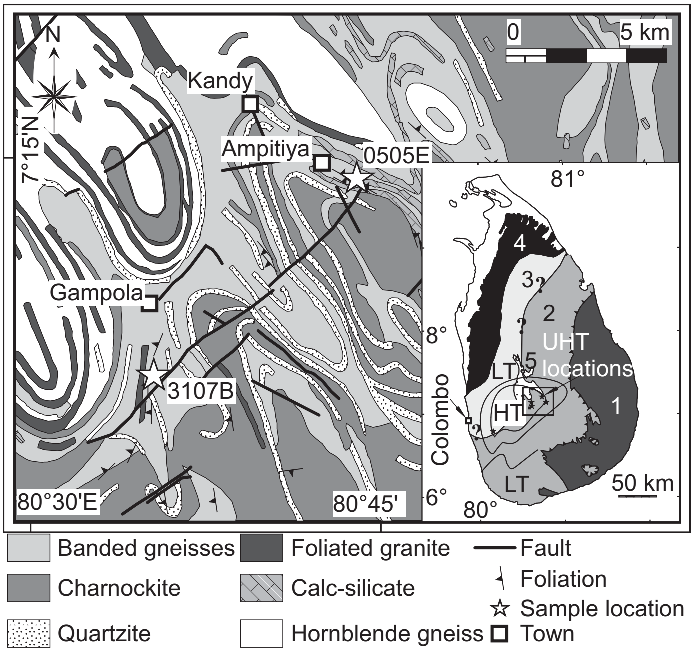

Figure 1. Geological sketch map of central Highland Complex with sample locations. Inset: Tectonic map of Sri Lanka with isotherms from Sajeev and Osanai (2005). 1—Vijayan Complex, 2—Eastern Highland Complex, 3—Western Highland Complex, 4—Wanni Complex, 5—Kadugannawa Complex. UHT—ultrahigh temperature; HT—high temperature; LT—low temperature.

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queried the validity of the whole-rock ages, however, arguing that metamorphism was more accurately dated using mineral isochrons.

Most mineral studies from the Highland Complex suggest that the high-grade metamorphism was late Neoproterozoic to early Paleozoic. Hölzl et al. (1991) reported Sm-Nd and Rb-Sr mineral ages of 560–465 Ma from metapelites and metabasites. Kröner and Williams (1993) argued from sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb analyses that the granulites of the Kataragama klippe were ca. 1.8 Ga rocks metamorphosed after 670 Ma. Hölzl et al. (1994) dated minerals from metapelitic granulites using U-Pb thermal ionization mass spectrometry (TIMS), obtaining ages of ca. 570 and 555 Ma (zircon, Zrn), 592 and 555 Ma (monazite, Mnz), and 538 Ma (rutile, Rt). A zircon age of 608 ± 4 Ma from a metabasite was considered the best estimate for peak-granulite metamorphism. Based on textural relations, Sajeev et al. (2007) interpreted the laser ablation–inductively coupled plasma (LA-ICP) zircon U-Pb age of a high-*P* granulite (ca. 580 Ma) as dating peak metamorphism, and its Sm-Nd mineral/whole-rock isochron age (ca. 535 Ma) as dating isothermal decompression.

None of the above results come from typical Mg-Al UHT (>900 °C) granulites. The *P-T* evolution of the UHT granulites is more complicated than that of the surrounding high-*T* rocks, so the question arises whether the UHT assemblages are actually relics of an earlier event later overprinted by the high-*T* event. Sm-Nd analyses (by Sajeev et al., 2003) raised this possibility; an isochron defined by orthopyroxene (Opx), whole rock, and plagioclase (Pl) + quartz (Qtz) was consistent with metamorphism ca. 550 Ma, but that including garnet gave ca. 1.48 Ga. Either garnet was partly residual from the source rocks, or it recorded an earlier metamorphic event.

SAMPLES AND METAMORPHIC CONDITIONS

Two UHT sapphirine (Spr) granulites from near Kandy were selected for this study. Sample 3107B was the same Qtz-saturated sample dated by Sajeev et al. (2003). It preserved relics of the peak metamorphic mineral assemblage. Sample 0505E was a Qtz-undersaturated sample containing several retrograde assemblages (Sajeev and Osanai, 2004). Sample 3107B was collected from south of Gampola (Fig. 1), where UHT granulite is interlayered with pelitic gneiss. Sample 0505E was collected from blocks within marble at Talatuoya, near Ampitiya.

Inclusions of Spr + Qtz in garnet cores in sample 3107B (Fig. 2A) are interpreted as the peak metamorphic mineral assemblage. Rims of the same garnet grains contain inclusions of Opx + sillimanite (Sil) + Qtz, another diagnostic UHT assemblage. That assemblage is also present in the matrix (Fig. 2B) associated with garnet. Porphyroblasts of Opx are also present (Fig. 2C). Retrograde textures include symplectites, rims and moats involving cordierite (Crd), Spr, Opx, and spinel (Spl). Biotite is always present in the late-stage assemblage. Minor pockets of leucosome are present within the retrograde matrix.

The diagnostic assemblages Spr + Qtz and Opx + Sil + Qtz indicate a peak metamorphic temperature of ~1150 °C (Sajeev and Osanai, 2004). Thermodynamic modeling of the stability fields, allowing for the effect of bulk chemical composition on the sapphirine solution model of Kelsey et al. (2004), gives a pressure of ~0.8 GPa. The transition from Spr + Qtz to Opx + Sil + Qtz indicates isobaric cooling, and the retrograde symplectites indicate near-isothermal decompression. On an FMAS (FeO-MgO-Al_2O_3-SiO_2) phase diagram for the calculated bulk composition for the peak mineral assemblage (see the GSA Data Repository[1]), the near peak *P-T* conditions estimated using X_{Mg} [Mg/(Fe + Mg)] isopleths for garnet (Grt), Spr, and Opx and the mineral compositions from Sajeev and Osanai (2004) give ~1050 °C at ~0.9 GPa.

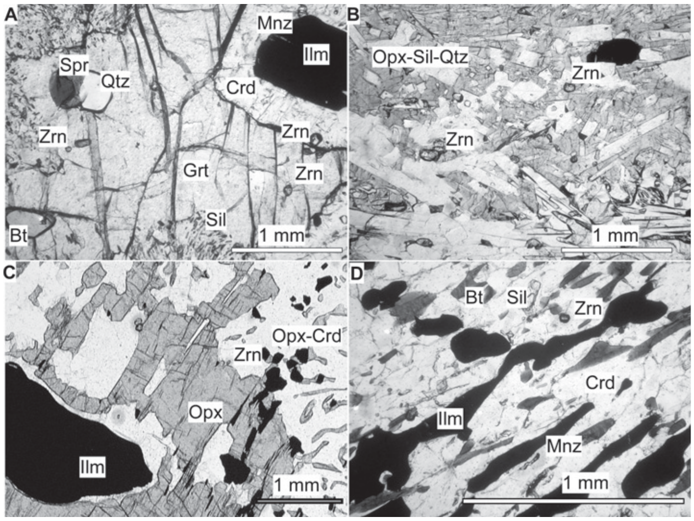

Figure 2. Photomicrographs of zircon and monazite in various textural settings. A: Zircon (Zrn) inclusion in garnet core in association with sapphirine (Spr) + quartz (Qtz). B: Zircon inclusions within orthopyroxene (Opx) + sillimanite (Sil) + Qtz assemblage. C: Zircon included in cordierite (Crd) in Opx-Crd symplectite. D: Zircon and monazite (Mnz) in a Crd-bearing symplectite assemblage. Bt—biotite; Ilm—ilmenite; Grt—garnet.

Zircon in sample 3107B is closely associated with the peak Spr + Qtz assemblage (Fig. 2A) and with Opx + Sil + Qtz in the matrix (Fig. 2B). Zircon also occurs within retrograde matrix minerals such as Crd (Figs. 2A, 2C, and 2D). In contrast, the scarce monazite is associated only with the retrograde Crd-bearing matrix (Figs. 2A and 2D).

Sample 0505E consists mainly of retrograde assemblages such as Opx-Spr, Opx-Spl and/or Opx-Crd symplectites, with or without relic garnet. Zircon is mainly associated with the Opx-bearing symplectites. There is no monazite. Textural evidence and phase diagrams (see the Data Repository) indicate isothermal decompression under UHT conditions.

SHRIMP GEOCHRONOLOGY

Zircon and monazite were dated using the Australian National University SHRIMP II and methods outlined in the Data Repository (see the Data Repository). Uncertainties in the mean ages are 95% confidence limits and include calibration uncertainties of ≤0.5%.

Granulite 3107B contained both zircon and monazite. Cathodoluminescence (CL) imaging showed three stages of zircon growth: subhedral cores, many with remnant concentric zoning; thick sector-zoned overgrowths; and thin CL-dark outer overgrowths (Fig. 3). There were also some large zircon grains with only weak concentric zoning. The monazite had backscattered electron zoning textures ranging from simple concentric to complex mosaic.

SHRIMP U-Th-Pb analyses of 46 zircons gave a narrow range in U (35–377 ppm), but a large range in Th/U (0.016–2.47) and isotopic dates (2490–515 Ma; Fig. 3). All the high ages came from cores; ca. 2.49, ca. 1.71, and 1.04–0.83 Ga. The lower ages were distributed between 590 and 515 Ma. Analyses of 16 thick, sector-zoned overgrowths and large grains with concentric zoning gave a weighted mean $^{206}Pb/^{238}U$ age of 569 ± 5 Ma. The remaining dates, all from low-Th/U, CL-dark outer overgrowths, were dispersed, but a group of 8 gave a weighted mean age of 551 ± 7 Ma. Two generations of metamorphic zircon grew at different times under different metamorphic conditions.

Monazite had a much wider range in composition (U: 130–7550 ppm, Th/U: 1.1–589), but a smaller range in apparent age. Except for the high ages from the core of one grain (ca. 608 Ma), all 13 monazite $^{206}Pb/^{238}U$ ages were equal at 547 ± 7 Ma.

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[1] GSA Data Repository item 2010271, supplemental material, including Tables DR1–DR3 and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

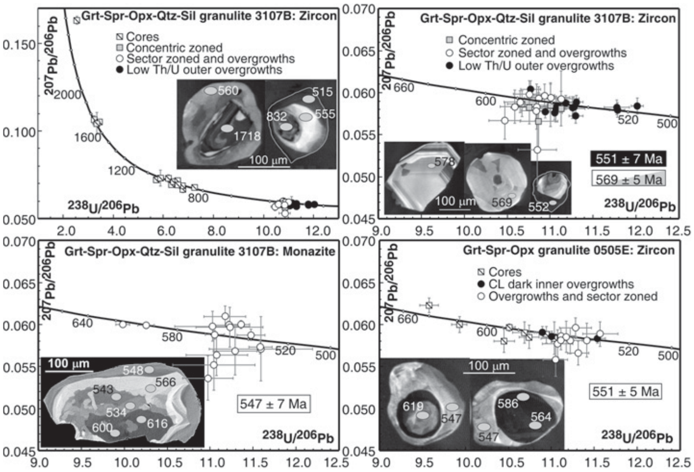

Figure 3. Concordia plots of U-Pb analyses of zircon and monazite from samples 3107B and 0505E. Zircon cathodoluminescence (CL) and monazite backscattered electron images show typical growth textures and U-Pb dates (Ma). Uncertainties = 1σ. Mineral abbreviations as in Figure 2.

Granulite 0505E contained only zircon. Superficially the grains appeared similar to those from sample 3107B, but their zoning was different. Very few grains had cores, and most cores were small (<50 μm), rounded, and sector zoned. All cores were surrounded by a layer of CL-dark zircon with either no visible zoning or very weak sector zoning. Overgrowing this, and also forming whole grains, was a thick layer of moderately luminescent, sector-zoned zircon. No grains or cores had the simple concentric zoning common in the zircon from sample 3107B.

There were 21 analyses that showed moderate ranges of low to medium U contents (90–700 ppm) and Th/U (0.05–0.45). Highest U contents were in the dark inner overgrowths. Th/U in the outer overgowths and sector-zoned grains was relatively uniform (0.26–0.30). The cores gave the widest range of ^{206}Pb/^{238}U dates, ca. 640–560 Ma. A lack of clustering suggests that this represented either a real age range, or varied resetting of older zircon (ca. 640 Ma or older) due to partial radiogenic Pb loss. Dates from the few CL-dark layers thick enough to analyze (566–536 Ma) had a slightly larger range than those from 10 outer overgrowths and sector-zoned grains, 560–534 Ma. The latter were all equal at 551 ± 5 Ma, consistent with the textural evidence that the CL-dark zircon was an earlier generation of growth.

NATURE AND TIMING OF METAMORPHIC PHASES

The two granulites studied represent contrasting lithologies that probably had the same UHT metamorphic history. The Qtz-saturated sample (3107B) preserved both peak and retrograde assemblages; the Qtz-undersaturated sample (0505E) was dominated by retrograde assemblages. Only sample 3107B contained monazite.

The presence of aluminosilicates and garnet in sample 3107B and the occurrence of the rock interlayered with pelitic gneisses indicate that its protolith was weathered sediment, an interpretation supported by the presence of abundant zircon cores of a wide range of ages, remnants of detrital zircon from a sedimentary rock. Despite the extreme metamorphic temperatures (~1050 °C), the cores not only preserve their original igneous zoning but also a range of Th/U distinct from that in the younger metamorphic zircon overgrowths. Zircon U-Pb survival of UHT (albeit short lived) has also been reported in Norwegian orthogneisses (Möller et al., 2002).

Given experimentally measured rates of Pb diffusion in zircon, such Pb-U survivals are anomalous. Lee et al. (1997) estimated a closure temperature for Pb diffusion in 100-μm-diameter zircon grains of ~920 °C. Cherniak and Watson (2000) estimated ~990 °C. Both estimates are well below the temperature reached by granulite 3107B, yet the zircon cores have survived, apparently without significant loss of radiogenic Pb.

Internal chemical differences, zoning, and the Pb-U isotopic system in the zircon cores probably survived because the metamorphic conditions were dry. This would also explain the absence of monazite in the peak metamorphic assemblages. Phase diagram calculations predict no melt phase under peak conditions of ~1050 °C at 0.9 GPa. The metamorphic overgrowths were possibly generated through Zr-bearing silicate reactions (e.g., Harley et al., 2007) or Ostwald ripening.

Our first-order conclusion, based on the zircon growth textures and the mineral ages, is that the UHT metamorphism was of late Neoproterozoic age. The Sm-Nd isochron age of 1478 ± 58 Ma (measured by Sajeev et al., 2003), originally interpreted as the age of metamorphism, probably reflects the failure of the Sm-Nd isotopic system in garnet to equilibrate during the UHT event. If so, the closure temperature for Nd diffusion in millimeter-sized garnet exceeds 1050 °C.

The evidence from monazite is critical in deciding which generation of metamorphic zircon growth in sample 3107B records peak metamorphism. Monazite is part of the retrograde assemblage and occurs, with some zircon, in the matrix surrounding Grt and Opx. Th/U in the outermost, younger zircon overgrowths is very low, consistent with zircon growth coeval with monazite. The U-Pb ages of the monazite (547 ± 7 Ma) and outer zircon overgrowths (551 ± 7 Ma) are indistinguishable. Thus there is chemical, petrographic, and isotopic evidence that the monazite and outer zircon overgrowths formed at the same stage of retrogression.

The stability of monazite during metamorphism is critically dependent on the light rare earth element (LREE) content of the host rock, and its abundance is controlled by the LREE content of the melt phase (Rapp and Watson, 1986; Rapp et al., 1987). The formation of Crd after Grt in the presence of melt in the retrograde assemblage of 3107B, thereby releasing Zr and REEs (Fraser et al., 2000; Tomkins et al., 2005), would have promoted growth of both retrograde zircon and monazite. The retrograde assemblage indicates near-isothermal decompression, probably by exhumation, so the age of ca. 550 Ma measured on zircon and monazite probably records uplift after the metamorphic peak. The older inner overgrowths, in contrast, have moderate to high Th/U, inconsistent with growth coeval with monazite. The age of those overgrowths, 569 ± 5 Ma, is interpreted as the age of prograde or peak metamorphism, possibly recording the first appearance of a melt phase (Williams, 2001).

The thick outer zircon overgrowths from sample 0505E all have very similar Th/U, consistent with growth in a uniform chemical environment. The presence of melt in this sample is not well established, but several retrograde textures are similar to those in melt-bearing sample 3107B. Textural studies and thermodynamic modeling indicate that sample 0505E underwent near-isothermal decompression similar to that of sample 3107B. This conclusion is supported by the zircon dating, which records growth of thick zircon overgrowths at the same time (551 ± 5 Ma) as the growth of zircon and monazite during the decompression of sample 3107B. However, the rare zircon cores in sample 0505E have relatively low Th/U and are the same age as the first episode of metamorphic zircon growth in 3107B, consistent with zircon growth in the presence of a Th-rich mineral during prograde or peak metamorphism. Possibly that mineral became unstable later in the metamorphic cycle, releasing Th such that the Th/U ratio in zircon grown during subsequent retrogression was higher.

Our combined data indicate that the Sri Lankan UHT granulites approached or reached peak metamorphic conditions ca. 570 Ma, then cooled and decompressed nearly isothermally ca. 550 Ma (Fig. 4). This conclusion is supported by petrographic observations and the results of thermodynamic modeling. In this specific case, zircon overgrowths formed both before or during, and after peak metamorphism, while monazite crystallized during decompression, possibly due to reactions involving LREE-rich silicate melt at very high temperatures.

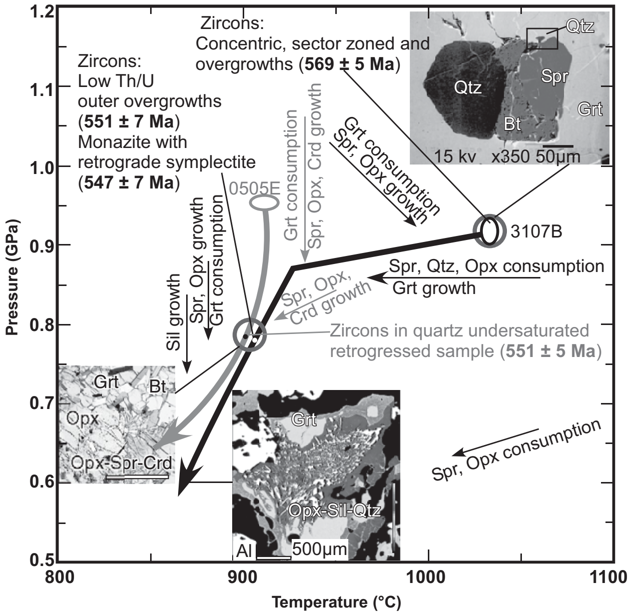

Figure 4. Pressure-temperature-time path for evolution of ultra-high-temperature granulites from Highland Complex, Sri Lanka. Peak pressure-temperature conditions are calculated based on compositional isopleths and mineral consumption, and growth directions are base model proportion isopleths on phase diagrams (see footnote 1). Mineral abbreviations as in Figure 2.

Few tectonic models can explain crustal metamorphism at ~1050 °C and 0.9 GPa followed by rapid decompression, so the tectonics of regional UHT metamorphism remain problematic (Harley, 2004; Kelsey, 2008). Of several models that might be viable (magmatic overaccretion; lithospheric removal after crustal thickening; channelized extrusion of deep crustal rocks after inhomogeneous extension; high heat flow in a backarc basin; viscous heating in a collisional orogen), the most likely to apply to central Sri Lanka is ultrahot collisional orogeny during the assembly of Gondwana (Tsunogae and Santosh, 2010), locally superheated by basaltic underplating, followed by rapid extensional exhumation.

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