Implications of Zn-Spinel + quartz association during high-grade metamorphic rocks of Trivandrum Block, southern India

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Coexisting spinel+quartz in aluminous granulites often considered a robust indicator of ultrahigh-temperature metamorphism. Here we describe eleven spinel+quartz (the association notation cannot be used without being defined, in any case it is irrelevant in the abstract) assemblages from distinct microdomains in three closely associated migmatite samples from the Kerala khondalite belt within the Trivandrum Block of southern India. Whole-rock geochemical data indicate high-Zn (157.3, 109.1, 67.0 ppm) content in the spinel-bearing samples whereas this value is low (31.1 ppm) in spinel-absent samples. Spinel closest to the leucosome domain has an X_{Mg} [Mg/(Mg+Fe)] of 0.29-0.30 and shows the highest Zn contents (if you want to give these numbers, you must define the variable, as for X_{Mg} above, e.g., Zn/(Mg+Fe+Zn)). Spinel from the less migmatised is less rich in Mg X_{Mg} = 0.24-0.25 and Zn (X_{Zn} = 0.07-0.08). Isochemical phase diagram sections show that the Grt-Sil-Spl-Qtz-Ilm-melt assemblage is stable only at relatively low-temperatures (T ≈770-830 °C, P ≈4.5-6 kbar) while the low-Zn microdomain has a larger stability field of c. 769 to 950 °C at pressures between *c*. 4.5-6 kbar. Petrographic observations and thermodynamic modeling indicate the peak-metamorphic assemblage (Grt-Sil-Spl-Qtz-Ilm-melt) was stable over a wide range of *P-T* conditions, with peak metamorphism at around 920 °C at 5.5 kbar. From microstructural observations we infer a clockwise evolution trajectory for the UHT granulites in the Trivandrum block. Microstructurally-controlled, in-situ, EPMA-age dating of monazites from these rocks yields three age populations that correlate with the timings of prograde (*c*. 600 Ma), peak (*c*. 580 Ma) and retrograde (*c*. 520-500 Ma) metamorphism. These results demonstrate that low-Zn spinel in otherwise proven UHT rocks need not imply high-temperature conditions. This observation should motivate a re-evaluation of reports on natural Zn-bearing and absent spinel+quartz assemblages from high-grade terranes in the context of UHT metamorphism.

Keywords: spinel+quartz, ultrahigh-temperature metamorphism, partial melting, Gondwana

LA-ICP-MS Zircon U-Pb ages for metamorphic rocks from the Highland and Wanni Complexes, Sri Lanka.

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Sri Lanka has been considered to locate inside the collision zone during amalgamation of Gondwana supercontinent (e.g. Meert, 2003). Therefore, Sri Lanka plays an important role to elucidate the process of amalgamation of the Gondwana supercontinent. However, the origin, tectonic evolution and even lithological divisions of Sri Lankan metamorphic rocks are still unclear, although many petrological and geochronological works have been carried out previously. One of the reasons is the shortage of reported zircon U-Pb ages which provide us some information about protolith formation and metamorphism. This study reports LA-ICP-MS zircon U-Pb ages from 45 metamorphic rocks in the high-grade complexes (Highland and Wanni Complexes), and reconsiders about the lithological boundary between these complexes and their origin.
On the Basis of rock type, metamorphic grade and Nd model ages, the metamorphic rocks in Sri Lanka are subdivided into three major crustal units (e.g. Cooray, 1994), which are Wanni Complex (WC), Highland Complex (HC) and Vijayan Complex (VC). The HC is composed of interlayered granulites including charnockite, pelitic to psammitic gneiss, marble, quartzite and mafic granulite with Nd model ages of *ca.* 2.0-3.0 Ga. On the other hand, the WC consists of amphibolite to granulite-facies, banded orthogneiss, charnockite, pelitic to psammitic gneiss, migmatite and minor quartzite, calcsilicate rocks with Nd model ages of *ca.* 1.0-2.0 Ga.
Geochronologically, the HC and WC are clearly characterized by > *ca.* 1500 Ma of detrital zircon ages with *ca.* 2000-1800 Ma of protolith (igneous) ages and *ca.* 1100-700 Ma of detrital zircon ages with *ca.* 1100-800 Ma of protolith ages, respectively. The age differences between them strongly indicate that their origins are different. Therefore, considering with zircon ages, rock distributions, the direction of metamorphic foliations and geography, the boundary between the HC and WC are reconsidered. Additionally, metamorphic ages of *ca.* 650-500 Ma are widely recognized from the HC and WC. The age distributions of metamorphic ages can be broadly divided into three age peaks of *ca.* 650-600 Ma, *ca.* 600-550 Ma and *ca.* 550-500 Ma. It may imply three metamorphic events for metamorphic rocks in the HC and WC. In view of field occurrence, petrography and areal distribution, *ca.* 550-500 Ma of metamorphic ages may be related with post-tectonic events (igneous and fluid activities). Although the lack of petrological evidences, *ca.* 650-600 Ma and *ca.* 600-550 Ma of metamorphic ages may be related with collision events among the HC, WC and VC. Finally, based on the detrital zircon ages and protolith ages, the HC and WC are clearly comparable with Trivandrum Block (TB) and Southern Madurai Block (SMB) in southern India, respectively. This suggests the possibilities of same origin between HC and TB, and WC and SMB.

Keywords: LA-ICP-MS zircon U-Pb age, Highland Complex, Wanni Complex, Sri Lanka, Gondwana supercontinent

The growth history of continents delineated by compilation of detrital zircon ages

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The current understanding on the growth history of continents needs a major revision in view of granitoid recycling into the mantle. At present, Archean continental crusts occupy less than 20 % in area of the modern continents; on the other hand, various previous studies on geochemistry and thermal evolution suggest active production of the continental crust since the Hadean. Production of the continental crust and the growth of the continents in large-term should be differentiated. In order to reconstruct the secular change in continental growth from ca. 3 Ga (Meso-Archean) to the present, we conducted global compilation of detrital zircon U-Pb ages from sandstones of various depositional age in the world. Using this database, the growth patterns of continents, at the timing of ca. 2.9, 2.6, 2.3, 1,0 and 0.6 Ga, are estimated for each continent first, then overall picture was reconstructed, as follows. Before ca. 2.3 Ga (Archean and Paleoproterozoic), the production and recycling of the continental crust were likely relatively short-cycled, and the net continental growth was probably slow. The short cycle was likely driven by the numerous formation of small-sized embryonic continents, much smaller than modern ones, and by the more ubiquitous subduction. From ca. 2.3 Ga to 1.0 Ga, the average size of continent became larger, comparable to the modern ones. Especially after ca. 1.8 Ga formation of the continent Nuna, more efficient continental growth started by the accretion of island arcs to continental margins. Since ca. 1.0 Ga, the breakup of the supercontinent Rodinia, the total volume of the continental crust likely has decreased according to the more effective recycling of relatively young continental crust.

Keywords: continental growth, detrital zircon, U-Pb age, embryonic continent

SHRIMP U-Pb zircon age determination of Pan-African orogeny from a single outcrop in South Sudan

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We collected granitic gneiss (SSD-1) and intruding leucocratic gneiss (SSD-2) samples from a single outcrop (N4.840556, E31.552778) exposed in Jebel Mountain of the Juba Area, South Sudan. SSD-1 and SSD-2 are plotted within the granodiorite and trondhjemite field of the An-Ab-Or diagram, respectively. We determined SHRIMP U-Pb zircon ages of the gneisses and the results are quite distinct from each other. The granitic gneiss sample has two age populations. The older population of SSD-1 shows scattered $^{207}Pb/^{206}Pb$ age distribution near the Archean-Paleoproterozoic boundary (ca. 2500 Ma), and most of analyzed ages are more or less discordant. The younger population displays much younger and more concordant ages, yielding weighted mean $^{238}U/^{206}Pb$ age of 993.8±7.1 Ma (n=34), close to the boundary between Mesoproterozoic and Neoproterozoic. Because Th/U ratios of the zircons from SSD-1 are greater than 1 in general, ca. 995 Ma is interpreted as an emplacement age of the granitic gneiss, probably indicate early Neoproterozoic magmatism within the Mozambique Belt. The leucocratic gneiss (SSD-2) intruding the granitic gneiss displays rather scattered age distribution. Except one Archean age of ca. 2580 Ma, most of the near concordant ages are concentrated in late Neoproterozoic, yielding weighted mean $^{238}U/^{206}Pb$ age of 593±20 Ma (n=20). Because Th/U ratios of the zircons from SSD-2 are typically lower than 1, such an age of ca. 600 Ma seems to indicate partial melting event accompanied to Pan-African Orogeny.

Keywords: South Sudan, SHRIMP U-Pb ages, Pan-African orogeny

Post-tectonic granitoid magmatism in the Natal-Maud-Mozambique Provinces

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Grenville-age provinces around the Archean Kalahari Craton have contributed to hypotheses that they were part of the locus of the assembly of Rodinia (Dalziel 1991). We carried out ion microprobe (SHRIMP) U-Pb zircon dating on Late Mesoproterozoic post-tectonic A-type granitic intrusions from Natal Province in South Africa, Dronning Maud Land (DML) in Antarctica, and Nampula Province in Mozambique in order to constrain the termination of the Grenville age granulite event in these areas. Zircons from ten granitoid intrusions analyzed in this study yield overall 1100-1040 Ma age range, which confirm widespread Grenville-age A-type granitic magmatism in these regions. No older inherited zircon grains were seen, consistent with the interpretation that these granitoid intrusions were formed through juvenile magmatism (Grantham et al., 2001). In the Natal region, mean 207Pb/206Pb ages apparently decrease from north (1100-1090 Ma at Nthilimbitwa Pluton) to south (1060 Ma from Mvoti and Glendale Plutons to 1040 Ma from Kwalembe and Ntilbankulu Plutons). The sample from Sverdrupfjella, Antarctica has ~1093Ma old zircons, and also shows a ~530Ma metamorphic rim whereas none of the Natal samples show any younger overgrowths. Three samples from Nampula Province in Mozambique suggest 1091-1074 Ma magmatic crystallization ages. The limited metamorphic age data available from country rocks to the intrusions suggest that the intrusions have been generated and emplaced syn- or post-metamorphic. Our data, therefore, can constrain the termination of high-grade metamorphism to be no younger than 1040 Ma. The available chronological data of the post-tectonic mainly A-type granitoides show a crude spatial-age relationship with the younger ages <~1060Ma being restricted to the southern and western margins of the Kalahari Craton (southern Natal and Namaqualand) whereas the older ages >1060Ma are restricted to the eastern margin (Mozambique, Antarctica and northern Natal) of the Kalahari Craton.

New data on the structural evolution of western Dronning Maud Land, Antarctica: Focus on the Neoproterozoic –Cambrian and implications for the amalgamation of Gondwana.

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Data collected during four field seasons from 2012-2016 from Ahlmannryggen, Sverdrupfjella and Gjelsvikfjella are described focussing on younger structures potentially correllatable with the amalgamation of Gondwana between 500-600Ma.

In Ahlmannryggen, the Straumsnutane Formation basaltic andesites underlying the Straumsnutane area of western Dronning Maud Land show a complex structural history. Limited primary features include columnar jointing, pillow lavas, amygdaloidal layering,volcanic breccias, cooling cracks and ropy lava. Early planar and linear fabrics and thrust faulting suggest top to the NW tectonic transport directions under brittle-ductile greenschist facies conditions. Syntectonic sedimentary basins combined with published geochronology from synchronous intrusiuons suggest the NW directed deformation is Mesoproterozoic in age.

Right dihedral paleoanalysis of later shallow-dipping slickensided fault planes indicate top to the NW and SE tectonic transport directions. Quartz veining, typically forming multi-generational rotated en-echelon arrays have top-to-SE geometries.The later deformation also occured under greenschist facies conditions as indicated by extensive epidote deposition on the slickenside surfaces. SE vergent overturned folds have been reported in NE Straumsnutane. Reported K-Ar data from mica the slickensides suggest a circa 500Ma age.The data suggest two phases of deformation - an early Mesoproterozoic top-to NW phase involving folding with SE dipping axial planes, thrust faulting and a later Neoproterozoic-Cambrian age SE oriented deformation involving SE oriented quartz veining, SE faulting and folding.

In Sverdrupfjella, early tight D1 and D2 deformation was toward NW involving recumbent folding with strong planar fabrics and lineations. Later D3 deformation with top to the SE geometry is recorded in upright folds as well in deformed granitic veins and pegmatites, as well as younger syntectonic granites and pegmatites. The younger syntectonic granites have circa 500Ma ages.

In Gjelsvikfjella, early D1 and D2 deformation was toward the NW. Later D3 deformation comprises mesoscale scale folds, mesoscale shear zones and syntectonic granitic veins. The mesoscale shear zones show both extensional and compressional geometries, both with top to the SE geometries and typically have syntectonic pegmatitic intrusions. Ages reported from the granitic veins are circa 500Ma

The younger top to SE deformation may suggest that the cratonic cover rocks of the Ritscherflya Supergroup as well as the basement gneisses of W Sverdrupfjella were possibly submerged in the footwall of the meganappe structure interpreted as part of the process of the amalgamation of Gondwana, involving collision between N and S Gondwana in the Kuunga Orogeny (Grantham et al., 2008; Meert, 2002), between ~550-600Ma ago. In contrast, it is possible that rocks in E Sverdrupfjella formed part of the overriding nappe complex.

Keywords: Gondwana Amalgamation, Kuunga Orogeny, Neoproterozoic Cambrian

Geological evolution of the Archean Chitradurga schist belt, Dharwar Craton, southern India

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The Archaean strata of the Dharwar craton, southern India, comprises of Sargur supracrustals, the peninsular gneiss complex and the Dharwar Supergroup. The Dharwar Supergroup is further subdivided into the Bababudan and Chitradurga Groups. For the past six years we have been carrying out systematic geological field survey in the Chitradurga Schist belt, along with detailed geochemical studies and zircon U-Pb dating to not only reconstruct the lithostratigraphy and geological evolution of the Archean schist belt, but also to test the tectonic regimes that created the Dharwar craton. The evolution of basement TTG gneisses are also of significance. Our studies on TTG and granitic suits reveal that in the Paleoarchean, the western Dharwar craton was intruded by many slab-derived TTGs have intruded and the granitic activities were strongly controlled by magma differentiation and/or crustal reworking. In the supracrustal rocks above, the lower Bababudan unit (post-3.0 Ga) consists of basal conglomerate, stromatolitic carbonate, silici-clastics with diamictite, chert/BIF and pillowed basalt, in ascending order, all of which are older than 2.67 Ga magmatic zircon ages from dacitic dyke intruded into the topmost pillowed basalt (Hokada et al., 2013). The upper unit unconformably overlies the pillow lava, and consists of conglomerate/sandstone, komatiite lava, BIFs and silici-clastic sequence with mafic volcanics. Geochemical characteristics of volcanic rocks and BIFs helped us to delineate the tectonic setting of the oceanic basin in which they have deposited. The major and trace element compositions of the samples from three units can be grouped into 2 types. The first type is characterized by flat REE pattern and spider diagram. The second group of rocks have enriched compositions of LIL, LREE and slightly depleted HREE than the first type. In addition, Nd isotope ratio is also different, the first group have near zero to positive Nd values compared to negative values for the second group. The geochemical and isotopic variations observed between the two types of volcanic rocks were cause by the difference in source magma genesis due to a difference in tectonic settings. The first type is related to a possible upwelling mantle plume. On the other hand, the second type can be related to an arc setting possibly associated with subduction.
Geochemical characteristics of chitradurga BIFs indicate that deposition was controlled by hydrothermal flux, however the epsilon Nd(T) values fluctuate from negative to positive values. The majority of epsilon Nd(T) values show only small variation between -1 and +2. The depositional environment can be modeled by a mixing between seawater with positive epsilon Nd values and hydrothermal flux derived from enriched mantle with negative epsilon Nd values, and the variations we observe depends on the hydrothermal flux from enriched mantle. This result is consistent with the REY characteristics, large positive Eu anomaly and low Y/Ho value, and suggest a deep sea hydrothermally controlled depositional environment. However, the BIFs associated with dolomite,

have high Y/Ho ratio, positive Eu anomaly and broad range of Nd isotope ratio, which suggests that they were deposited in a shallow sea environment.
In addition, stromatolitic and massive carbonate rocks in the lower unit of Bababudan formation show large variation in carbon, oxygen, sulfur and strontium isotopic composition. Multiple sulfur isotope studies of pyrite in carbonate rocks from Bababudan Group show very large variation of sulfur isotopic composition, upto +19.4 per mil with negative cap delta 33S, whereas other sedimentary rocks show near 0 permil value. Based on the above results, we also discuss the changes observed in the atmospheric oxygen contents before the GOE.
Reference: Hokada, T. et al. 2013, Precambrian Research, 227, 99-119.

