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.

Contrasting pressure-temperature records from the Altai Range, Mongolia; constraints from multiple growth of garnet, aluminosilicates and monazite

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Pelitic gneisses from the western Mongolian Altai Range of the Central Asian Orogenic Belt exhibit multistage aluminosilicate formation and various chemical zoning patterns in garnet. The studied pelitic rocks are divided into four types; garnet-kyanite-biotite gneiss, garnet-cordierite-biotite gneiss, garnet-staurolite-sillimanite-biotite gneiss, and garnet-staurolite-kyanite-biotite gneiss. The former two gneisses contain kyanite in the matrix and sillimanite inclusions in garnet. The Ca concentrations in garnet from the garnet-kyanite-biotite gneiss increase and those from garnet-cordierite-biotite gneiss decrease from centre to inner rim in the core. In garnet-staurolite-sillimanite-biotite gneiss, and garnet-staurolite-kyanite-biotite gneiss, sillimanite or kyanite occurs in the matrix, respectively, and both have kyanite inclusions in garnet. The garnet has homogeneous high-Ca core part, and the mantles are characterized by low-Ca. Monazite U-Th-Pb dating for the studied samples shows the bimodal ages; c. 360 Ma and c. 260 Ma. Combining the microstructural information, thermodynamic calculations, and geochronology suggests all rock types experienced compression at c. 360 Ma, but this compression occurred at different crustal levels. The garnet-kyanite-biotite gneiss and garnet core in garnet-cordierite-biotite gneiss represent compression at low-pressure conditions (~5.2 to 7.2 kbar) under moderate-temperature conditions (~620-660 C). In contrast, the garnet cores in garnet-staurolite-sillimanite-biotite and garnet-staurolite-kyanite-biotite gneisses were formed during compression at higher pressure conditions (~7.0 to 8.9 kbar at ~600-640 C). It is still obscure why the different thermal gradients existed during the compression but it is likely due to presence of ridge subduction in the Altai Range reported by several workers. The subducting ridge could supply heat to the accretionary wedge and produced new geotherm. The difference in thermal gradients observed in this study might be due to variations in thermal regimes from the subducting ridge, which has an important role in developing the variations in prograde pressure-temperature paths during burial of the accretionary wedge. Garnet mantles and the matrix mineral assemblages in three rock types except garnet-kyanite-biotite gneiss were recrystallized during the c. 260 Ma event characterized by amphibolite-facies metamorphism with a metamorphic thermal gradient of ~25 C/km, which might be caused by collision-related granitic activity and re-equilibrium at middle crustal depths. This study also suggests monazite U-Th-Pb dating combined with the occurrence, texture, and chemistry of associated mineral phases in amphibolite-facies rocks will allow us to recognize multiple events and the equilibrium phases during each event.

Keywords: garnet, aluminosilicate, monazite, pressure-temperature path, Altai, Mongolia

Petrological and chronological constraints of UHT granulites from Highland Complex, Sri Lanka: implications on Gondwana correlation

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The high-grade ultrahigh-temperature regional metamorphism of Sri Lanka has a significant role in understanding the tectonics and formation of Gondwana super-continent. Sri Lanka in specific is important because of its position in Gondwana assembly, placed close to southern India, Madagascar and eastern Antarctica. The central Highland complex in Sri Lanka consists of UHT granulites intercalated with pelitic and mafic granulites along with calc-silicates, which preserves textural evidence for UHT metamorphism. The U-Pb zircon dating of sapphirine bearing granulites yielded two major age populations 565-620 Ma and 525-563 Ma without older zircon cores. Another granulite sample with Grt-Sil-Spl-Crd assemblage has similar metamorphic age ranging *ca*. 526, 563 and 602 Ma concordant clusters, with inherited zircon core ages from 1600 to 2040 Ma. The Fe-Al rich pelitic granulites also had undergone bimodal metamorphism (520-565 Ma and 590-622 Ma). Some of these samples have inherited zircon cores ranging from with 760 to 3060 Ma. The zircons in mafic granulite samples have age range of 533-566 Ma and 578-620 Ma. The scapolite bearing calc-silicate sample also has similar age populations at *ca*. 533 Ma and 560-570 Ma. The compilation of the new results and available ages from Sri Lanka and its adjacent continental fragments of the Gondwana, we propose the Northern Madurai Block, Southern Madurai Block, Wanni Complex and Highland Complex are alternate older and younger terranes formed in a major convergent regime, metamorphosed during Ediacaran–Cambrian regional UHT event. The petrological and geochronological similarities indicate that the Highland Complex, Sri Lanka, Madurai Block, southern India and Lützow-Holm Complex, Antarctica and central Madagascar should have been together during the closure of the Mozambique Ocean as part of the Gondwana amalgamation.

Keywords: U-Pb zircon LA-ICP-MS dating, Late Neoproterozoic, ultrahigh-temperature granulite, Highland Complex, Sri Lanka

Depositional ages for metacarbonate rocks from the Highland Complex, Sri Lanka

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Sri Lanka is an integral part of the Late Proterozoic to Early Cambrian collision zone of the so-called East African-Antarctic Orogen (EAAO) that includes Mozambique, Madagascar, southern India and the Dronning Maud Land in East Antarctica. The Mozambique Ocean is supposed to have existed between the different continents between East and West Gondwana, before its final amalgamation. The carbonate rocks in the EAAO are considered to have chemically deposited. Therefore, these rocks are ideal for obtaining the geochemical information of the Mozambique Ocean. The 540-600 Ma metasedimentary rocks in the Highland Complex (HC) is the only unit in Sri Lankan basement containing metacarbonate rocks. In this study, we attempt to apply the strontium (Sr) isotope chemostratigraphy to estimate the sedimentation age of the Highland Complex. In order to estimate the depositional age, it is necessary to consider the influence on carbonate rocks by metamorphism. For example, the oxygen isotope records fluid-rock interaction, while carbon isotopes alter with lithification or rare earth element + yttrium pattern changes by the contamination with the mixing of continental rocks. In addition, it is necessary to consider the effect of radioactive decay of rubidium to strontium. Thus in this study, taking advantage of the characteristics of metacarbonate rocks, samples that were least influenced by alteration were selected by chemical screening. For this purpose oxygen and carbon isotopic composition and trace and rare earth element pattern and Sr isotope ratio were used. $\delta^{18}O$ and $\delta^{13}C$ values of the samples range between 19 to 25 ‰and -2.0 to 1.5 ‰. The results indicate that they preserve the primary depositional marine chemical composition. REE + yttrium patterns had oceanic characteristics as well. However, the Sr initial ratios have regional differences, $^{86}Sr/^{84}S$ (850 Ma) values ranges from 0.70431 to 0.70711. These values when correlated with the late Proterozoic Sr isotope chemostratigraphic curve of Halverson et al. (2010) suggest the depositional age in between 900 to 660 Ma.

The depositional ages are consistent with the inference from the youngest detrital ages of 834±12Ma and 722±14Ma for zircons in the metapelitic rocks, though there is considerable regional differences. Our estimate of the depositional age are also comparable with the depositional age of metacarbonate rocks from the Sør Rondane Mountains (SRM), East Antarctica (880-850Ma and 820-790Ma; Otsuji et al., 2013), and those of Mozambique belt (890-860Ma; Melezhik et al., 2008). The results indicate that the carbonate sedimentation in the Mozambique Ocean persisted extensively from southeastern Africa to east Antarctica, through southern India and Sri Lanka during the late-Tonian to early-Cryogenian periods. The result also places important constraints on the temporal and spatial extent of the Mozambique Ocean, which may lead to the understanding of the processes and timing of Gondwana formation. Further detailed analytical studies are being carried out, to understand the reliability and regional extent of depositional ages for the metacarbonate rocks in the Highland Complex, Sri Lanka.

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Keywords: metacarbonate rocks, Sri Lanka, Chemostratigraphy

Neoproterozoic (ca. 860 Ma) A-1 type volcanic activity of the Gyemyeongsan metavolcanics in the Okcheon Metamorphic Belt, Korea: a prelude to the Rodinia breakup?

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The Gyemyeongsan Formation is composed of mainly metavolcanic rocks and is distributed over the northeastern part of the Okcheon Metamorphic Belt. In general, constituent rocks show very high abundances of rare earth elements (REE) and high field strength elements (HFSE). In part, contents of magnetite and/or rare earth minerals approach to ore grade. Lack of noticeable Nb negative anomaly on spider diagram indicates negligible contribution of crustal material in their generation and also excludes the arc environment for their tectonic environment. If we apply the tectonic discrimination diagram utilizing immobile HFSE Nb and Y, the metatrachytes of the Gyemyeongsan Formation are categorized as within-plate products. They also show the typical features of A-type magma, such as noticeably high contents of REE, HFSE and Ga. Their geochemical characteristic can be classified further as A-1 type that is one of the distinctive features of the continental rifting. Hafnium isotopic composition of zircons yields positive initial epsilon values about 5, indicating their derivation from slightly enriched mantle. SHRIMP U-Pb zircon age determination of the metavolcanics yields eruption ages of ca. 860 Ma in the Neoproterozoic. The age of metavolcanics of the Gyemyeongsan Formation is somewhat earlier than generally accepted initiation of breakup of the supercontinent Rodinia, i.e. ca. 830 Ma based on evidences from the South China Block. However, considering the facts that the metavolcanics of the Gyemyeongsan Formation have A-1 type geochemical characteristics and hafnium isotopic signature of mantle, it would be natural to seek possible link with a continental rifting event. Probably it was a prelude to the breakup of supercontinent Rodinia.

Keywords: A-type, U-Pb zircon age, breakup, Rodinia

Late Permian plume-related magmatism and tectonothermal events in the Kontum Massif, central Vietnam

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The Kontum Massif is situated in the southern part of Trance Vietnam Orogenic Belt (TVOB), central Vietnam. The massif consists of various kinds of metamorphic rocks including ultrahigh-pressure/ultrahigh-temperature metamorphic rocks and intrusive rocks. While the geochronological data indicates two tectonothermal events (480 –420 Ma, 270 –240 Ma), the intense metamorphic and magmatic activities occurred during Late Permian –Early Triassic as a result of the continental collision between South China and Indochina cratons. In this study, geochrological analyses for three samples (2 metagabbros and 1 charnockite) were conducted with zircon U-Pb LA-ICP-MS dating. The zircon dating gave a magmatic age range of 260 –250 Ma for the three samples and an inherited age of ~1400 Ma for the charnockite. The magmatic ages were found to be identical with those of peak metamorphic periods in the Kontum Massif. These results combined with Nd isotopic data for the granitic rocks and pelitic gneisses from the Kontum Massif suggest that the massif may have been derived from a reworked continental crust. Geochemical features of the metagabbros reveal that the parental basaltic magma corresponds to the Song Da igneous suite situated in the northern part of TVOB, and has been assimilated by crustal materials. The Song Da igneous suite is a member of Emeishan large igneous province, and has been derived from the Late Permian mantle plume. It is concluded that the plume-related magma has intruded into the deeper part of Kontum Massif, and led the ultrahigh-temperature metamorphism by acting as a heat source.

Keywords: metagabbro, mantle plume, zircon U-Pb dating, Late Permian, Kontum Massif

Igneous activity of Paleoarchean TTGs around Chitradurga, western Dharwar craton, India

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The western Dharwar craton (WDC) comprises mainly of TTG-type peninsular gneiss, greenstone belts, and high-potassium granites (e.g. Chadwick et al., 2000; Jayananda et al., 2013). The TTGs are widely distributed in the WDC as 3.4–3.2 Ga basement rock and occasionally contain more older sediments and volcanics (i.e. the Sargur Group) (e.g., Peucat et al., 1993). The greenstone belts, named the Bababudan Group and the Chitradurga Group, unconformably overlies the TTGs as 2.9–2.6 Ga sedimentary covers (Hokada et al., 2013). These groups consist mainly of conglomerate/quartzite, BIFs, and mafic to felsic volcanics (e.g. Chadwick et al., 1981). The high-potassium granites crop out as several isolated intrusions in both the TTGs and the greenstone belts. The intrusive ages of the granites are mostly around 2.61 Ga (e.g. Jayananda et al., 2006). The aim of this study is to discuss the igneous activity in the Paleoarchean TTGs based on the petrographic and geochemical characteristics of the peninsular gneiss around Chitradurga in the WDC, southern India.
Although the TTGs are generally composed of granitic to tonalitic gneisses, we can group them into two types in correspondence with their petrographic features; K-feldspar (Kfs)-poor meta-trondhjemite and Kfs-rich meta-granite. The Kfs-poor meta-trondhjemite has suitable petrographic feature of slab-derived TTGs. On the other hand, the Kfs-rich meta-granite contains abundant K-feldspar, a mineral phase that is not common in the TTGs.
The Kfs-poor meta-trondhjemite (SiO2: 65-75 wt%) have typical TTGs in composition, with high Al2O3 (14.7-19.1 wt%) and Na2O contents (3.6-5.2 wt%), and correlated low K2O/Na2O (0.27-0.74) as well as moderately high Sr (195-527 ppm) and Sr/Y (21-109), although the REE patterns have fairly variable from flat to fractionated ((La/Yb)n=1.2-26), with no Eu anomaly. However, the Kfs-rich meta-granite (SiO2: 69-78 wt%) shows different geochemical characteristics than that of TTGs. In particular, their Al2O3 (13.4-15.7 wt%) and Sr (68-310 ppm) contents are not enriched, and their K2O/Na2O (0.5-1.9) ratios are higher. The REE patterns are largely sub-divided into two types, one is fractionated ((La/Yb)n=10-64) with no Eu anomaly, the other is moderately fractionated ((La/Yb)n=1.8-21) associated with significant negative Eu anomaly. Probably, the Kfs-rich meta-granite had been formed by several different types of magmatic activities. In Paleoarchean, the western Dharwar craton was intruded by many slab-derived TTGs. In addition, it is probable that the various granitic activities were derived from strong magma differentiation and/or crustal reworking operated simultaneously to form a stable continental crust.
References: Chadwick et al., 1981, Precambrian Research 16, 31-54, Chadwick et al., 2000, Precambrian Research 99, 91-101, Jayananda et al., 2006, Precambrian Research 150, 1-26, Jayananda et al., 2013, Precambrian Research 227, 55-76, Hokada et al., 2013, Precambrian Research 227, 99-119

Keywords: TTG, Dharwar Craton, India

Timing of melt metasomatic event at arc deep crust beneath Ichinomegata crater (Northeast Japan) constrained by LA-ICP-MS U-Pb geochronology of zircon from the mafic xenoliths

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In the Ichinomegata crater, Oga peninsula in the Northeast Japan, abundant amphibole-bearing ultramafic to mafic xenoliths occurred with andesitic magma erupted 0.06-0.08 Ma. The previous studies on their texture and isotope composition suggest that they were metasomatized by aqueous fluid or silicate melt at deep crustal levels. In order to constrain timing of the metasomatic event, we obtained ^{206}U-^{238}Pb ages of zircon from three biotite-bearing hornblende gabbro xenoliths consisting of amphibole (Mg/Mg+Fe$_{total}$= 0.60-0.65), plagioclase (An$_{53-86}$), biotite (Mg/Mg+Fe$_{total}$= 0.62-0.68), magnetite, apatite and zircon. Zircon grains collected from these biotite-bearing gabbros displayed sub-rounded morphology and complex zoning in cathodoluminescence and BSE images. The textual variation of zircon grains was divided into three types: (1)heterogeneous zircon, which is characterized by heterogeneous Th concentration domains with thorite and rhyolitic melt inclusion, (2)magmatic zircon characterized by oscillatory zoning, and (3)mixed zircon characterized by the “heterogeneous zircon” mantled by the “magmatic zircon”. All the zircon grains exhibited sub-rounded to rounded form. The microstructure of the heterogeneous and mixed zircons suggests that those zircon grains were subjected to recrystallization coupled with dissolution and reprecipitation (CDR) mediated by felsic melt. The rounded shape of most zircon grains suggests that they experienced dissolution in the last stage although magmatic growth followed the CDR for the mixed zircon. The spot ^{206}U-^{238}Pb dating of heterogeneous and magmatic zircon, conducted with a LA-ICP-MS at National Museum of Nature and Science, revealed that concentrations of radioactive Pb derived from U decays in zircon were very low, close to or lower than the detection limit. This means that the recrystallization ages were significantly young (< 1.0 Ma). This is consistent with the observation that the metasomatic agent (silicate melt) has similar isotopic signature to the andesitic host magma (Yamamoto et al. 2013). The recrystallization of these zircons is likely to have occurred in the pre-eruptive activity on the felsic magmatism at a deep crust beneath the Ichinomegata crater.

Reference

Yamamoto et al. (2013) Lithos, 162-163, 88-106

Keywords: Ichinomegata crater, Lower crust, Mafic xenolith, Zircon age, Metasomatism

Graphitization of cabonaceous materials from the Archaean Chitradurga schist belt, Dharwar Craton, Southern India

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Sedimentary rocks often include small amounts of organic material as an accessory phase, called as "Carbonaceous Material" (CM), during sedimentation. In this study, we report that the structural change and the isotopic composition of CMs within the carbonate rocks from the Chitradurga schist belt, Dharwar craton, southern India. Because CM (RSCM) geothermometer have been mainly developed by using pelitic rocks, this study verifies whether graphitization of CM in carbonate rocks is suitable as a geothermometer. The carbonate rocks from this region can be divided into two types by its occurrence and mineral assemblage Type-I is partly exposed at the southern part of the study area, and it is characterized by the lens-shaped limestones in dolostones. XRD patterns, Raman spectroscopy along with SEM observations indicate that the CM contained in Type-I carbonate rocks has been metamorphosed to about 450 ~ 500ºC, and the graphite show a hexagonal platy structure. In addition, $\delta^{13}C$ value of CM ranged between -11 and -7.8 permil. On the other hand, Type-Ⅱ is exposed at the northeastern part of the schist belt and is characterized by laminated dolomite which is cut across by numerous quartz and carbonate veins. The CM in Type-2 carbonate rocks has been affected by the metamorphism at about 350 ~ 400ºC, and the graphite was found to be characterized by sheet-like and two-dimensional crystal structure (2H) based on the analysis with XRD and Raman spectroscopy and the observation with SEM. In addition, the $\delta^{13}C$ value ranged between -16.1 and -10.9 permil, which is suggesting a temperature dependent equilibrium carbon isotopic fractionation between graphite and carbonate. On the other hand, CM of pelitic rocks and CM in stromatolites from this region retain original $\delta^{13}C$ value (-29 ~ -22.9 permil) of organic matter origin. However, some samples of Type-II carbonates showed anomalous $\delta^{13}C$ values (-16.1 permil)., and the morphology of graphite differs from the Type-I. They have globule forms and secondary overgrowth was observed on the sheet-like graphite. We consider these graphite to have recrystallized under the presence of a carbon-bearing fluid. The fluid crystallized graphite was found to have globular form, heterogeneous crystallinity and negative $\delta^{13}C$ values. Furthermore, it was found that metamorphic temperature estimated using CM in carbonate rocks have larger error even at high metamorphic grades as compared with those of the pelitic rocks. We discuss the reasons for this differnce and whether the graphitization process has been affected by the difference in fluid composition, abundance of CO_2 and recrystallization and growth rate of the host mineral. The results of this study might put forward questions on the suitability of RSCM geothermometer in low to medium grade metacarbonate rocks and suggests the necessity of selecting samples which are suitable for analysis through the comprehensive evaluation.

Keywords: Graphite, Raman spectra, carbon isotopes, X-ray diffraction

Geochemical study of Archean greenstones of Ingaldhal Formation in the Chitradurga schist belt, Southern India

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Archean greenstone and TTG gneiss are widely distributed over the western Dharwar craton in southern India. Especially, the komatiite occurrences in the Paleoarchean greenstone belts have been geochemically studied well and the influence of Archean volcanic activity and mantle geodynamics are often discussed from their magma genesis.
In this study, we focused on the greenstones in the Chitradurga schist belt, western Dharwar craton, in southern India. There are many occurrences of volcanic rocks in this belt, all of which were altered by low- to medium-grade metamorphism. After carrying out a detailed thin section petrography, we performed various geochemical analyses on whole rock samples. Based on the results of petrography and geochemical analyses, the greenstones were divided into 4 units. The oldest unit A is affected by amphibolite facies metamorphism, whereas the units B and C are greenschist facies metabasalts and they usually have dendritic texture made of amphibole or pyroxene similar to the texture shown by komatiites. Rarely, pillow lava structures were observed and it indicate that the volcanic activity has occurred under subaqueous (marine?) conditions. The unit D is the youngest unit and most altered one among the 4 units studied. These rocks have high calcite content and the LOI was very high (>12wt.%). Because of this reason, we decided to select the samples that contain LOI less than 5 wt.% in order to restrict the effect of alteration in the geochemical data.
The major and trace element compositions of the samples from three units can be grouped into 2 types. The first type of rocks occurring in the unit A and unit C are characterized by flat REE pattern and spider diagram. The second group of rocks, occurring in the unit B, have enriched compositions of LIL, LREE and slightly depleted HREE than the first type. In addition, Nd isotope ratio was different for these 2 types, the first group have near zero to positive Nd values compared to negative values for the second group.
Three possibilities were considered based on the geochemical differences observed: the difference in the degree of partial melting, the effect of crustal contamination and the changes in tectonics setting. The Nd isotopic data and various discrimination diagrams indicate that the source mantle was different. So it is difficult that this difference occurred by the partial melting. Secondly regarding the crustal contamination, we calculated AFC model, but in this model the trace elements didn’t follow the AFC curves. In addition, it was recognized that if the difference had been generated by contamination it is necessary to link it with a felsic contaminant such as continental crust. However, the volcanic activity at this time has occurred in a marine environment where a corresponding contaminant is lacking. Considering these points, it was concluded that the compositional 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 units A and C have likely oceanic ridge type characteristics as evidenced by the REE patterns and Nd isotopic ratio related to a possible upwelling mantle plume. On the other hand, the unit B volcanism can be related to an arc setting possibly caused by subduction. However, some features of geochemical discrimination diagrams suggested that units A, B and C have formed under different settings, which needs further evaluation. The difference in tectonics setting is also complemented by negative

epsilon Nd values suggestive of possible sediment input by subduction. In summary, the geochemical characteristics shown by the Ingaldhal volcanic rocks represent a drastic change in the tectonic setting related to plate tectonics as early as MesoArchaean.

Keywords: Archean, greenstone, Nd isotope, Dharwar craton

Depositional environment of Archaean BIFs in the Chitradurga Schist Belt, Dharwar Craton, Southern India

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Banded Iron Formations (BIFs) are chemically precipitated from the ocean and formed mostly in the Archaean and early Paleoproterozoic, and therefore record the information of the ancient oceanic environment. In this study we present the geochemical characteristics, in particular the REY (rare earth elements plus yttrium) and Nd isotopic composition of BIFs in the Chitradurga Schist Belt, western Dharwar craton, Southern India. The Chitradurga Schist Belt is a typical Archean greenstone belt that preserves strata roughly between 3.3 Ga and 2.5 Ga and three BIF distinct layers of different sedimentary age occur in this region. Correlating each BIFs located on different region is very difficult because Chitradurga Schist Belt is deformed highly with very complex geological structures. Therefore, we compared their geochemistry to reveal the formation history and discuss their sedimentary environment.
Chitradurga BIFs are mostly comprised of quartz and iron oxide such as hematite and magnetite, similar to many other Archean BIFs. Bulk rock geochemistry results revealed that the BIFs contain only very less amount of continental components, such as Al_2O_3 (<1wt.%) and TiO_2 (<0.05wt.%). Chitradurga BIFs are classified into four groups by REY pattern normalized with PAAS (Post-Archean Average Shale). Type-1 has positive Eu anomaly and Y anomaly. Type-2 has no positive Eu anomaly, large Y anomaly and some of them have negative Ce anomaly. Type-3 has extremely high positive Eu anomaly, whereas Y anomaly is absent. Type-4 has positive Eu anomaly and no Y anomaly. Most of the Chitradurga BIFs have positive Eu anomaly, which is related to hydrothermal flux, however the epsilon Nd(*T*) values of all types fluctuate from negative to positive values. The majority of epsilon Nd(*T*) values for Type-3 BIFs show only small variation between -1 and +2. Moreover, on a meso-band scale the REY patterns are similar, but epsilon Nd(*T*) values of neighboring layers have negative and positive values, suggesting a short lived fluctuations Nd source. However, the epsilon Nd(*T*) values of Type-1, 2 and 4 BIFs show a broad range between -8 and +18, deviating from the normal mantle-continent range, possibly due to secondary alteration effects.
To understand the environment of deposition, we focused on Type-3 BIFs, interbedded with pillow metabasalts and meta-pyroclastic rocks. Deposition of Type-3 BIFs is perhaps influenced of two different volcanic activities: one is enriched and the other is depleted in Nd contents. The Nd isotopic ratio of Archaean seawater was dominated by positive Nd input through active hydrothermal flux related to volcanic activity from a depleted mantle source (Alexander et al., 2009). This suggests that the depositional environment of Type-3 BIFs can be modelled 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 for the Type-3 BIFs. Type-1 BIFs are 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. The depositional site of Type-2 and 4 BIFs could not be constrained well due to lack of unaltered samples, but it is assumed that Type-2 and 4 BIFs were affected by less

hydrothermal input, when compared with Type-3 BIFs. In summary, our results indicate that negative epsilon Nd(*T*) values does not necessarily need a source from continental crust, but can result from the mixing of Nd from an enriched mantle with Nd reservoir in the seawater.

Keywords: Banded Iron Formation, Dahrwar craton, Nd isotope

