

## Delineation and characterisation of major tectonic provinces of Dronning Maud Land (East Antarctica) and significance for Rodinia assembly

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We present a large new geochronological data set from a critical transition zone in central Dronning Maud Land, East Antarctica, where Grenville-age rocks of the Maud Belt are juxtaposed along the juvenile Tonian Oceanic Arc Super Terrane (TOAST). Previously, central Dronning Maud Land had been interpreted as part of the Kuunga Orogen (580-500 Ma) by some researchers, because of the lack of metamorphic ages of ca. 630-600 Ma, though based on a relatively small study. However, our new study clearly highlights the significance of metamorphic ages also in the range from 670 –600 Ma in this region and shows that a subdivision into Kuunga vs. East African Orogen is not valid. Our new data rather support a long-lasting, protracted Late Neoproterozoic/Early Palaeozoic tectono-metamorphic history along the margin of Kalahari. We can trace characteristic Kalahari-type rocks until the Wohlthat massive (12°E), to the E of which typical TOAST-related rock crop out. The boundary zone coincides largely with the Forster Magnetic Anomaly, a major aeromagnetic lineament in the region. The second part of this study includes the age analyses of glacial drift from the southern side of the Dronning Maud Land Mts.. The moraines stranded as a result of the northward flowing ice-sheet and they therefore should characterise the cryptic subice geology inboard of the Dronning Maud Land Mts. Nine moraine bulk samples from 15-25°E resulted in ca. 1100 new U-Pb zircon spot ages that range between ca. 2000 and 500 Ma. The very few oldest Palaeoproterozoic ages come from the easternmost localities and may indicate a provenance of the Ruker Craton. All samples are dominated by a major TOAST age peak of ca. 990 –900 Ma, clearly indicating that the TOAST reaches far inland, as has also been suggested by geophysical data. In addition, however, a significant Stenian age peak of ca. 1080 Ma also occurs. Although Late Mesoproterozoic ages are common in both the Maud Province of western-central DML as well as in the Rayner Complex to the E, the Stenian moraine sample differ with respect to composition and/or isotope geochemistry. They are juvenile, with depleted mantle extraction ages around 1.3 Ga, are subduction-related, and therefore resemble an early phase of oceanic arcs that was so far unknown in this region. Thus, TOAST related rocks are produced over a protracted period of time from ca. 1080 to at least 900 Ma. There is no sign of major metamorphic overprint immediately after crust formation. Therefore, these island arcs may have formed independent or peripheral to Rodinia and may reveal major accretionary tectonics outboard of Rodinia. Much later, the TOAST underwent major tectono-metamorphic overprint at 670 –500 Ma, as a result of the extroversion of Rodinia and its subsequent incorporation into Gondwana.

Keywords: Tonian Oceanic Arc Super Terrane (TOAST), Supercontinent assembly, Dronning Maud Land, East Antarctica

## Oxygen isotope evidence for growth of zircon in metacarbonate rocks from Sør Rondane Mountains, East Antarctica

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Zircons in metasedimentary rocks are extensively studied to understand the provenance and tectonic evolution of orogenic belts, since it is believed that zircon can preserve the isotopic composition of different stages of orogenesis. In this study we report SHRIMP ages and geochemical characteristics of zircons in impure metacarbonate rocks from the Sør Rondane Mountains (SRMs), East Antarctica. The SRMs, located in the Neoproterozoic to Early Cambrian East African-Antarctic collisional orogen, are composed of medium- to high-grade metasedimentary, metaigneous and intrusive rocks of diverse composition. Multidisciplinary geological studies have revealed that this region can be separated into two distinct terranes, a metasedimentary and metaigneous dominated Northeastern (NE) and a meta-tonalitic and meta-sedimentary dominated Southwestern terrane (SW), that collided at around 650-660 Ma along the Main Tectonic Boundary [1] [2]. Strontium isotope chemostratigraphy of pure metacarbonate rocks suggested late-Tonian (880-850 Ma) apparent depositional ages in the SW terrane, whereas those in the NE terrane recorded early Cryogenian ages (820-790 Ma) [3]. Furthermore, a detailed study of Nd isotopes in the metacarbonates has helped to identify the existence of an extinct East Antarctic Ocean and its peripheral oceanic island arc system that preceded the formation of the East Antarctic continent in the Neoproterozoic before the final assembly of Gondwana.

In contrast to the typical sedimentary O and C isotopic composition, low concentrations for mobile trace elements and flat REE patterns for pure metacarbonates, the impure metacarbonates have heterogeneous O and C isotopic compositions, high concentrations of mobile elements and LREE enriched patterns. These together with the presence of hydrous minerals in impure metacarbonates suggest that they have been affected extensively by fluid infiltration events. Petrographic observations revealed that zircon is abundant. Superficially the grains appear detrital, but CL imaging revealed textures consistent with metamorphic growth. SHRIMP analyses of zircons in three impure metacarbonate rocks gave well defined tight concordia U-Pb zircon ages of 545 +/- 1 Ma (n=55), 546 +/- 2 Ma (n=33) and 549 +/- 2 Ma (n=58), younger than the peak metamorphism of the SRMs.

Oxygen analyses of dolomite/calcite and zircon in these rocks yielded interesting results—high  $d^{18}\text{O}_{(\text{SMOW})}$  for zircon of about 23.4‰, and 24‰ in the surrounding dolomite. Similar to the previous reports on high oxygen isotope ratios for zircons in metacarbonate rocks from Sri Lanka and Myanmar [5], the zircons in the Sør Rondane impure metacarbonate rocks have not only re-equilibrated with the U-Pb system at c.550 Ma, but also for the oxygen isotopes with the surrounding carbonate minerals. Based on the evidence from oxygen isotopes, we suggest the possibility of oxygen isotope equilibration between zircon and carbonate and total dissolution-reprecipitation of zircons in metacarbonate rocks during the last stage of fluid infiltration coeval with the granitic activity. We also discuss the possible role of alkaline Ca-bearing fluids that might have been instrumental for the recrystallization process of zircon in metacarbonate rocks.

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Keywords: zircon, oxygen isotope, Antarctica

## New Ar<sup>40</sup>/Ar<sup>39</sup> data from western, Dronning Maud Land, Antarctica: possible implications for Gondwana amalgamation.

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Biotite and amphibole Ar<sup>40</sup>/Ar<sup>39</sup> data on mineral separates from gneisses from the Sverdrupfjella and Kirwanveggan areas of Maud Province of western Dronning Maud Land (DML), Antarctica are reported. The samples were collected from “basement gneisses” the crystallisation ages of which are typically ~1000 and ~1200Ma old. The data provide insights into the post-orogenic evolution of western DML recognising that the area was involved in the amalgamations of Rodinia and Gondwana at ~1000-1150 Ma and ~500-600Ma respectively .

The data from the two areas show distinct differences. Data from six samples from Sverdrupfjella show that the dates from Bt-Hbl are similar. The dates range between ~460Ma and ~550Ma except for one severely disturbed Bt sample suggesting a date of ~326Ma. In four of the six samples the dates from Hbl are older than those from Bt with differences between Hbl-Bt pairs of between ~20-40Ma whereas in a sixth sample Bt yields a ~30Ma older date than Hbl.

In contrast data from six samples from Kirwanveggan show greater variability. The dates from four of five Bt samples range between ~498Ma-~520Ma with one sample yielding a date of ~868Ma. The dates from seven Hbl samples range from ~480Ma to ~1260Ma. This latter range in age correlates very crudely spatially with the youngest dates being from northern Kirwanveggan, to the oldest from the most southerly basement exposures in Kirwanveggan at Skappelnabben.

Immediately south of Skappelnabben, virtually undeformed quartz arenites and grits of the Urfjell Formation with ages of ~530Ma (from whole-rock Rb-Sr data), ~566Ma (SHRIMP U/Pb minimum detrital zircon age) and ~579Ma (Ar-Ar detrital muscovite age) are reported. The ages of detrital zircons suggest a provenance area similar to northern Mozambique and/or central to eastern Dronning Maud Land.

The data from Sverdrupfjella suggest a relatively short lived thermal pulse between ~460Ma and ~550Ma with the narrow range between older Hbl and younger Bt pairs being consistent with rapid cooling. In Sverdrupfjella and more broadly, DML, this age range is coincident with widespread granitoid intrusion, inferred to provide an advective heat source during this period. In contrast, in Kirwanveggan, where younger granites are absent, the range in ages for Hbl are consistent with a crustal gradient between N. Kirwanveggan (~5-6kb) and near surface at south central Kirwanveggan at Skappelnabben. The data are consistent with deposition at surface of the Urfjell quartz arenites approximately ~550Ma ago.

The crustal gradient is consistent with post- orogenic erosional uplift of Sverdrupfjella and northern Kirwanveggan with Sverdrupfjella having experienced thermal input from granitoid intrusions and is consistent with the post -orogenic evolution of a mega-nappe collisional model for Gondwana amalgamation proposed by Grantham et al. (2008) in which granitoid genesis is related to anatexis in the footwall of the mega-nappe complex. The crustal gradient described above is consistent with thinning of the nappe complex southwards and termination north of the Urfjell area of Kirwanveggan.

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Keywords: Ar40/Ar39 ages, Western Dronning Maud Land, Gondwana

## Timing of UHT metamorphism in eastern Gondwana.

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The east Gondwana reconstruction is extensively done based on the geochronological and structural studies. In this study we attempt to bring out a precise correlation using the timing of UHT metamorphism and representative mineral assemblages from Antarctica, Sri Lanka, and southern India. East Gondwana continental fragments including Trivandrum Block and Madurai Block southern India, Highland Complex Sri Lanka, southern Madagascar and East Antarctica consist of several occurrences of metapelitic rocks, orthogneiss and charnockite. This study focuses on sapphirine-quartz bearing ultrahigh-temperature metapelites from Rajapalayam, Madurai Block, southern India, Gampola, Highland Complex, Sri Lanka and Rundvågshetta, Lützow-Holm Complex, East Antarctica.

Samples of Cordierite-rich metapelites with sapphirine-quartz assemblage within garnets porphyroblasts were selected for U-Pb geochronology, Ti-in-zircon thermometry and REE analysis by Sensitive High Resolution Ion Microprobe (SHRIMP) from each location. Zircons were analysed both as separated grains and in-situ in thin-sections. Monazite grains separated from the same sample were analysed for U-Pb geochronology. The zircons were classified according to their morphology and REE patterns in the respective zones.

The cathodoluminescence images of zircons from Rajapalayam, Madurai block, showed distinct core with grey mantle and dark rims. On the basis of the chondrite-normalised Yb-Tb ratio, the REE patterns were categorized as 'high' (4.7-6.6) and 'flat' (0.8-1.5). The cores gave a 'high' REE pattern while the grey and dark zones outside the cores gave 'flat' pattern. The Ti in zircon thermometry yielded a range of temperatures between 756°C and 794°C. The cores gave discordant ages as expected from detrital zircons and the oldest age observed was 2.8 Ga. The grey mantle region gave a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $528.6 \pm 4.5$  Ma and the dark rims gave  $522.5 \pm 3.7$  Ma (95% c.l.). Monazite also gave  $^{206}\text{Pb}/^{238}\text{U}$  age  $554.6 \pm 7.2$  while the  $^{208}\text{Pb}/^{232}\text{Th}$  age was  $544.7 \pm 7.2$  (95% c.l.). Metamorphic monazite crystallized before metamorphic zircon.

The zircons from Highland Complex, Sri Lanka has detrital cores with pale or grey outer zone. On the basis of the chondrite-normalised Yb-Tb ratio the cores gave 'high' (7.5-23) REE pattern and the outer zone gave 'flat' (0.2-1.4) REE pattern. The Ti in zircon thermometry produced a temperature range from 682°C to 914°C from the separated and in-situ zircon grains. The core ages plots at ca. 900 Ma. The outer regions gave two groups of higher (n=38) and lower (n=42) weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age at  $560.4 \pm 4.4$  Ma and  $554.0 \pm 4.2$  Ma respectively.

The Rundvågshetta zircons in CL showed cores, black inner zone and differentiated inner and outer zones. The cores and the black inner zones gave 'high' (8.1-14.8) REE patterns on the basis of chondrite-normalised Yb-Tb ratio and the inner and outer regions gave 'low' (0.2-0.6) REE pattern. The Ti in zircon thermometry yielded 735°C to 858°C. The cores gave dispersed  $^{206}\text{Pb}/^{238}\text{U}$  age between 2.5-2.4 Ga. The black inner zone gave a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $596 \pm 11$  Ma (n=6). The inner zone formed two groups to produce an older age of  $556.3 \pm 7$  Ma (n=5) and a younger age of  $532.0 \pm 4.5$  Ma (n=14). The outer zone also formed an older group at  $549.0 \pm 5.8$  Ma (n=12) and a younger group at  $533.3 \pm 5$  Ma (n=15). Monazite also gave  $^{206}\text{Pb}/^{238}\text{U}$  age  $586.1 \pm 5.5$  Ma while the  $^{208}\text{Pb}/^{232}\text{Th}$  age was  $580.1 \pm 6.7$  Ma (95% c.l.). Monazite also gave  $^{206}\text{Pb}/^{238}\text{U}$  age  $554.6 \pm 7.2$  while the  $^{208}\text{Pb}/^{232}\text{Th}$  age was

544.7 ±7.2 (95% c.l.). Metamorphic monazite crystallized after metamorphic zircon. The above results enable us to understand the linkage between high temperature lower crust of eastern Gondwana. We compare and contrast the UHT conditions in each terrain and present a model of Gondwana correlation

Keywords: UHT metamorphism, Gondwana, Spr-Qtz

# Regional age zonation and multiple tectonic pulses of Neoproterozoic-Cambrian age from the western boundary of Eastern Ghats Belt, India: A comprehensive tectonic model for final amalgamation

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Eastern Ghats Belt (EGB), India is a Proterozoic orogenic belt characterised by the UHT-HT metamorphism. The status of EGB evolving in between the proto-India and its Precambrian neighbours (e.g., East Antarctica) is important and intriguing in terms of the Proterozoic “supercontinent” cyclicality. Although, the precise timing of cratonisation of northern EGB with Proto-India is still unclear. The timing of final thrusting of EGB on adjacent Proto-India (Bastar Craton=BC) is intuitively correlated at ~500-550 Ma (Upadhyay et al., 2008 among others). This cratonisation history is obscured as the tectonic model of cratonisation, tightly constrained by high-precision geological time, is absent from the marginal rocks. To delineate the exact age and tectonic model of cratonisation of EGB with respect to Proto-India, a detailed study of microtextural evolution coupled with high precision dating techniques (U-Pb SHRIMP zircon and U-Th-total Pb EPMA monazite dating) were carried out on the rocks along an east-west transect at the western boundary between EGB and BC.

At the eastern side of the western boundary, zircon and monazite grains of charnockite yield ~950 Ma age, which roughly coincides with the granulite metamorphism of Eastern Ghats Province of EGB. The youngest date recorded from the zircon and monazite grains of the charnockite is ~775-850 Ma. On the western side, the monazite grains closely associated with garnet grains in the sillimanite-bearing pelitic granulite exhibiting ~800 Ma ages from the Y-rich portion. The Y-enrichment in monazite grains and development of symplectite texture around garnet grains in mafic granulite is possibly in the response of garnet breakdown during an early phase of exhumation at ~800 Ma (Chatterjee et al., 2017). The appearance of late-hornblende in mafic granulite and the presence of fibrolite inclusion within ~500-550 Ma zircon grains in pelitic granulite suggest retrogression from granulite facies to granulite-amphibolite transitional facies occurred during ~500-550 Ma. However, this age of retrogression was exclusively confined near the western boundary due to the presence of adjacent shallow and cold craton. Thus, a spatially high-resolution geochronological data from the systematically sampled rocks exhibits a domainal age zonation across the western boundary of EGB for the first time. Eventually, textural evolution combined with geochronological data facilitate to construct a *P-T-t* path of the granulites.

Zircon dating of migmatitic hornblende gneiss of BC suggests that the rock formed at ~2400 Ma, which later suffered a younger thermal event at ~550 Ma due to thrusting of deep crustal EGB rocks on shallow crustal BC rocks during cratonisation ( “hot” on “cold” thrusting, Gupta, 2012). On the other hand, detrital zircon and monazite of foliated quartz breccia (parallel to the local shear fabric) near the thrust contact exhibit a wide age span with multiple age peaks in between ~3100 and ~500 Ma. Since the quartz breccia preserves the thrust-related foliation, it is inferred that the quartz breccia deposited contemporaneously with the thrusting in an incipient basin adjacent to thrust front. The youngest detrital monazite grain record ~495 Ma age, which imply that thrusting was continued overstepping the Precambrian-Cambrian boundary. Finally, collating all the textural and geochronological results from the marginal rocks of EGB and BC, a comprehensive tectonic model of deep to shallow crust related to the cratonisation of EGB with Proto-India is offered.



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Keywords: SHRIMP dating, Tectonic model, Cratonisation history of EGB

## Garnet granulites from the Palghat-Cauvery suture zone, southern India: indications of high-temperature Gondwana suture

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The  $P$ - $T$ - $t$  evolution and significance of garnet-bearing granulites from the Palghat-Cauvery Shear Zone is considered as a trace of the Gondwana suture in southern India. The garnet-kyanite rock preserves inclusions of gedrite, spinel and quartz within garnet. Further, the inclusions of sapphirine with spinel in garnet mark the prograde formation of garnet from a low-pressure hydrous condition to higher pressure. The formation of garnet-rim around gedrite, supports the garnet forming reaction after gedrite. The garnet-corundum-staurolite-kyanite assemblage stable at higher pressures probably represents the peak metamorphic stage. Garnet core with inclusions preserves a Fe-rich composition while the rims are Mg-rich and poor in inclusions. The variations in rare earth element chemistry of garnet-core and rim are consistent with the major element variation reaction textures. The rare earth element chemistry of garnet is compared to that in zircons. Most of the staurolite in the studied samples show moderate to high Mg-content. The thermodynamic modeling results assessed the  $P$ - $T$  peak of this unusual granulite to be around 14-15 kbar at temperature around 900°C. Textural features, petrogenetic and phase diagram consideration delineate a tight *hairpin*-type anticlockwise  $P$ - $T$  path for this granulite. The U-Pb zircon geochronological results correlate the timing of near-peak metamorphism in the Palghat-Cauvery Shear Zone to the Late Neoproterozoic ( $537 \pm 5.1$  Ma), probably linked to the East African Orogen and the closure of Mozambique Ocean. This age data are broadly consistent with the zircon SHRIMP ages reported in Collins et al. (2007), as well as the larger database of EPMA ages from monazite and zircons in several ultrahigh-temperature granulite localities in the Madurai Block as well as from the Palghat-Cauvery Shear Zone (Santosh et al., 2006). The extreme crustal metamorphism recorded from the Palghat-Cauvery Shear Zone mark this region as the thermal front between the Proterozoic granulite terranes in the south and the Archean terrane in the north in southern India. The presence of dunite and chromite-bearing lithologies in this belt further confirms the probability of this zone being an oceanic suture. Collins et al. (2007) also considered this zone as a probable trace of the Gondwana suture. The inherited zircon ages recorded in our study indicate that the sediments were derived from an Archean igneous province, similar to the Betsimisaraka suture in eastern Madagascar.

Keywords: Gondwana suture , southern India, UHT metamorphism

## Petrogenesis and Tectonic evolution of Madras Block, southern India

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Madras Block, one of the least studied crustal domain in southern India, has an important role in palaeogeographic reconstruction because of its geographical position. The block lies towards the south-eastern part of Archean Dharwar Craton and north-eastern margin of Archean to Proterozoic Southern Granulite Terrain, separated from the Namakkal Block by Salem - Attur Shear Zone (SASZ) in the south, and from Shevaroy Block by Nallamali Shear Zone (NMSZ) in the west. Its eastern part is covered with younger sediments. Extensive studies have been made on adjacent regions such as north eastern Dharwar Craton and Palghat Cauvery Shear Zone correlating them with Napier complex and Lützow-Holm complex (in Enderby Land, Antarctica), whereas there have been no significant studies of the Madras Block so far. A detailed petrological, geochemical, geochronological, and isotopical study of the Madras block will help us to understand the crustal evolution of this region and also give us an idea about the connections with Rayner Complex, East Antarctica.

The Madras Block consists mainly of a massif charnockite. Few locations have been examined so far regarding its geochemical and geochronological signatures (Howie, 1955; Subramanian, 1959; Sen, and Sahu, 1970; Sen, 1970; Sen, et al., 1970, Glorie et al., 2014). From a recent field survey carried out in this region, it is observed that the east to central part of the block mainly consist charnockite exposures. Other than charnockite, this region also has significant exposures of Hbl-Bt gneiss/Quartzofeldspathic gneiss/Bt-gneiss/TTG, Ep-Hbl Gneiss, 2-Px granulite, Amphibolite and Metagabbro intruded by younger dolerite dykes and granites. These ortho-gneiss are also associated with meta-pelites, Grt-Bt Gneiss, and calc-silicates. The northern side of the region consists mainly of amphibolites. The west and southern side consists mainly of Hb-Bt gneiss and granitic plutons. Pink granitic plutons can be found along the centre of the block, intruded into the charnockite. 2-Px granulites co-exist with charnockite. Contact zones between charnockite - granite, charnockite -TTG, and TTG- amphibolites are very evident.

From this block, we can see three types of charnockite: high-grade Opx bearing granulite (Charnockite), Cpx and Opx bearing granulite (Cpx Charnockite), and Grt-Opx bearing granulite (Grt charnockite). Grt bearing charnockite are observed around Palar river and NSZ region, Cpx-rich charnockite is also exposed along the northern side of the block. The presence of hemo-ilmenite in these samples indicates these rocks are highly oxidized. The charnockite is present along the east to central part of the block.

Charnockite from the type area (St. Thomas Mount -Pallavaram) are Cpx-bearing charnockite and are gabbroic in nature. Po, Ccp and Py are common in all the charnockite samples. These sulfides have been remobilized along the Plg grain boundary. Ilm and Mag are also present in these samples. Samples from the shear zone show a linear orientation and gneissic texture rich in Bt and Amph. The shear zone rocks are well hydrated such Opx is rehydrated back to odel for the genesis and evolution of Madras block of precise radiometric dating techniques. graph Bt.

The whole rock chemistry of the charnockite gives: SiO<sub>2</sub>: 62.75; TiO<sub>2</sub>: 0.89; Al<sub>2</sub>O<sub>3</sub>: 14.68; Fe<sub>2</sub>O<sub>3</sub>: 7.97; MnO: 0.10; MgO: 2.42; CaO: 4.46; Na<sub>2</sub>O: 3.78; K<sub>2</sub>O: 2.04; P<sub>2</sub>O<sub>5</sub>: 0.28. From the Harker Variation Diagrams, MgO, CaO, TiO<sub>2</sub>, and Fe<sub>2</sub>O<sub>3</sub> indicates a negative trend with SiO<sub>2</sub> whereas K<sub>2</sub>O shows a positive trend. Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> show only scatter. Based on the EPMA analysis of the charnockite, Opx has the X<sub>Mg</sub> of 0.306, Cpx have X<sub>Mg</sub> of 0.43, and the Grt is Fe rich. From the petrography and geochemistry, there are clear indications for a metamorphic grade zoning in Madras Block.

Keywords: MADRAS BLOCK, SOUTHERN INDIA, CHARNOCKITE, ORTHOPYROXENE

## Petrology and geochemistry of post-tectonic dykes in Tiptur area, Western Dharwar craton, Southern India

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Mafic dyke swarms are one of the major geologic features that represents crustal extension episodes during which basaltic material from the mantle is transferred to the continental crust. The study of these dykes will help to understand the nature and composition of the mantle source. The emplacement of dykes is regarded as one of the final stages of cratonization and hence the study of these dykes throws light into the accretionary history of the craton. In the Dharwar craton of Southern Peninsular India, mafic dykes are densely spread like other Precambrian terranes of the world. Although dykes are well distributed in Dharwar craton, only those of Eastern part of the craton have been extensively studied and less attention has been given to the detailed petrologic, geochemical and geochronological studies of the dykes in the Western Dharwar Craton (WDC). Studying the mafic dykes in the WDC will help to understand the activity of the craton during Late Archean to early Proterozoic and this will help to obtain a complete picture of the tectonic evolution of Dharwar craton.

One of the major dyke swarms in the WDC is Tiptur dyke swarm, where NE-SW as well as NW-SE dykes are densely distributed. Preliminary petrological studies were carried out to understand the nature and composition of this dyke swarm and the studied dykes falls into two distinct groups. The NW-SE trending dykes were unaltered, composed predominantly of plagioclase and pyroxenes with minor opaque minerals. The NE-SW trending dykes showed high degree of alteration with the preservation of only 50% or less remnant ophitic textures as well as original mineralogy. The bulk rock geochemical analysis using XRF has been conducted. Loss on ignition were found to be less than 1% for all the samples. In the wt% of major oxides, SiO<sub>2</sub>, CaO, Fe<sub>2</sub>O<sub>3</sub> and alkalis shows smaller variations whereas MgO and Al<sub>2</sub>O<sub>3</sub> show large differences. The overall chemical composition of the dykes indicate sub-alkaline tholeiitic nature with the NE-SW dykes falling into basalt field and NW-SE dykes in basaltic andesite fields. In the trace element geochemical characteristics, an overall enriched pattern is observed. Primitive mantle-normalized multi-element diagram of NW-SE dyke samples showed an LILE enriched pattern. Significant negative Nb and Ta anomaly along with a negative correlation between Zr and Sr is observed which may indicate the interaction of continental/ oceanic materials through subduction process. NE-SW dykes shows a slight LILE enrichment. Chondrite-normalized REE diagram shows that the NW-SE dykes have an LREE enrichment and flat HREE pattern whereas a relatively flat pattern for both LREE and HREE for NE-SW dykes. The (La/Lu)<sub>N</sub> ratio for NW-SE dykes is >2, which indicate derivation from a more enriched source and for NE-SW dykes is <2 indicative of a depleted mantle source. Immobile incompatible element (Th-Yb-Nb) distribution also indicate an enriched mantle source for NW-SE dykes and a depleted or more primitive mantle source for NE-SW dykes.

Preliminary assessment of petrologic and geochemical features suggest that NW-SE dykes and NE-SW dykes may not be co-genetic, they might have formed from different mantle sources and might have emplaced in two different episodes. The NW-SE dykes of the present study is comparable to the dyke swarms in the eastern Dharwar craton which is linked to the global mafic magmatism at around 2.2 Ga that led to intracontinental rifting and related breakup of Archean continents. Based on mineralogy and alteration index the NE-SW dykes can be thought to be a part of an older event. WDC being older than the EDC, the NE-SW dykes might be older than the NW-SE dykes and might have emplaced prior to the amalgamation of the current eastern and western part of the craton, and carry important information on mantle dynamics in the Archean and Paleoproterozoic, although age dating of the dykes is essential to

confirm their temporal and spatial relations.

Keywords: Mafic dyke swarms, Precambrian, Dharwar craton

## Paleozoic multiple thermal events in the Altai Range, Mongolia

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Altai Mountains are mainly situated in western Mongolia and northwestern China where correspond to heart of the Central Asian Orogenic Belt. The orogenic belt is the largest and longest-lived accretionary and collisional orogen on Earth, from the Ediacaran to the Permian. Therefore, study of Altai Mountains may provide some constraints on the growth of continent during the Paleozoic period.

The Altai Mountains are composed mainly of Paleozoic sedimentary and metamorphic rocks that were intruded by voluminous granitic intrusions. The metamorphic rocks that are focused in this study are in thrust contact with surrounding sedimentary rocks. Two metamorphic age clusters have been identified by our widespread monazite U-Th-Pb EMP dating; c. 350 Ma and 260 Ma. Samples containing normal-zoned garnet yield an age of c. 350 Ma or 260 Ma. However, samples containing garnet that shows discontinuous zoning in Ca have two monazite ages (i.e. c. 350 Ma and 260 Ma). The younger monazite grains are observed in the matrix and in garnet rim. Therefore, based on the metamorphic ages, there are three rock types; 1) rocks metamorphosed at 350 Ma, 2) at 260 Ma, and 3) both at 350 Ma and 260 Ma. Detrital zircon U-Pb ages from all three rock types show similar features each other, which are also consistent with the zircon ages in surrounding accretionary prism.

The 350 Ma metamorphic event that is well-preserved in the rocks from the western Altai Range, has been considered to be related with arc setting and burial of accretionary prism. The metamorphic pressure-temperature gradient and prograde metamorphic trajectory are various may due to the effect of ridge subduction during this period. The 260 Ma metamorphism mostly observed in rocks from the eastern Altai Range is characterized by hairpin-shaped anticlockwise pressure-temperature path. Considering the metamorphic age (c. 260 Ma) and the youngest age of the surrounding accretionary prism (Carboniferous), the event is final activation event in the Central Asian Orogenic Belt that may relate with closure of ocean and continental collision tectonics. During the presentation, we will discuss on the metamorphism and the ages.

キーワード : metamorphic rocks, Altai Range, Mongolia

Keywords: metamorphic rocks, Altai Range, Mongolia

# Metamorphic $P$ - $T$ evolution and U-Pb dating of the high-grade metapelitic rocks from the Khondalite Belt, North China Craton

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The Wulashan-Daqingshan Complex and the Jining Complex in the Khondalite Belt, the North China Craton yield high-grade sillimanite-cordierite-garnet metapelitic rocks with representative metamorphic assemblages and microstructures. In combination with petrological observation and  $P$ - $T$  pseudosections, a clockwise  $P$ - $T$  path involving periods of near-peak, post-peak near-isothermal decompression and decompressional cooling is therefore inferred. For the garnet-cordierite-sillimanite metapelitic rocks of the Wulashan-Daqingshan Complex, the peak assemblage is garnet + biotite + K-feldspar + plagioclase + sillimanite + quartz + ilmenite + magnetite + liquid with  $P$ - $T$  conditions of 830–860 °C and 9.5–11 kbar. The following near-isothermal decompression assemblage is garnet + biotite + cordierite + K-feldspar + plagioclase + quartz + magnetite + ilmenite + liquid at 840–880 °C and 6.0–7.5 kbar, characterized by matrix cordierite isolated from garnet by biotite decompressional dehydration melting reaction of  $Bt + Sil + Qz \pm Pl \rightarrow Crd + Kfs \pm Ilm + Melt$ . Subsequent decompressional cooling processes resulted in cordierite and biotite + plagioclase symplectites surrounding garnet due to the following reactions of  $Grt + Sil + Melt \rightarrow Crd + Bt + Fe\text{-oxide}$  and  $Grt + Melt \rightarrow Bt + Qz \pm Pl$ . The sillimanite-cordierite-garnet metapelitic rocks of the Jining Complex have preserved polyphase mineral assemblages and microstructural evidence of anataxis, resulting from biotite dehydration melting. Petrological observations revealed that these rocks contain three metamorphic assemblages: a peak assemblage of garnet porphyroblast and matrix biotite + sillimanite + K-feldspar + plagioclase + quartz + ilmenite + magnetite, a post-peak near-isothermal decompressional assemblage of garnet + cordierite + biotite + sillimanite + K-feldspar + plagioclase + quartz + ilmenite + magnetite, and a decompressional cooling assemblage of garnet + biotite + cordierite + K-feldspar + plagioclase + quartz + ilmenite + magnetite. A clockwise  $P$ - $T$  path was defined involving the inferred peak stage followed by post-peak near-isothermal decompression and decompressional cooling stages, with  $P$ - $T$  conditions of 790–825 °C and 9–10 kbar, 810–890 °C and 6.0–6.5 kbar, and 780–810 °C and 4.0–5.5 kbar, respectively. Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) U-Pb analyses of the sillimanite-cordierite-garnet metapelitic rocks on detrital zircons yield yielded a protolith age of ~2.0 Ga. Moreover, metamorphic zircons yielded the late Paleoproterozoic metamorphic age of 1850 ~ 1950 Ma with age groups of ~1950 Ma, ~1900 Ma, and ~1850 Ma. The clockwise  $P$ - $T$  paths and new zircon data reveal that the Paleoproterozoic Khondalite Belt involved in continent-continent subduction and collision followed by exhumation and cooling between the Yinshan and Ordos Blocks in the Western Block of the North China Craton, and experienced the Paleoproterozoic granulite-facies metamorphism.

Keywords: metapelitic rocks, partial melting, phase equilibria modeling,  $P$ - $T$  path, Khondalite Belt



# The growth, reworking and evolution of early Precambrian crust in the Jiaobei terrane, the North China Craton: Constraints from U-Th-Pb and Lu-Hf isotopes, and REE concentrations of zircon from granitoid gneisses

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The early Precambrian crustal growth and reworking of the North China Craton (NCC), its tectonic subdivision and amalgamation, and its major magmatic and metamorphic events are important issues of considerable controversy. The high-grade metamorphic Jiaobei terrane located at southeastern NCC, mainly composed of Archean and Paleoproterozoic granitoid gneiss and metamorphic supracrustal rocks, is generally considered to be the southern extension of the Jiao-Liao-Ji belt which has commonly been regarded as a Paleoproterozoic active belt on the eastern margin of the NCC.

To better understand the growth, reworking, metamorphism and tectonic evolution of the Jiaobei terrane, Jiao-Liao-Ji belt as well as NCC, we have conducted a coupled LA-ICP-MS U-Th-Pb dating, trace element and in situ Hf isotopic study of zircons from Archean and Paleoproterozoic granitoid gneisses which mainly comprise Archean TTGs (tonalite-trondjemite-granodiorite) and Paleoproterozoic deformed monzogranitic gneisses, undeformed syenogranites and pegmatitic granites. A comprehensive dataset of CL-images, Th/U ratios, REE (rare earth element) concentrations,  $^{176}\text{Lu}/^{177}\text{Hf}$  and  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios of distinct zircon domains from the early Precambrian granitoid gneisses is presented. The results defined three stages of Archean continental crustal growth by TTGs magmatisms at  $\sim 2.9$ ,  $2.7$  and  $2.5$  Ga, respectively. The TTGs have positive zircon  $\varepsilon_{\text{Hf}(t)}$  values, and two-stage Hf model ages clustering at ca.  $3.3$ - $2.7$  Ga. We also defined multi-stage Paleoproterozoic granitic magmatisms by remelting of continental crust during  $2.2$ - $2.0$  and  $1.8$  Ga. The Paleoproterozoic granitoids show negative  $\varepsilon_{\text{Hf}(t)}$  values, and two-stage Hf model ages mainly ranging from  $3.2$ - $2.7$  Ga. We also obtained two groups of metamorphic ages of  $\sim 2.5$  and  $\sim 1.86$  Ga. The  $\sim 2.5$  Ga metamorphic event which is widely occurrences in the NCC is thought to be linked to underplating of large amounts of mantle-derived magma, and the  $1.86$  Ga metamorphic event which is occurrences in western Khondalite belt, Trans-North China Orogen and Jiao-Liao-Ji belt is thought to be linked to arc (continent) -continent collision responding to assembly of supercontinent Columbia.

Based on our new results, combined with the previous researches, we summarized that the growth and evolutionary history of early Precambrian continental crust in the Jiaobei terrane is following: 1)  $> \sim 2.9$  Ga, the Jiabei terrane were dominated by basic crust (oceanic crust) with limited early Archean continental crust which had been denuded; 2) At  $\sim 2.9$  Ga,  $2.7$  Ga and  $2.5$  Ga, the  $\sim 3.3$ - $2.7$  Ga juvenile thickened basaltic lower crust experienced episodic partial melting companied with remelting of continental crust triggered by upwelling of mantle plume, and formed the Archean continental crust consisting of plenty of TTGs and minor continental crust-remelted (high K) granites; 3) During  $\sim 2.2$ - $2.0$  Ga, the continental crust took place rifting and thinning caused by upwelling of mantle materials, resulting in formation of  $\sim 2.2$ - $2.0$  Ga granitoids by remelting of the continental crust; 4) During  $\sim 1.95$ - $1.85$  Ga, the Jiaobei terrane underwent granulite to high amphibolite facies metamorphism caused by collision-related tectonic processes and closing of the rift; 5) At  $\sim 1.8$  Ga, the continental crust underwent extension and thinning again caused by upwelling of mantle materials, which resulted in formation of  $\sim 1.8$  Ga granites by remelting of the continental crust.

Keywords: The Jiabei Terrane, Early Precambrian geology, Continental crustal growth, Archean TTGs gneiss, North China Craton

## Origin of felsic middle crust: Evidence from experimental study for Cretaceous I-type granodiorite in Kyushu, SW Japan

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The Asian continent was formed by continental collision during the Late Paleozoic. Japanese island was situated along the active continental margin before opening into the Sea of Japan. The matured continental crust is generally made of mafic lower crust and felsic middle to upper crust in terms of seismic profiles. Here, we report the formation of felsic middle crust along the active continental margin during the Cretaceous, the eastern end of Asian continent. The northern part of Kyushu is underlain by the Cretaceous granitoids. The granitoids consist mainly of hornblende granodiorite with small amounts of coeval diorites, and include cumulous gabbros as blocks. The granodiorite contains magmatic epidote and its emplacement depth is of the middle crust. The granodiorite and diorite make different chemical trends on some variation diagrams. The initial Sr-Nd isotopic compositions, however, resemble each other among three lithologies. The cumulous gabbro contains euhedral hornblende and clinopyroxene with trace amounts of plagioclase. The hornblende could be equilibrium with the granodiorite melt in terms of trace element compositions. Considering geological and geochemical signatures, the granodiorite magma can be produced by partial melting of the cumulous gabbro. To verify the petrogenesis of granodiorite magma, we performed melting experiment by the piston-cylinder apparatus using the cumulous gabbro as a starting material with 900 degree and 800 MPa. The chemical composition of synthetic glasses resembles that of the high-silica samples of granodiorite. The mineral compositions of run products are the same as cumulous gabbro. Results of this experiment can duplicate the formation of high-silica granodiorite magma. The granodiorite magma was chemically modified by mixing with coeval diorite. The magma ascended through the crust and was emplacement at the middle crust. It is an essential process to form the felsic middle crust underneath the volcanic arc setting.

キーワード：珪長質中部地殻、部分溶融、溶融実験

Keywords: Felsic middle crust, Partial melting, Melting experiment

## Trace element partitioning during partial melting in main zone of the Hidaka metamorphic belt

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The Hidaka metamorphic belt which represents a titled crustal section of a magmatic arc of tertiary age, is situated in the central part of Hokkaido, northern Japan. Opx amphibolite which were metamorphosed under granulite-facies conditions, are distributed in this area, and has been reported orthopyroxene bearing leucosome by dehydration melting of hornblende (Osanai et al., 2006). In recent years, new partition coefficient be reported from migmatite in lower crustal condition (e. g. Nehring et al., 2010). This study focus on Opx amphibolite involving Opx leucosome, and discuss about trace element partitioning at lower crustal P-T condition.

Opx amphibolite consist of orthopyroxene ( $En_{0.58-0.62}$ ), brown-hornblende, plagioclase, quartz and ilmenite. Plagioclase rim show high-anorthite (An) content ( $An_{70-85}$ ) against low-An core ( $An_{45-69}$ ). Opx leucosome contain euhedral orthopyroxene ( $En_{0.54-0.64}$ ) which be thought as new product by following incongruent melting;  $Hbl+Qz \rightarrow Opx+melt$  (Osanai et al., 2006). Opx leucosome lacks K-feldspar, and consist of orthopyroxene, plagioclase ( $An_{28-43}$ ), quartz, ilmenite and apatite.

We analyzed bulk and mineral composition including trace elements (Rb, Sr, Y, REEs and Hf). Kawanami et al. (2006) report bulk chemical composition of low-grade amphibolite which show N-MORB characteristics. REE pattern of Opx amphibolite show same or higher REE than N-MORB, and have a negative Eu anomaly. Opx leucosome show 52.8-64.4 [wt. %] of  $SiO_2$ , and LREE-rich and HREE-deplete REE pattern having negative to positive Eu anomaly. REE pattern difference remarkably depend on modal amount of apatite.

We estimated melt compositions using simple calculation that remove orthopyroxene composition from bulk chemical composition, and calculate trace element ratio between orthopyroxene and melt. REE ratio between orthopyroxene and melt, become less than 1, and show LREE-deplete and HREE-enrich (0.6-6.1) pattern. This pattern almost same as previous partition coefficient (e. g. Green et al., 2000). And, we also find characteristics that minerals/plagioclase REE ratio in Opx leucosome become almost same between each samples collected from different place in main zone of the Hidaka metamorphic belt. In this presentation, we discuss more detail about melt composition, equilibrium and meanings of mineral/melt and mineral/mineral trace element ratio.

キーワード：日高変成帯、微量元素、分配、LA-ICP-MS

Keywords: Hidaka metamorphic belt, Japan, trace element, partitioning, LA-ICP-MS

# Role of Basaltic Magma in the Evolution of Continental Crust: Formation process of Nikanbetsu Gabbro Complex in the Hidaka Metamorphic Belt

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The net growth of continental crust and the development of layered structure occur owing to the addition of basaltic magma and heat from the mantle in arc environment. The purpose of this study is to clarify the role of basaltic rocks, now frozen as gabbroic bodies in an exposed section of arc crust as metamorphic belt, in the heat and mass transportation processes through the crust. We have chosen the Hidaka metamorphic belt, which is a high-temperature medium-pressure type and was uplifted by collision of two island arcs. It is believed that the metamorphic belt represent a cross section of the arc crust exposed continuously from the upper crust (eastern side), through the lower crust, to the upper mantle (western side) (Komatsu et al., 1986). We particularly focus on the southern area, where several peridotite bodies are associated with large gabbroic-tonalite bodies, one of which is the Nikanbetsu gabbro complex, our study target. The gabbro complex consists of various lithologies such as troctolite, olivine gabbro, gabbro-norite, and quartz diorite, all of which shows diverse variation in grain sizes and complex contacting relationships in the field. There is a systematic lithological distribution; less fractionated rocks such as olivine gabbro are distributed in the peripheral (northeastern) part, the more fractionated quartz diorite in the central part of the complex, and moderately fractionated gabbro-norites in between. The complex can be regarded as a zoned pluton, which is similar to the Opirarukaomappu gabbro/tonalite complex (Honma, 1997) located to the northeast of the Nikanbetsu gabbro complex.

The  $An \# = Ca / (Ca + Na + K)$  of plagioclase, and  $Mg \# = Mg / (Mg + Fe)$  of clinopyroxene and orthopyroxene, decrease continuously from olivine gabbro to quartz diorite. By investigating the whole rock chemical composition focusing on fine grained rocks, which better reflect the melt composition, it was found that the less fractionated magmas, such as olivine gabbro, are classified as the tholeiite series, whereas more fractionated ones, such as quartz diorite and some gabbro-norites, are classified as calc-alkaline series. This contrast is also evident in their rare earth element (REE) concentration patterns. The former shows a REE pattern depleted in LREE, whereas the latter shows a pattern enriched in LREE. Any crystal fractionation models cannot reproduce the latter from the former as a parental magma. It is concluded that there were at least two contrasting parent magmas: one belonging to the tholeiite series and the other to the calc-alkaline series. It can be inferred from its trace element pattern that the parent magma of olivine gabbro formed by adiabatic decompressional melting of the Middle Ocean Ridge Basalt (MORB) source mantle. We propose a scenario that the heat released by the crystallization of this magma elevating the temperature of the lower part of the Hidaka crust to form the parent magma of quartz diorite belonging to the calc-alkaline series by partial melting. The Nikanbetsu gabbro complex gives us an excellent chance to scrutinize processes of heat and material transportation, which takes place deep in the crust and is usually not accessible.

# Geochemical and Geochronological records from South section of the Kongling Complex: Implications for the complex growth and reworking process of the Yangtze Craton nucleus

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The Archean Kongling Complex is an ideal target to investigate the Precambrian accretion and evolution process of the Yangtze Craton, for it experienced multiple episodes of growth and reworking events. This study aims to provide systematical understanding of the formation and evolution process of the South section of the Kongling Complex (SKC) and contrasting geochemical and geochronological records from both sections of the Complex (SKC and NKC). Basement rocks and supracrustal rocks were picked from the SKC, in where the geological process was unknown during 2.9 Ga to 1.0 Ga. Zircons from the biotite plagioclase gneiss, biotite two-feldspar gneiss, biotite amphibolite plagioclase gneiss, plagioclase-amphibolite suggest that the basement rocks of the SKC involved with Archean 2.9 Ga and 2.7–2.6 Ga growth and reworking events, followed by latter ~2.4 Ga and ~1.7 Ga geological events. The major and trace elements of the SKC metasedimentary rocks imply their protolith are Archean Kongling TTG and amphibolite. The zircon U-Pb-Hf data from the SKC are similar with those in the NKC during 2.9–2.6 Ga and 1.8–1.7 Ga, indicating both the SKC and the NKC have Archean basement rocks and suffered from the Paleoproterozoic extension event. However, the SKC is not the miniature of the NKC for it had no response to the Paleoproterozoic ~2.0 Ga collisional event. Compiled with all available data of the formation and reworking ages of entire Kongling Complex, the NKC could be further divided as west NKC, middle NKC and east NKC while the SKC is as same as the west NKC. Based on our new analyzed data and comparative study of the SKC and NKC, all previous files were put into order to understand the formation and evolution process of the Craton nucleus.

Keywords: Yangtze Craton, Kongling Complex, Craton nucleus, Formation and evolution

## Geological and geochemical characteristics of UHT metamorphic rocks from the Amundsen Bay region in the Napier Complex, East Antarctica

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The Tonagh and Bunt Islands locate in the southern-end of Amundsen Bay, northern Enderby Land, which belongs to the central Napier Complex and shows a part of the highest-grade metamorphic region in the Napier Complex. The islands are mostly underlain by various kinds of ultrahigh-temperature (UHT) metamorphic rocks. UHT-metamorphic rocks from the Tonagh Island are subdivided into five lithologic units (Units I to V) owing to their lithologies and geological structures from north to south bounded by thrust-shear zones, accompanying with remarkable anhydrous mylonite and later pseudotachylite-cataclasite.

A geological perspective of the metamorphic rocks from the Tonagh and Bunt Islands is generally classified into 8 types on the regional map scale such as (1) Opx-bearing quartzofeldspathic charnockitic gneiss, (2) Grt-bearing quartzofeldspathic gneiss, (3) Opx-Cpx-bearing mafic granulite, (4) Grt-Opx gneiss and granulite, (5) Mt-Qz gneiss, (6) metamorphosed ultramafic rocks, (7) layered gneiss 1 (composed mainly of mafic gneiss and Opx-bearing quartzofeldspathic gneiss), (8) layered gneiss 2 (composed mainly of mafic gneiss and Grt-bearing quartzofeldspathic gneiss) with subordinate meta-impure quartzite, Spr-bearing aluminous restitic granulite, and calc-silicate granulite. Types-(1) and -(2) are main constituents of the Tonagh Island and Osm- and Spr-bearing aluminous granulite is characteristically found in Bunt Island.

Especially the Unit I of the Tonagh Island has a peculiarity of predominance of layered gneisses showing thin alternation (centimeter to several meters in thickness) of various kinds of UHT metamorphic rocks (mafic, intermediate and felsic in bulk chemical compositions) and metamorphosed ultramafic rocks (pyroxenite and Iherzolite). All these metamorphic rocks show a simple variation trend from the komatiite field to the rhyolite field and have bimodal chemical clusters of ultramafic-mafic and highly quartzofeldspathic in compositions. Spr- and Osm-bearing granulite as a typical UHT metamorphic rock have silica-undersaturated and aluminous chemical compositions, which would have formed as the restite and/or metasomatic reaction product under the UHT condition. The Spr- and Qz-bearing granulites have also derived from partial melting of metamorphic rocks having pelitic composition. In any case, most of the metamorphic rocks from the Tonagh and Bunt Islands got the anhydrous mineral assemblages excepting later retrograde hydration with forming micas and amphiboles during the highest-grade metamorphism of 2480-2550 Ma.

キーワード：エンダービーランド、ナピア岩体、トナー島、バント島、超高温変成岩

Keywords: Enderby Land, Napier Complex, Tonagh Island, Bunt Island, UHT metamorphic rocks

# Neoproterozoic, Paleoproterozoic, and Neoproterozoic arc magmatism in the Lützow-Holm Complex, East Antarctica: implications for multiple collisional events during Gondwana amalgamation

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The Lützow-Holm Complex (LHC) of East Antarctica, which contains various amphibolite- to granulite-facies rocks with the latest Neoproterozoic peak metamorphic ages (600-550 Ma), forms a part of the crustal segment of the East African-Antarctic Orogen. Similar high-grade metamorphic rocks are exposed in adjacent Gondwana fragments such as Sri Lanka, Southern India, and Madagascar. Here, we present new petrological, geochemical, and zircon U-Pb data for meta-igneous rocks from the LHC, as well as our published data, and evaluate the presence of several magmatic arcs that accreted and collided each other before the final collision and formation of Gondwana Supercontinent.

The oldest crustal fragment in the LHC occurs in the southwestern part of the complex such as ca. 2.5 Ga charnockite from Vesleknausen and Sudare-iwa (Tsunogae et al., 2014, 2016). Geochemical signatures of the rocks suggest the protolith of the charnockite was formed through Neoproterozoic arc magmatism.

Zircon Lu-Hf data of the Neoproterozoic charnockites indicate that the protolith magma was sourced from Paleo- to Neoproterozoic juvenile components mixed with reworked ancient crustal materials.

Neoproterozoic arc magmatic rocks derived from juvenile sources have been reported from several localities throughout the LHC such as Hutatu-iwa, Innhovde, Tama Point, Kasumi-iwa, and Langhovde (Tsunogae et al., 2015, 2016). Metagabbro from Akarui Point shows zircon U-Pb age of ca. 850 Ma with minor xenocrystic zircons of 1026-882 Ma (Kazami et al., 2016), suggest crustal reworking.

Paleoproterozoic magmatic ages of ca. 1.8 Ga have been reported from Austhovde, Telen, Skallevikshalsen, and Skallen, which corresponds to the highest-grade portion of the complex. Geochemical signatures of the ca. 1.8 Ga meta-igneous rocks also suggest arc magmatism for the formation of the protolith. The ca. 1.8 Ga magmatic terrane occurs as a belt between the ca. 2.5 Ga microcontinent and ca. 1.0 Ga magmatic arc, suggesting that the LHC was formed by a series of arc-continent collisional during the latest Neoproterozoic.

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キーワード：火山弧火成作用、 Gondwana、ジルコン年代

Keywords: arc magmatism, Gondwana, zircon geochronology

# High-pressure granulites in North China Craton and its implications for the Columbia supercontinent evolution

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High-pressure (HP) granulites are widely distributed within the Paleoproterozoic Jiao-Liao-Ji Orogenic Belt (JLJB), Trans-North China Orogen (TNCO), and Khondalite Belt (KB) of the North China Craton (NCC). HP granulites in the SW segment of the JLJB in the eastern part of the NCC occur as irregular lenses or dike swarms in the Paleoproterozoic metamorphic complex, which extend from NE Yantai to SW Anqiu about 300 km in length. Petrographic examination has revealed that HP granulites record a peak HP granulite-facies assemblage ( $M_1$ ) of Grt + Cpx + Pl + Qtz, and a subsequent decompression assemblage ( $M_2$ ) of Opx + Cpx + Pl  $\pm$  Amp  $\pm$  Fe-Ti oxides, which formed at 755–866 °C and 1.28–1.44 GPa, and 780–840 °C and 0.5–0.8 GPa, respectively. U–Pb dating of distinct zircon domains revealed the protolith ages of 2.2–2.0 Ga, the timing of the peak HP granulite-facies metamorphism at 1.95–1.9 Ga, and the subsequent retrogression at 1.86–1.84 Ga, respectively. Comprehensive petrographic and geochronological investigations of the HP granulites defined a clockwise P–T–t path involving a near-isothermal decompression and near-isobaric cooling process. The TNCO is a nearly north-south-trending ~1200 km long and 100–300 km wide belt in the centre part of the NCC. HP granulites mainly distribute in Hengshan, Huai'an, Xuanhua and Chengde areas, which record a similar metamorphic history characterized by near-isothermal decompressional clockwise P–T paths with peak metamorphic conditions of 800–870 °C and 1.05–1.6 GPa. Geochronological data of the HP granulites in the TNCO reveal two group metamorphic ages of 1.95–1.92 Ga and ~1.85 Ga, representing the timing of peak metamorphism and subsequent retrogression, respectively. HP granulites from the KB in the western part of the NCC occur as irregular lenses within granitic gneisses and Khondalite series, which outcropped from Xiaoshihao to Baiyuanhua about 100 km in length. The HP mafic granulites preserve a typical HP granulite-facies assemblage of Grt + Cpx + Pl + Amp  $\pm$  Qtz  $\pm$  Fe-Ti oxides. Pseudosection modeling and conventional thermobarometers constrain the peak HP granulite facies metamorphic conditions of 760–845 °C and 1.25–1.4 GPa, and a subsequent retrogression of 825–860 °C and 0.72–0.8 GPa with a typical clockwise P–T path. In-situ U–Pb dating of zircons show the protolith ages of 2.1–2.0 Ga, peak HP granulite-facies metamorphism at 1.96–1.94 Ga, and subsequent retrogression at 1.86–1.82 Ga, respectively.

The consistency of the petrography, clockwise P–T–t path and metamorphic timing for the HP granulites of the JLJB, TNCO and KB within the NCC indicate that the micro-blocks occurred continent-continent (or arc) collision at the Paleoproterozoic (1.96–1.9 Ga), resulting in the final amalgamation of the NCC. This newly summarized result has an important significance for the studies in-depth of the global Columbia supercontinent evolution.

Keywords: HP granulite, P–T–t path, Paleoproterozoic orogenic belts, North China Craton

## Sri Lanka - Correlation with N. Mozambique at the heart of Gondwana: North and South.

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Grantham et al., (2008) positioned Sri Lanka adjacent to N. Mozambique, prior to Gondwana breakup, in a position requiring *ca* 90° clockwise rotation (Reeves 2004) with the result that the Vijayan Complex is correlatable with the Nampula Terrane (NT) of N. Mozambique. The Lurio Belt, bounding the Nampula Terrane to the N. was correlated with the shear zone separating the Vijayan and Highland Complexes. Exposures in N. Mozambique are poor, hampering studies of structural kinematics within the Lurio Belt.

Lithologies and structures in the Vijayan Complex (VC) exposed in quarries and along the S. coast of Sri Lanka show that the rocks consist dominantly of migmatitic tonalite and granitic (mostly porphyroclastic augen) gneisses with strong, mostly shallow dipping, planar fabrics. At one quarry, banded migmatitic tonalitic gneisses show strong folding and shearing. The folds and shears typically show a top-to-the east geometry. Lineations plunge shallowly N and S. The data suggest a transpressional deformation setting.

Comparison of lithologies and structures from the VC with data from the Nampula Terrane (NT) of N. Mozambique show that the tonalitic and granitic gneisses are similar to the Mocuba and Culicui Suites of the NT. The geometry of structures in the VC, rotated *ca* 90°, consistent with its position in Gondwana, are comparable to structures from northern Mozambique from the NT. Plunges of lineations in the NT in the Meconte-Monapo areas cover a broad arc of westerly to NE with three crude groups of WNW, NW to NNE and NE respectively. The WNW direction, is largely seen in the N of the Meconte-Monapo sheet, approaching the Lurio Belt. Its orientation is similar to the rotated orientation of lineations from S. Sri Lanka. The Meconte-Monapo sheet lineations plunge dominantly NW to NNE over most of the area but rotate sinistrally toward the Lurio Belt in the north. Broad fold patterns show two phases with ENE oriented fold axial traces and cross cutting NNW fold axial traces. Planar fabrics in Mozambique dip dominantly SE. Limited planar fabric data from Sri Lanka, rotated through 90° dip to the S.

Comparison of limited radiogenic isotope data (Sr,Nd) from the NT with published data from the VC show that they are similar. Comparison of published zircon crystallisation and metamorphic ages show peaks of ~1000-1100Ma and ~550Ma respectively. Available structural, isotopic and geochronological data consequently support correlations between the Vijayan Complex of Sri Lanka with the Nampula Complex of northern Mozambique and its extensions via the Barue Complex, N. Mozambique to the Maud Belt of western Dronning Maud Land, Antarctica

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Keywords: Sri Lanka, Mozambique, Gondwana

## Sr isotope chemostratigraphy of metacarbonate rocks from East Gondwana; Implications for depositional environments and correlations

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Sri Lanka, southern India, Madagascar, Mozambique and the Dronning Maud Land in East Antarctica forms an integral part of the Latest Proterozoic to Early Cambrian collision zone in the East African-Antractic Orogen (EAAO). The Mozambique Ocean is supposed to have existed between East- and West-Gondwana, before its final amalgamation to form a single Gondwana supercontinent, where carbonate depositions by chemical precipitation was prominent. Carbonate rocks can be ideal for considering the geochemical information of the paleo-ocean that separated continents and cratons that existed prior to the Gondwana amalgamation.

Taking advantage of the characteristics of metacarbonate rocks to understand the depositional history of oceanic basins, we compile data from several terrains in the EAAO belt and attempt to correlate between the terrains. Pure carbonate samples that were least influenced by alteration (that consist of calcite/dolomite mineral or only with minor amounts of calc-silicate minerals) were selected for this purpose. Based on thin section observation, oxygen and carbon isotopic composition and trace and rare earth element patterns we selected the purest samples for Sr isotope analysis. The  $\delta^{18}\text{O}$  values of meta-carbonate rocks above 20 ‰ and those with flat REE patterns were the best candidates for Sr isotope analysis.

The Sr isotopic compositions was compared with standard late Proterozoic Sr isotope chemostratigraphic curve, which suggest apparent depositional ages between 900 Ma to 660 Ma. Comparable Neoproterozoic sedimentation histories were obtained from the Highland Complex, Sri Lanaka, Madurai Block, southern India, and Dronning Maud Land, East Antarctica. In this presentation we discuss the possible correlation between different blocks within the East Gondwana ensemble.

Keywords: Sr isotopes, Gondwana, Chemostratigraphy

# Petrological, geochemical and geochronological insights to the stature of Mercara Suture Zone in the Southern Peninsular India and its role in Gondwana

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Southern India was the leading vertex of India as it collided with the other Gondwana continents in Ediacaran-Cambrian times. The south Indian shield which preserves early formed crust (prior to 2500 Ma) has been divided into the Dharwar Craton (DC) and the Southern Granulite Terrain (SGT) by Fermor (1936), is a transition between the charnockitic and non-charnockitic terrains (Fig. 1 a). The Mercara Shear Zone is sandwiched between the Western Dharwar craton and the Coorg block in the northern periphery of the SGT (Fig. 1 b). The shear zone is marked by steep gravity gradients reflecting the presence of under plated high-density material, along with the electrical anomalies suggestive for vertical conductive structure extending from the lower crust into the upper mantle coinciding with this geologically marked transition zone.

Previous studies correlated the trace of this zone to Mesoproterozoic Rodinian suture, in which the Betsimisaraka suture from the Madagascar cross over to the Indian sub-continent at the Karwar Kumta region (Karwar-Kumta suture zone), as well as the northernmost part of Dharwar Craton. Even though it was structurally and geochronologically challenged by other workers they accept the correlation between the Mercara Shear Zone and the ca. 2.4 Ga Betsimisaraka Suture Zone in east-central Madagascar.

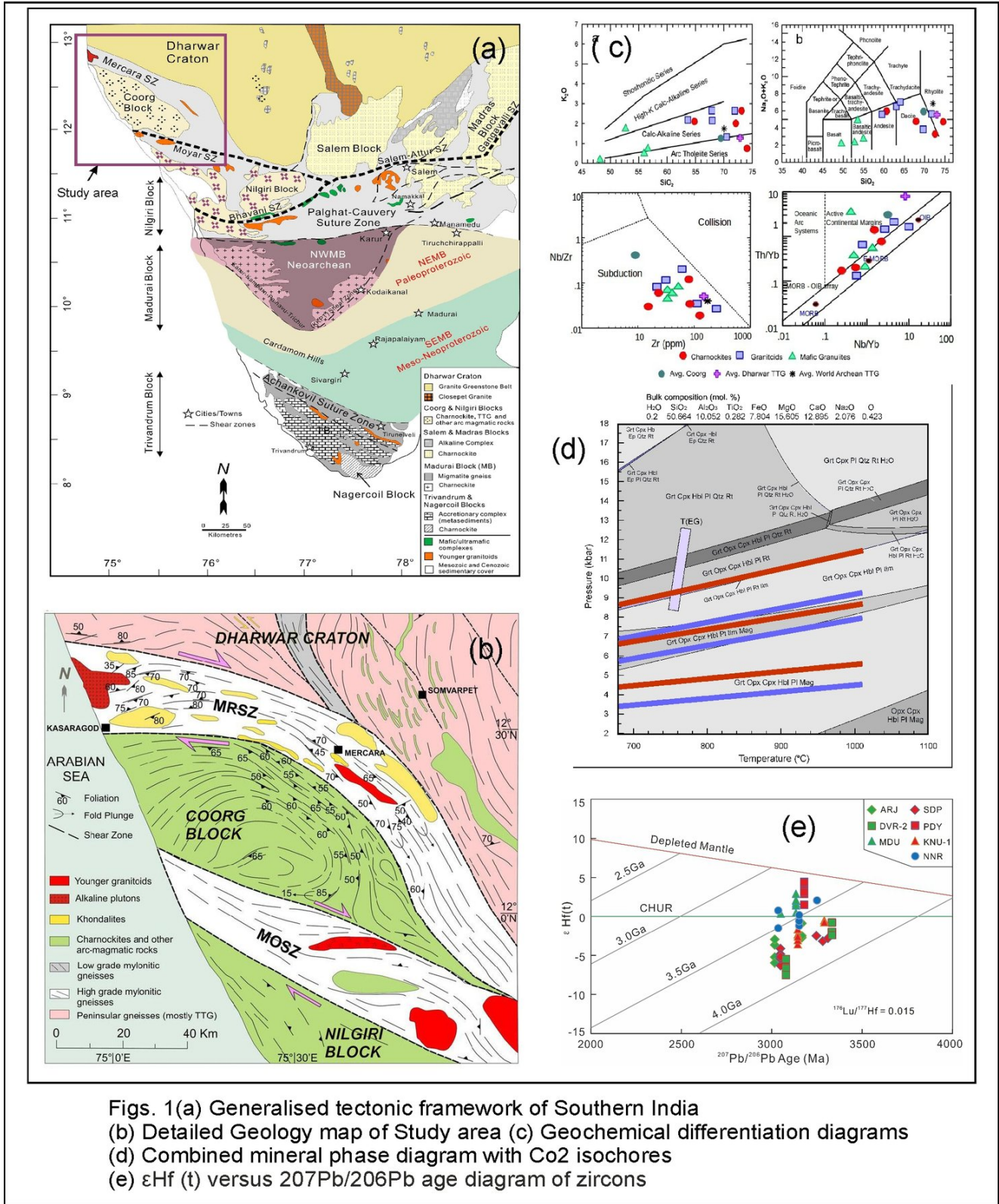
In this context our study try to elucidate the geological, petrological, geochemical, geochronological and genetical aspects from a suite of metaigneous (TTG-related gneisses, charnockite, metagabbro, mafic granulite) and metasedimentary (quartz mica schist, khondalite, garnet biotite gneiss, kyanite-sillimanite bearing metapelite) rocks from Mercara Shear Zone.

Conventional geothermobarometry and pseudosection computations indicate that the metapelites and mafic granulites from the Mercara Suture Zone have undergone high grade metamorphism at granulite facies conditions, possibly associated with a collisional event. Geochemical data on the magmatic suite suggests formation through subduction-related arc magmatism, whereas the metasediments represent volcano-sedimentary trench sequences (Fig. 1 c). The fluid inclusion microthermometry of inclusions in quartz and garnet reporting high-density carbonic ( $1.15 \text{ g/cm}^3$ ) fluids from the charnockites and mafic granulites. The fluid inclusion data extracted from these granulites is in conjunction with the mineral thermobarometry of the terrain and suggest deep subduction and subsequent exhumation (Fig. 1 d).

The zircon U-Pb age data from the magmatic rocks indicate crystallization ages between 3.1 Ga. to 3.2 Ga Ma whereas the detrital zircons from the sedimentary sequences provide an age range of 3.1 Ga to 3.5 Ga. The tightly defined ages of 3.1 to 3.2 Ga from igneous zircons in the magmatic suite suggest prominent Mesoarchean convergent margin magmatism. Hf isotope features suggest magma derivation mostly from juvenile sources and the Lu-Hf model ages indicate that the crust building might have also involved partial recycling of basement rocks as old as ca. 3.8 Ga (Fig. 1 e).

The zircon data in our study clearly show metamorphic overgrowth at ca. 3.0 Ga suggesting collisional suturing in the Mesoarchean, rather than Neoproterozoic or Mesoproterozoic. It is possible that the younger events recorded in the other studies represent reactivation of a Mesoarchean suture. Future studies focusing on the timing of metamorphism of the rocks along this suture might provide further insights into this intriguing problem and the debate over the age and reactivation history of the Mercara Suture Zone. Our study defines the Mercara Shear Zone as a terrane boundary, and possible Mesoarchean suture along which the Coorg Block was accreted to the Western Dharwar Craton.

Keywords: Petrology and Geochemistry, Fluid Inclusion, Zircon Geochronology, Mercara Suture Zone, southern India



Figs. 1(a) Generalised tectonic framework of Southern India  
 (b) Detailed Geology map of Study area (c) Geochemical differentiation diagrams  
 (d) Combined mineral phase diagram with CO<sub>2</sub> isochores  
 (e)  $\epsilon_{\text{Hf}}(t)$  versus  $^{207}\text{Pb}/^{206}\text{Pb}$  age diagram of zircons



## Significance of corona textures in ultrahigh temperature metamorphic assemblages: A study between southern Indian and east- Antarctic sections

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Lithological relationships between continents have been an important topic of research for geoscientists for the past decades. A number of tools are used in developing the updates regarding this topic, and petrology is the rarest among them. In this study, a significant similarity between the mineralogical and textural assemblages are reported between samples from east Antarctica and southern India using corona textures in ultrahigh-temperature metamorphic assemblages.

The region of Enderby Land in north-eastern Antarctica consists of regionally metamorphosed amphibolite to granulite facies rocks. This can be divided into several sub-regions such as- Napier complex (Archean), Rayner complex (Proterozoic), Lützow Holm complex (late Paleozoic) and Yamato-Belgica complex (early Paleozoic). Samples from Akarui point, LHC consist of porphyroblastic corundum partly or completely rimmed by spinel-sapphirine-plagioclase coronas. The matrix assemblage is mainly coarse to medium grained calcic amphibole and minor Fe-Ti phases. Similar unique textural assemblage is also observed in the UHT granulites from Palghat-Cauvery shear zone situated within the Southern Granulite Terrain, southern India. In this sample first two corona around corundum (Spl and Spr) is same as the samples from Akarui point, however the outer rim is of cordierite. The amphibole matrix in the Palghat-Cauvery shear zone sample is of gedrite composition. The reaction between the amphibole matrix and corundum core are further studied towards the formation of reaction coronas and their distribution in both the scenarios. The composition of Sapphirine from both the samples shows a significantly matching peraluminous distribution. The results enable us to understand the role of local bulk chemical composition in the textural formation at similar metamorphic condition. The resulting observations are further studied through the aspects of correlating continents and a new implication is made considering the two regions as counterparts for the giant Gondwana jigsaw puzzle.

Keywords: UHT, Gondwana, Corona

# Petrology and Geochemistry of Metamorphic rock from the Kabul Block, Afghanistan

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## 1. Introduction

Afghanistan is located in the tectonically active collision zone between the Eurasian and Indian Plates, which is the reason that has complex geology. Tectonically Afghanistan is composed of a series of terranes which split from the main Gondwanan supercontinent before colliding, with each other, or with the Eurasian plate (Sengor, 1984; Boulin, 1988; Treloar and Izatt, 1993). The northern part belongs to Eurasia, The Central is made up of accreted fragments of Gondwanan supercontinent, and south East belong to India Plate.

The Kabul Block is a tectonic fragment that occurs at the junction between the Indian and Eurasian plates. Along with the Farah and Helmand Blocks, it is part of a series of NE–SW aligned terranes that comprise the Central Afghanistan Blocks. (Abdullah and Chmyriov, 1977). The Basement rocks in Kabul block are metamorphic rocks covered by sedimentary rocks and intruded by granitoids. Basement rocks are exposed in the central part of the Kabul and these rocks are represented by three formation, called the Sherdarwaza, Kharog and Welayati Formations (Abdullah and Chmyriov, 1977; Karapetov et al., 1981; Bohannon, 2010). which are consist of amphibolite, biotite gneiss, mica schist, migmatites and small amounts of higher-grade granulite-facies rock.

## 2. Abstract

We are reporting petrology and geochemistry of metamorphic rocks from the Kabul block. The importance for this study is that there is no recent systematic and detailed petrographic and geochemical studies for metagranite and amphibolite from the Kabul block. These metagranites and amphibolites occur in northeastern and southern parts of Kabul city, respectively.

Metagranite cropped out in the northern part of the Kabul city, the boundary between metasedimentary rocks and metagranitic rocks are not clear and difficult to distinguish because of the sediments that are covered the area.

The garnet amphibolite and garnet-bearing mica schist are dominant in south part Kabul block, the amphibolite exhibits metamorphic foliation, The main mineral assemblage of the metagranites are biotite + plagioclase + K-feldspar + quartz ± kyanite ± sillimanite ± rutil ± garnet. Some metagranites contain sillimanite as inclusion in garnet and kyanite in the matrix, suggesting P-T change from sillimanite stability field to kyanite field. Corundum and spinel are rarely observed from highly aluminous domain in metagranite sample.

Aluminum saturation index ( $Al_2O_3 / (CaO + Na_2O + K_2O)$ ) in metagranite samples is higher than -1.0, In the Rb against Y + Nb diagram (Pearce et al., 1984), the metagranites show affinities to volcanic arc granites (VAG).

Main mineral assemblage of amphibolites is (hornblende + plagioclase + quartz + epidote + titanite + opaque), and that of garnet amphibolites is similar, except the presence of garnet. The TAS (Total Alkali Silica) & AFM discrimination diagram, all Amphibolite rocks plot in basalt field, with the signature of

E-MORB.

The result of FE-EPMA dating of monazite from metagranite indicates ca. 800 Ma, 1400 Ma and 1900 Ma for the timing of metamorphic event in this area metamorphism. We will add result of zircon U-Pb and discuss P-T-t history of metamorphic rocks in the Kabul block.