Japan Geoscience Union Meeting 2012
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SCG06-01 会場:301A 時間:5 月 25 日 13:45-14:00

Unravelling metamorphic-fluid events in Gondwana collision: U-Pb-REE constraints from Sor Rondane Mountains, Antarctica

Unravelling metamorphic-fluid events in Gondwana collision: U-Pb-REE constraints from Sor Rondane Mountains, Antarctica

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Assembly of Gondwana supercontinent has been argued in numerous studies. Generally the reported ages of Gondwana collision zones are in the range of 750-500 Ma, and two main age groups of 750-620 Ma and 570-530 Ma are estimated (e.g., Meert, 2003). The first episode (~620Ma) is mainly reported from eastern Africa to East Antarctica, and the second episode (~530Ma) is dominated in southern Africa through East Antarctica-Sri Lanka-southern India to eastern Australia. It is, however, not yet fully understood the superimposition of these two events in the crossing region.

Sor Rondane Mountains in East Antarctica is one such area where 640-630 Ma and 550-520 Ma metamorphic-fluid events are recorded (e.g., Shiraishi et al., 2008. Adachi, 2010). Greenschist-facies through amphibolite-facies to granulite-facies metamorphic rocks occupy the area, and the granulite-facies rocks are dominated in the northeastern-central part of the area (e.g., Shiraishi et al., 1992; Osanai et al., 1992). Multiple leucocratic veins and granitic intrusives are also developed. We present zircon and monazite U-Th-Pb and REE analyses by using ion microprobe and electron microprobe applying to garnet-biotite-sillimanite gneiss and associated leucoveins in the central part of Sor Rondane Mountains. Zircon in garnet-sillimanite-biotite gneiss yields c.640-630 Ma with minor >700 Ma and 550-520 Ma ages, and gives clear age-chemistry relation that HREE/MREE ratios drop in c.640-630 Ma zircon crystals compared with older and younger grains that are presumably controlled by REE partitioning with the coexisting garnet. Zircon and monazite in multiple generations of leucoveins also yield >700 Ma, 640-630 Ma and 550-520 Ma ages. Combined rare earth elements (REE) chemistry with the U-Th-Pb age domains in syn- and post-metamorphic leucoveins suggests contrasting isotopic and chemical signatures, and could provide constraints for decoding Neoproterozoic-Cambrian metamorphic-fluid regimes in the Gondwana collision zone.

キーワード: ゴンドワナ, 東南極, セールロンダーネ山地, 変成作用, ジルコン, モナザイト
Keywords: Gondwana, East Antarctica, Sor Rondane Mountains, metamorphism, zircon, monazite

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SCG06-02 会場:301A 時間:5 月 25 日 14:00-14:15

東南極セール・ロンダーネ山地におけるリソスフェアの進化
Evolution of continetal lithosphere in the Sor Rondane Mountains, East Antarctica

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The Sor Rondane Mountains is situated within the collision zone between the West and East Gondawana and the time of collition is regarded as the late Proterozoic (650-600 Ma). The mountains consist of greenschist- to granulite-facies metamorphic rocks and various kinds of intrusive rocks. The tonalite complex is exposed in the southern part of the mountains and its magmatic age is considered to be at the middle Proterozoic (990-920 Ma). This tonalite would originaly be formed at the subduction related tectonic setting priore to the collision event. Large amouts of microgabbro occure as mafic magmatic enclaves (MMEs; 990 Ma) and dikes (950 Ma) in the tonalite complex. Unmetamorphosed lamprophyre dikes intrude the tonalite complex and gneisses during the late- to post-collisional stages. The intrusive age of the lamprophyre is of 560 Ma. The magma processes of the tonalite complex together with the late- to post collisional lamprophyre dikes, therefore, provide us useful information of the evolution of continental lithosphere during the formation of Gondwana supercontinent.

The microgabbro represents the low-K and tholeiitic series, and is geochemically classified into Low-Ti and High-Ti microgabbros. The MMEs and dikes of microgabbros are equivalent to the Low-Ti and the High-Ti microgabbros, respectively. The Low-Ti and High-Ti microgabbros shows geochemical signature similar to the Oceanic Arc Basalts and the Back-Arc Basin Basalts, respectively. The middle Proterozoic magma processes would, therefore, proceed at a subduction zone with back arc spreading in an oceanic arc environment. The lamprophyre corresponds to alkaline rocks in the TAS diagram, and are characterized by high abundances of LIL elements and REE, especially Rb, Ba, Sr and LREE. The trace element abundances normalized to primitive mantle display enrichment of LILE and depression of HFSE with Nb and Ta negative anomalies. The lamprophyre is plotted in the within-plate field and a part of the island arc field that is close to the within-plate field on some discrimination diagrams. Considering the geochemical features, the lamprophyre was formed in a within-plate tectonic setting by the mixing of subduction-related materials.The initial Sr isotopic ratios (SrI) range from 0.7022 to 0.7040 (epsilon SrI = -14 to 12) for the Low-Ti microgabbro and from 0.7024 to 0.7030 (eSrI = -14 to 1) for the High-Ti microgabbro. The initial epsilon Nd values for the Low- and High-Ti microgabbros are calculated within the same range (eNdI = -0.1 to +0.5). On the other hand, the isotopic compositions of the lampropyre show SrI = 0.7043 - 0.7044 (eSrI = +7.6 to +9.2) and eNdI = -0.62 to -0.34.

The geochemical studies including Sr-Nd compositions reveal that the microgabbros have been originated from a depleted source, whereas chemical compositions of the lamprophyre is more enrichment rather than those of the microgabbros. Consequently, the magma processes in the Sor Rondane Mountains reflect the evolution of lithosphere from the middle Proterozoic to the early Paleozoic; the depleted mantle at the initial subduction stage then changing to the enriched mantle at the continental collision stage. This lithospheric evolution can be explained by interaction between the depleted mantle and the enriched materials (e.g., slab-derived fluids, melting product of subducted crustal rocks, or reaction with fossil wedge mantle) during closure of the Mozanbique Ocean.

キーワード: ゴンドワナ超大陸, 南極, セール・ロンダーネ山地, トーナル岩, 細粒斑れい岩, ランプロファイアー
Keywords: Gondwana supercontinent, Antarctica, Sor Rondane Mountains, tonalite, microgabbro, lamprophyre

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SCG06-03 会場:301A 時間:5 月 25 日 14:15-14:30

東南極 Lutzow-Holm 岩体に産するアルカリ～高カリウム貫入岩の産状と化学組成
Occurrence of alkali ~ highly potassic dykes intruded into metamorphic rocks on Lutzow-Holm Complex, East Antarctica

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東南極 Dronning Maud Land の Lutzow-Holm Complex（LHC）は、Rayner Complex の西方・Yamato-Belgica Complex の東に位置する、東南極楯状地の高温変成岩体の一つである。これまでの日本隊による南極観測（JARE）における地質調査では東経 45 度?37 度に分布する沿岸露岩において変成岩の詳細な調査が行われている。また、非変成の火成岩の貫入も認められている。JARE-52 における野外調査では、LHC の数カ所の露岩にてアルカリ?超カリウム岩岩脈の存在が新たに認められた。そのうち、Skallevikshalsen と Rundvagshetta にて見いだされた苦鉄質岩脈は、ほぼ南北方向（わずかに NNE-SSW 方向）の走向で東に急傾斜し、厚さは数センチメートルから 0.5 メートルまで変化する。一方、Prince Orav Coast の二番岩では走向 N70 °W で東北東に傾く厚さ 20-30 センチメートルの苦鉄質岩脈が見いだされた。Rundvagshetta の苦鉄質岩脈の一部は苦鉄質岩貫入後に活動したペグマタイトの影響で粗粒角閃石を伴う角閃岩に変化している。貫入岩は完晶質で粒径は 0.1-2 ミリメートルにおよび、斑晶鉱物が認められない。主にカリ長石からなり、黒雲母、角閃石、チタン石、燐灰石を伴う：これらの鉱物の量比は、その有無も含めて産地ごとに変化する。少量の石英と希に斜長石が含まれる。黒雲母・角閃石は貫入方向に並列する。岩脈の化学組成は、今回調査時に観察された 5 カ所の露岩毎に異なる： SiO_2 含有量は 46.3-60.2wt.%で、MgO 含有量は 9.48-0.69wt.%まで変化する。K_2O 含有量は 3.42-10.83wt.%におよび、一般的な火成岩より高い K_2O/Al_2O_3・K_2O/Na_2O 値を示す。全アルカリ-SiO_2 含有量の関係では、テフライト・粗面安山岩・粗面岩に相当する。この岩脈の中で、Skallevikshalsen に産する超カリウム苦鉄質岩脈（MgO = 7.92 - 9.48wt. %、K_2O = 8.10 - 8.72wt. %）は高い微量元素含有量を示し、ランプロアイトに似ている。Rundvagshetta の苦鉄質岩脈の一部母岩は加水変質反応を被り、その影響で母岩中のザクロ石が分解して黒雲母に変化する。この変化は苦鉄質岩岩脈との境界付近で最も強く見られ、境界から離れると変化の程度が低い。岩脈が交代作用のための流体を供給したと考えられる。

キーワード: アルカリ岩, 超カリウム火成岩, 岩脈
Keywords: alkali rock, ultrapotassic rock, dyke

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The stability of sapphirine + quartz in high/low oxygen fugacity rocks: a case study of Southern India/East Antarctica

The stability of sapphirine + quartz in high/low oxygen fugacity rocks: a case study of Southern India/East Antarctica

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Sapphirine has been the focus of many petrological investigations for the last two decades as the mineral often occurs in Mg-Al rich and pelitic rocks formed at high temperature to ultrahigh temperature (UHT). Particularly, sapphirine coexisting with quartz is considered as one of the most diagnostic mineral assemblages of UHT metamorphism. It is also known that sapphirine often occurs in magnetite-bearing high oxygen fugacity rocks, and, in such cases, the mineral can incorporate considerable quantity of ferric iron as well as Fe^{2+}. It is therefore important to evaluate the effect of Fe^{3+} content on the stability of sapphirine-bearing assemblages for estimating peak conditions as well as constructing *P-T* paths. In this study, we compared the stability of sapphirine + quartz in magnetite-bearing high-oxygen fugacity rocks from India (Madurai Block in the southern granulite terrane) with that in magnetite-absent low-oxygen fugacity rocks from Antarctica (Bunt Island in the Napier Complex) using mineral equilibrium modeling technique. The calculations have been done in NCKFMASHTO system using THERMOCALC 3.33 with an updated version of the internally consistent data set.

The Madurai Block is the largest granulite block in the Southern Granulite Terrane, India, which was formed by collisional orogeny related to the assembly of the Gondwana Supercontinent. The block contains granulites with various UHT mineral assemblages including sapphirine + quartz, orthopyroxene + sillimanite + quartz, and Al-rich orthopyroxene. Magnetite-bearing quartzo-feldspathic garnet-sillimanite granulites from Rajapalaiyam area in the southern part of the block, for example, contain sapphirine + quartz inclusion in garnet as a stable mineral assemblage at the peak of metamorphism. The calculated *T-X* pseudosections suggest that the stability temperature of sapphirine + quartz is lowered from 1000^{o}C at reduced condition (X_{Fe2O3} = 0.02) to 910^{o}C at oxidized condition (X_{Fe2O3} = 1.0).

The Napier Complex of Enderby Land, East Antarctica, underwent regional UHT metamorphism at ca. 2.5 Ga. Bunt Island in the Napier Complex, located in the highest-grade region of the complex, contains various kinds of UHT granulites including sapphirine-bearing rocks. Sapphirine + quartz assemblage, probably formed at the peak UHT condition, occur in sapphirine- and osumilite-bearing layers of the granulite. The absence of magnetite in the rocks indicates the sapphirine granulite was formed at reduced condition. *T-X* pseudosection of the rock suggests that the stability field of sapphirine + quartz is T $>$ 1050^{o}C at X_{Fe2O3} = 0.04, while it will be lowered in more oxidized condition (T $>$ 800^{o}C at X_{Fe2O3} = 0.24).

The results of this study demonstrated that the occurrence of sapphirine + quartz in UHT rocks is highly controlled by the oxidation state of the host rocks, particularly low oxygen fugacity rock is especially strongly influenced. In the case of Bunt Island, if X_{Fe2O3} increases by 0.04, the stability temperature of sapphirine + quartz will be lowered by 50^{o}C. It is therefore important to evaluate the effect of Fe^{3+} content of the stability of sapphirine-bearing granulites for estimating peak conditions as well as constructing *P-T* paths even if granulites were formed at reduced condition.

キーワード: サフィリン＋石英共生, 南インド, 東南極, シュードセクション, THERMOCALC, 酸素フガシティー
Keywords: sapphirine + quartz, Southern India, East Antarctica, pseudosection, THERMOCALC, oxygen fugacity

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Petrology of garnet-clinopyroxene rocks from the Gondwana suture zone in southern India

Petrology of garnet-clinopyroxene rocks from the Gondwana suture zone in southern India

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The Palghat-Cauvery Suture Zone (PCSZ) in the southern granulite terrane, India, which separates Pan-African granulite blocks (e.g., Madurai and Trivandrum Blocks) to the south and Archean terrane (e.g., Salem Block and Dharwar Craton) to the north is regarded as a major suture zone in the Gondwana collisional orogeny. It probably continues westwards to the Betsimisaraka suture in Madagascar, and eastwards into Sri Lanka and possibly into Antarctica. The available geochronological data including U-Pb zircon and EPMA monazite ages indicate that the rocks along the PCSZ underwent an episode of high-grade metamorphism at ca. 530 Ma that broadly coincides with the time of final assembly of the Gondwana supercontinent. Recent investigations on high-grade metamorphic rocks in this region have identified several new occurrences of garnet-clinopyroxene rocks and associated meta-gabbros from Perundurai, Paramati, Aniyapuram, Vadugappatti, and Mahadevi areas in Namakkal region within the central domain of the PCSZ. They occur as elongated boudins of 1 m to 1 km in length within hornblende-biotite orthogneiss. The garnet-clinopyroxene mafic granulites contain coarse-grained (up to several cm) garnet (Alm30-50 Pyr30-40 Grs10-20) and clinopyroxene (XMg = 0.70-0.85) with minor pargasite, plagioclase (An30-40), orthopyroxene (hypersthene), and rutile. Garnet and clinopyroxene are both subidioblastic and contain few inclusions of clinopyroxene (in garnet) and plagioclase. Orthopyroxene occur only as Opx + Pl symplectite between garnet and clinopyroxene in almost all the localities, suggesting the progress of decompressional reaction: Grt + Cpx + Qtz => Opx + Pl, which is a dominant texture in the PCSZ. The prograde mineral assemblage of the rocks is therefore inferred to be Grt + Cpx + Qtz, although quartz was probably totally consumed by the progress of the reaction. The metamorphic P-T calculations using Grt-Cpx-Pl-Qtz geothermobarometers yield T = 850-900 ℃ and P >13 kbar, which is consistent with the occurrence of high-pressure Mg-rich staurolite in Mg-Al-rich rocks from this region. Fluid inclusion study of some garnet-clinopyroxene rock samples identified CO2-rich fluid inclusions trapped as primary phases within garnet, suggesting that prograde high-pressure metamorphism was dominated by CO2-rich fluids. The results therefore confirmed that the PCSZ underwent regional dry high-pressure metamorphism followed by the peak ultrahigh-temperature event probably associated with the continent-continent collisional and suturing history along the PCSZ.

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Mineral equilibrium modeling of incipient charnockite and adjacent garnet-biotite gneiss from southern India

Mineral equilibrium modeling of incipient charnockite and adjacent garnet-biotite gneiss from southern India

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The Southern Granulite Terrane (SGT) in India is known for its classic exposures of regionally metamorphosed granulite-facies rocks formed during the collisional orogeny related to the amalgamation of Gondwana supercontinent. The SGT is composed of a collage of Proterozoic crustal blocks dissected by large Late Neoproterozoic shear/suture zones. The Trivandrum Granulite Block (TGB) is comprises dominantly metasedimentary sequence with khondalites, leptynites and charnockites with subordinate quartzite, mafic granulite, calc-silicate rocks, and meta-ultramafic rocks. The TGB is known as one of the classic examples for the spectacular development of ‘ incipient charnockites ’within orthopyroxene-free felsic gneisses as exposed in several quarry sections in the states of Kerala and Tamil Nadu. The charnockite-forming process in the TGB is considered to have been triggered by the infiltration of CO2-rich anhydrous fluids along structural pathways within upper amphibolite facies gneisses, resulting in the lowering of water activity and stabilization of orthopyroxene through the breakdown of biotite. However, no quantitative study on the stability of charnockitic mineral assemblage using mineral equilibrium modeling approach has been done so far. In this study, we report a new occurrence of incipient charnockite from Mavadi in the TGB and discuss the petrogenesis of granulite formation in an arrested stage on the basis of petrography, geothermobarometry, and mineral equilibrium modeling. In Mavadi, patches and lenses of charnockite (Kfs + Qtz + Pl + Bt + Grt + Opx + Ilm + Mag) of about 30 to 120 cm in length occur within Opx-free Grt-Bt gneiss (Kfs + Qtz + Pl + Bt + Grt + Ilm) host rocks. The application of mineral equilibrium modeling on charnockite assemblage in NCKFMASHTO system to constrain the conditions of charnockitization defines a P-T range of 800 °C at 4.5 kbar to 850 °C at 8.5 kbar, which is broadly consistent with the results from the conventional geothermobarometry (810-880 °C at 7.7-8.0 kbar) on these rocks. The P-T conditions are lower than the inferred peak metamorphic conditions from the ultrahigh-temperature granulites of the study area (T >900 °C), which might suggest heterogeneity in peak P-T conditions within this crustal block in relation to local buffering of metamorphic temperature by Opx-Bt-Kfs-Qtz assemblage. The result of T versus mole H2O (M(H2O)) modeling demonstrated that Opx-free assemblage in Grt-Bt gneiss is stable at M(H2O) = 0.3 to 1.5 mol.%, and orthopyroxene occurs as a stable mineral at M(H2O) <0.3 mol.%, which is consistent with the petrogenetic model of incipient charnockite related to the lowering of water activity and stabilization of orthopyroxene through breakdown of biotite by dehydration caused by the infiltration of CO2-rich fluid from external sources. We also propose a possible alternative process to form charnockite from Grt-Bt gneiss through slight variations in bulk-rock chemistry (particularly K- and Fe-rich portion of Grt-Bt gneiss) that can enhance the stability of orthopyroxene rather than that of biotite.

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変成条件が局所的に異なる岩石間の変成反応の推定
Metamorphic reaction to describe local-scale difference in mineral assemblage stable under different conditions

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変成岩の鉱物組み合わせは主に温度、圧力、流体組成によって決まる。同じ鉱物組み合わせをもつ岩石が数十 km スケールで産する場合、その違いは主に変成時の温度や圧力の違いであることがわかっている。一方で鉱物組み合わせが局所的 (数十 cm スケール) に異なる変成岩の産状も報告されている。このようなスケールでの温度と圧力の違いは現実的でないが、その代わりに流体組成は狭いスケールで変化することが可能である。局所的な流体組成の違いは鉱物組み合わせの変化をもたらし、そのような鉱物組み合わせの違いは、脱水反応で表現されることが必要である。しかし、このような反応を隣接する岩石間の鉱物の化学組成や産状の違いによって見積もった例はほとんどない。本研究では、局所的に鉱物組み合わせが変化する一例として、スリランカに産するチャーノッカイトと周囲の岩石の構成鉱物の化学組成を比較し、二つの岩石間の変成反応を推定した。

チャーノッカイト中の黒雲母は片麻岩中のものと比べて、Fe+Mg に富み、Ti に乏しい。

この組成の違いを空席 [ ] として以下の置換で表現する。

$[\ ]\mathrm{Ti} = (\mathrm{Fe+Mg})_2$

チャーノカイトに含まれている普通角閃石は片麻岩中の普通角閃石と比べて K、Fe+Mg、Si に富み、Na、Ti、Al に乏しい。それは次のような置換で表される。

$[\ ]_{0.5}\mathrm{Na}^{M4}\mathrm{Ti}^{M1-3}\mathrm{Al}_{0.5} = \mathrm{K}_{0.5}(\mathrm{Fe+Mg})^{M4}(\mathrm{Fe+Mg})^{M1-3}\mathrm{Si}_{0.5}$

上記の置換から求められる斜方輝石生成反応は、次のように書くことができる。

Ti-rich biotite + quartz = Ti-poor biotite + orthopyroxene + ilmenite + alkali feldspar + H_2O (1)

Ti-rich holnblende + quartz = Ti-poor hornblende + orthopyroxene + ilmenite + anorthite + albite + alkali feldspar + H_2O (2)

以上より黒雲母と普通角閃石は、それぞれ独立の反応で斜方輝石を生成することがわかった。反応式から得られる斜方輝石の生成量は、実際のチャーノッカイト中の斜方輝石の存在量とよく一致した。本研究で推定した二つの反応式は脱水反応であるため、チャーノッカイト中の鉱物組み合わせは、CO_2 に富む流体の条件下で安定となる。従ってチャーノッカイトと片麻岩の違いは、局所的な流体組成の違いで理解できることが確かめられた。

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マダガスカル東部における太古代中期ー後期ＴＴＧ火成活動：全岩化学組成およびウランー鉛年代による考察
Mid to late Archean TTG magmatism in the eastern Madagascar; a view from whole rock geochemistry and U-Pb geochronology

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Madagascar occupies a key position in the East African Orogen for understanding the continental growth and the tectonics of collision between East Gondwanaland and West Gondwanaland. Especially in the eastern Madagascar is composed of mid Archean domain (Masora) in the east and late Archean domain (Antananarivo) in the west.

The magma genesis and timing of magmatism were studied by whole-rock chemical analysis and LA-ICP-MS U-Pb zircon age dating of granitoids in these domains.

Masora domain is divided into two parts, north and south region, defined by metamorphic grade. The rocks from the north region are only weakly deformed. The north region mainly consists of trondhjemites with subordinate amounts of metapelities including meta-BIFs, and late granitoids with mafic-ultramafic rocks. Trondhjemites in the northern Masora domain are characterized by high SiO2 (67.80-70.98 wt.%), high Al2O3 (15.86-18.44 wt.%), and high Na2O (5.35-5.98 wt.%), low TiO2 (0.27-0.40 wt.%), Mg# (31-35), CaO (1.90-2.24 wt.%), K2O (1.64-2.65 wt.%). Antananarivo domain is divided into two parts, north and south region, defined by lithology. The south region mainly consists of Hbl-Bt gneisses with subordinate amounts of Grt-Opx granuilites, amphibolites, quartzites and metapsammites including meta-BIFs. Whole rock chemical analyses for the major and trace elements demonstrate that Hbl-Bt gneisses in the southern Antananarivo domain are of igneous origin and chemically comparable with CIPW normative tonalities. Hbl-Bt gneisses are characterized by high SiO2 (71.00-73.16 wt.%), high Al2O3 (15.89-16.33 wt.%), and high Na2O (4.41-4.67 wt.%), low TiO2 (0.18-0.23 wt.%), Mg# (38-43), CaO (3.40-3.82 wt.%), low K2O (1.04-1.71 wt.%). All of these granitoids (trondhjemites and Hbl-Bt gneiesses) show pronounced negative Nb, Ti, P anomalies on the primitive mantle-normalized spidergram. These characteristics are comparable to Archean TTG (tonalite-trondhjemite-granodiorite) (e.g. Martin et al., 2005).

A xenocrystic zircon in a trondhjemite sample collected from the northern part of the Masora domain gives a single grain concordat age of mid Archean (ca. 3.2 Ga). Hbl-Bt gneiss sample in the southern part of the Antananarivo domain shows slightly scattered and discordant late Archean age (ca. 2.7 Ga). This new age is slightly older than reported oldest ages of Antananarivo domain (ca. 2.5 Ga; Kroner et al., 2000).

These results show that the area between mid Archean (Masora) and late Archean (Antananarivo) domains is underlain by ca. 2.7Ga tonalitic rocks. Similar magmatic age is reported from the southern India. Late Archean magmatic age of the charnockite and meta-granite (ca. 2.65-2.53) were reported from the Salem Block in the southern India (Clark et al., 2009; Sato et al., 2011), where located between the mid to late Archean Dharwar Craton (e.g. Peucat et al., 1993) to the north and late Archean Madurai Block (Plavsa et al., 2012) to the south. Hence we speculate that Madagascar and India records progressive outward continental growth by accretion of mid-to-late Archean (ca. 2.7-2.6 Ga) crust and the late Archean (ca. 2.5 Ga) crust to ca. 3.2Ga Dharwar nuclei crust. Although Tucker et al. (2011) suggested the 'Greater Dharwar Craton' model to explain the juxtaposition of Madagascar with India from the late Archean (ca. 2.5 Ga), we suggest more stepwise crustal growth in the Archean era.

Keywords: Madagascar, Achean TTG, geochronology, geochemistry