Monazite and xenotime U–Th–Pb_{total} ages from basement rocks of the (central) Shillong–Meghalaya Gneissic Complex, Northeast India

PRITOM BORAH^{1,*}, PRANJIT HAZARIKA¹, AMULYA CHANDRA MAZUMDAR¹
and MRIDUL RABHA²

¹*Department of Geological Sciences, Gauhati University, Guwahati 781 014, India.*

²*Department of Geology, Pragjyotish College, Guwahati 781 007, India.*

*Corresponding author. e-mail: pritomborah90@gmail.com

MS received 6 February 2018; revised 12 May 2018; accepted 28 May 2018; published online 11 March 2019

Monazite and xenotime are the two most useful and commonly used geochronometers for deciphering ages from metamorphic rocks. The low analytical cost involved in electron probe micro-analyser chemical dating, ease of sample preparation and abundance in metamorphic rocks of wide P – T conditions make monazite and xenotime dating most widely used technique for age determination amongst metamorphic petrologists. This contribution presents age comparisons between coexisting monazite and xenotime in the basement metapelitic rocks of the central part of the Shillong–Meghalaya Gneissic Complex (SMGC). Thermobarometric estimates in the studied samples indicate granulite facies conditions of metamorphism with peak P – T conditions of ~ 6.5 kbar and $\sim 750^\circ\text{C}$. Results indicate that xenotime in the basement rocks in the central SMGC formed in four discrete geological events while monazite either formed only in the latest Pan-African granulite grade metamorphic event or recrystallised during this event. Monazite in the studied samples yielded a single ubiquitous age of ca. 500 Ma. Xenotime in the study area, although found in only one sample, preserves four distinct ages at 1153 ± 29 , 930 ± 36 , 823 ± 41 and 490 ± 11 Ma. Preservation of Grenvillian ages in xenotime from central SMGC marks the eastward extension of Rodinia amalgamation front in the Indian Shield. The Neoproterozoic ages in xenotime from central SMGC suggest that the ca. 820 Ma high-grade metamorphism in the Eastern Indian Tectonic Zone had a wider impact in the SMGC than perceived previously.

Keywords. Monazite; xenotime; U–Th–Pb_{total} dating; Shillong–Meghalaya.

1. Introduction

Monazite [(LREE)PO₄] and xenotime [(Y,HREE)-PO₄] are relatively common accessory minerals in both magmatic and metamorphic rocks and have significant concentrations of Th, U and Pb.

The occurrence of insignificant amount of common Pb relative to radiogenic Pb produced by the decay of Th and U in monazite and xenotime makes them ideal for retrieving age information using electron probe micro-analyser (EPMA) U–Th–Pb_{total} dating method (Suzuki and Adachi

1991; Williams *et al.* 2007; Hetherington *et al.* 2008; Suzuki and Kato 2008; Hazarika *et al.* 2017). The in-situ EPMA U–Th–Pb_{total} monazite and xenotime dating has become a powerful technique to elucidate the timing of tectonothermal events for establishing their relationship with regional and global tectonic processes. The stability of monazite mostly depends on the bulk rock compositions in which the less commonly identified xenotime crystals may not be stable (Hetherington *et al.* 2008). Additionally, monazite grows in a wide range of ambient temperatures in diverse geological environments from diagenetic to high-grade metamorphic and igneous, thereby preserving complex compositional zoning (Harlov *et al.* 2007). The occurrence of xenotime in low-temperature environments such as diagenetic sediments and low-grade metamorphic rocks (Rasmussen 1996), in high-temperature environments such as granulites, migmatitic zones (Heinrich *et al.* 1997; Spear and Pyle 2002) and peraluminous igneous rocks (Wark and Miller 1993; Bea 1996; Förster 1998) promises new avenues in application of xenotime dating for deciphering multiple geological events in complex terranes. Both monazite and xenotime are considered as geochronometers capable of deciphering multiple growth events in response to changing metamorphic conditions (Schenk *et al.* 2005; Boniface *et al.* 2012).

Several authors have used diverse dating methods to report different geological events (e.g., ~2.6, 1.6, 1.0, 0.5 Ga, etc.) from stratigraphically distinct lithounits in the central and eastern part of the Shillong–Meghalaya Gneissic Complex (SMGC) (Ghosh *et al.* 1991, 1994, 2005; Bidyananda and Deomurari 2007; Chatterjee *et al.* 2007, 2011; Yin *et al.* 2010; Kumar *et al.* 2017). Chatterjee *et al.* (2007, 2011) have reported well constrained ~500 Ma monazite chemical ages from different localities of Sonapahar (central SMGC) metapelitic rocks suggesting it to be a part of western margin of Pan-African Prydz Bay suture of East Antarctica. Being the frontal edge of the Indian plate, the SMGC provides one of the best regions in the world for evaluating the assembly of the East Gondwana during Pan-African period. It has been conventionally considered that the assembly and break-up of Rodinia and subsequent amalgamation of Gondwana occurred in the Neoproterozoic. Li *et al.* (2008) proposed a model on assembly and break-up of Rodinia and formation of Gondwana. The authors suggested that the collision of India with East Antarctica occurred at

ca. 900 Ma during Rodinia assembly and subsequently rifted and moved away towards northwest from Australia at ca. 780 Ma. However, chronologically constrained palaeomagnetic data indicate that India was at 30° north latitude with Australia at 755–750 Ma (Torsvik *et al.* 2001). Palaeomagnetic data indicate that the Indian shield moved southward after ~750 Ma and subsequently collided with Australo-Antarctica crustal block of the assembled East Gondwana at Ediacaran–Cambrian period (Powell and Pisarevsky 2002; Collins and Pisarevsky 2005; Kelsey *et al.* 2008; Li *et al.* 2008). The 876–784 Ma metamorphic belt, the Eastern Indian Tectonic Zone (EITZ), of Indian shield, shows its extension into East Antarctica defined by the occurrence of 884–770 Ma event at Oygarden Group and western Rayner complex (Kelly *et al.* 2002). The sinistral shearing and high-grade metamorphism of the EITZ at 876–784 Ma indicate the southward movement of India relative to the East Antarctica post ~1000–900 Ma Rodinia amalgamation (Chatterjee *et al.* 2010). Chatterjee *et al.* (2011) encountered evidence of the EITZ high-grade metamorphism in the western part of the SMGC (820 ± 21 Ma monazite ages), which was not observed in the central to eastern part.

Well-defined high-grade metapelitic assemblages from SMGC with profusely developed monazite and xenotime have immense potential in constraining distinct geological events. In recent attempts in Pan-Gondwana reconstruction, several authors have suggested an oblique, early Palaeozoic collision between India and the western part of Australo-Antarctica. Further, metamorphic and geochronologic evidences indicate continuation of the Prydz Bay Pan-African suture of East Antarctica through Northeast India (Zhao *et al.* 1995; Fitzsimons 2000, 2003; Boger *et al.* 2001; Chatterjee *et al.* 2007; Kelsey *et al.* 2008). Chatterjee *et al.* (2007) proposed that Pan-African final amalgamation of the Indian plate with the Australo-Antarctic plate occurred along the northward extension of the Prydz Bay suture through the SMGC. The authors have inferred the occurrence of the western boundary of the suture between the Garo–Goalpara Hills (western SMGC) and Sonapahar areas (central SMGC). The eastward dominance of Cambrian metamorphism and felsic magmatism indicating Pan-African collision in SMGC shows poorly constrained older metamorphic events.

In this communication, we report U–Th–Pb_{total} ages of both monazite and xenotime from metapelitic rocks of the central SMGC. We have

obtained xenotime chemical ages using an improved EPMA analytical protocol in order to explore the potential of using xenotime as a chronometer in studying poly-metamorphosed poly-deformed terrane. Further, we draw inferences to the xenotime ages with reference to published ages in relation to evolution of the SMGC. It is worth mentioning that Chatterjee *et al.* (2007, 2011) have extensively studied the metamorphic and geochronological evolution of the western and central SMGC. Thus, in the present study, we compare the potential of monazite and xenotime as geochronometers in complexly evolved terranes. We have also estimated the metamorphic P – T conditions of the samples considered for the study.

From the present study, it is perceived that xenotime has the ability to record multiple growth events as compared to monazite, which only preserves tightly clustered ~ 500 Ma event. The preservation of merely ~ 500 Ma age in monazite in the studied samples from the central to eastern SMGC suggests obliteration of record of the earlier tectonothermal events by the latest high-grade metamorphic event (Holdsworth *et al.* 2001; Dutch *et al.* 2005) during the global Pan-African collision. However, the preservation of multiple ages in xenotime in the same sample underscores the potential of xenotime as a robust geochronometer in complexly deformed terranes.

2. Regional geology

The SMGC, the extreme northeastern extension of the Precambrian shield of Indian Peninsular which comprises (i) the Neoarchean–Proterozoic to Early Palaeozoic (2.6–0.5 Ga) basement gneissic rocks (Ghosh *et al.* 2005; Bidyananda and Deo-murari 2007; Chatterjee *et al.* 2007, 2011; Kumar *et al.* 2017), (ii) the Palaeo-Mesoproterozoic NE–SW trending intracratonic Shillong basin constituting metasedimentary supracrustal rocks of the Shillong Group (Mitra 1998; Bidyananda and Deo-murari 2007; Yin *et al.* 2010) and (iii) Proterozoic–Early Palaeozoic (881–479 Ma) equigranular to porphyritic granite plutons intruding the basement gneisses and the Shillong Group of rocks on the basis of whole rock Rb–Sr isotopic methods (Crawford 1969; Chimote *et al.* 1988; Van Breemen *et al.* 1989; Ghosh *et al.* 1991, 1994, 2005). The gneissic complex of the Shillong plateau and the Mikir Hills domain constitute the basement of the SMGC. The gneissic complex of the Shillong plateau is

separated from Mikir Hills domain by NW–SE trending dextral strike slip Kopili fault, and both are detached from the main part of Indian peninsular by Garo–Rajmahal graben (Evans 1964). Desikachar (1974) and Crawford (1974) suggested the region as eastern and northeastern extension of the Chottanagpur Gneissic Complex (CGC) and the Eastern Ghat Belt (EGB), respectively (figure 1a). The western SMGC is characterised by predominantly coronitic garnet-bearing metabasic rocks intercalated and co-folded with migmatitic metapelites and quartzo-feldspathic gneisses, and minor calc-silicate gneisses and younger dioritic intrusion. On the contrary, the central SMGC is dominated by metapelitic granulites with a development of coronitic cordierite, quartzofeldspathic gneisses, garnet-free metabasic rocks, banded iron formations and calc-silicate gneisses (Gogoi 1963; Mazumdar 1976; Chatterjee *et al.* 2007). The spectacular feature of the SMGC is the occurrences of a relatively higher proportion of granitoid intrusions towards the central and eastern parts. Monazite chemical dating of the amphibolite–granulite facies metapelites reveal predominantly Palaeo-Mesoproterozoic ages of 1832–1596 Ma (Chatterjee *et al.* 2007, 2011; Chatterjee 2017) with poorly constrained Grenvillian ages of 1141–946, 820 ± 21 and 649–524 Ma (Chatterjee *et al.* 2007, 2011) in the western SMGC, whereas the central part of SMGC indicates prevalent late Cambrian age of 494 ± 6 Ma (Chatterjee *et al.* 2011) with poorly constrained ages of 1472 ± 38 and 1078 ± 31 Ma (Chatterjee *et al.* 2007). SHRIMP U–Pb zircon geochronology suggests that the Neoarchean to Palaeoproterozoic ages (2566 ± 27 , 1758 ± 54 and 1617 ± 14 Ma) are inherited older zircon cores from basement granite gneisses implying recycled ancient crust in the generation of Cambrian granites (Kumar *et al.* 2017). On the other hand, occurrence of three episodes of igneous activity (1600, 1100 and 500 Ma) are revealed by U–Pb zircon dating from granite gneisses, granites and the Shillong Group (Yin *et al.* 2010).

The western and central parts of the SMGC preserves three phases of folding episodes and one phase of ductile/brittle–ductile shearing pre-dating the last folding episode (Mazumdar 1976; Lal *et al.* 1978; Bardoloi *et al.* 1994). Folds of earlier generation are later superposed by N–S sinistral shears and mylonitisation (Bhattacharjee and Baruah 1973; Mazumdar 1976). The greenschist facies intracratonic metasediments of the Shillong Group are also affected by three phases

Figure 1. (a) Regional geological map of the SMGC (modified after Chatterjee *et al.* 2011). Available ages (in Ma) for different locations in the west and central SMGC are indicated in the map. (1) Chatterjee *et al.* 2007 (monazite chemical ages); (2) Chatterjee *et al.* 2011 (monazite chemical ages). (b) Geological map of Umpyrtha–Patharkhammah area (modified after Dash and Chatterjee 1992) showing sample locations.

of deformation (Barooah and Goswami 1972). The widespread distribution of varying metamorphic grade of the characteristic NNE-trending sinistral shears and related folds throughout SMGC indicates early Palaeozoic southward movement of the Indian block relative to the Australo-Antarctic block in the east (Powell and Pisarevsky 2002).

3. Analytical methods

Polished thin sections of representative metapelitic samples from various locations of the central SMGC (figure 1) were studied under a JEOL JSM-6490 SEM to identify and interpret textural associations of monazite and xenotime. Major element analyses of different metamorphic minerals as well as monazite and xenotime were performed using a Cameca SX-100 EPMA equipped with four wavelength dispersive spectrometers at the Department of Geology and Geophysics, Indian Institute of Technology (IIT), Kharagpur. Major elements in metamorphic minerals were analysed at 15 kV accelerating voltage and 20 nA beam current using a 1 μm beam size. Na and K were analysed first in the fixed sequence to avoid migration (details of analytical protocol in Hazarika *et al.* 2015). All plagioclase analyses were carried out using a beam size of 5 μm . Dwell time for all the elements were set at 10 s on the peak and 5 s on the background on each side of the peak. The standards (and emission lines) used for calibration and analysis were: jadeite (Na-K α , Si-K α), diopside (Ca-K α , Mg-K α), orthoclase (K-K α , Al-K α), fluor-apatite (F-K α , P-K α), NaCl (Cl-K α), Fe₂O₃ (Fe-K α), rhodonite (Mn-K α) and TiO₂ (Ti-K α). The crystals used for analyses were Thallium acid phthalate (TAP) crystal for F, Na, Al, Si and Mg; pentaerythritol (PET) for Ca, Ti, K and Cl; large PET (LPET) for P; and lithium fluoride (LIF) for Mn and Fe. The matrix (ZAF) corrections were performed using Pouchou and Pichoir (1984) method for silicate (PAPSIL) program (Cameca supplied).

Major element analyses in monazite for chemical dating were carried out using the same EPMA at an accelerating voltage of 20 kV, beam current of 150 nA and 1 μm beam size. The standards (and emission lines) used are: pyromorphite (Pb-M α), UO₂ (U-M β), ThO₂ (Th-M β) and synthetic glass (La-L α , Ce-L α , Nd-L α , Pr-L β , Sm-L α , Ho-L β , Dy-L α , and Gd-L β). Because of an interference of U-M α with Th-M β , the U-M β line was used for U (Suzuki and Kato 2008). Counting times for

Pb-M α was kept at 300 s for peak measurement and 150 s on both sides for background measurement. The counting times for U-M β and Th-M β were fixed at 200 s for peak and 200 s for background measurements. The spectral overlap corrections for Y-L γ_2 and Y-L γ_3 lines on Pb-M α and for Th-M γ and Th-M₃N₄ lines on U-M β were performed during quantification. Along with the monazite samples, monazites of known ages from Moacyr pegmatite of Brazil (TIMS age 487 ± 1 Ma, Crowley *et al.* 2005; EMP age 497 ± 10 Ma, Spear *et al.* 2009) were analysed to test the accuracy on the age estimations.

Xenotime chemical dating was also conducted using the same EPMA instrument at IIT Kharagpur. Xenotime analyses were performed using an improved analytical protocol (Hazarika *et al.* 2017), which adopt simultaneous measurement of U, Th and Pb in multiple spectrometers in sub-counting mode. All xenotime analyses were performed at an accelerating voltage of 20 kV, beam current of 200 nA and 1 μm beam size. The standards (and emission lines) used for calibration and analysis are: vanadinite (Pb-M β), UO₂ (U-M β), ThO₂ (Th-M α), apatite (P-K α and Ca-K α), yttrium aluminium garnet (Y-L α), synthetic glass (La-L α , Ce-L α , Nd-L β , Pr-L β , Sm-L β , Eu-L α , Gd-L β , Tb-L α , Dy-L α , Ho-L β , Er-L α , Tm-L α and Yb-L α). The use of Pb-M β line over Pb-M α automatically surpassed the spectral interference of Y-L γ_2 and Y-L γ_3 lines on Pb-M α . A TAP crystal was used to analyse Y, a LIF for La, Ce, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb, a PET for Ca, P, Pr and Nd, and a PET and a large PET simultaneously for Pb, Th and U. For more details on analytical setup the readers are referred to Hazarika *et al.* (2017).

4. Sample description

For the present study, polished thin sections of metapelitic rocks were prepared from different localities (Kynshi, Umling, Guwahati and Umpy-rtha-Patharkhammah) of the central SMGC (figure 1 shows sample locations). Four metapelitic samples (KY201A, KY201B, UM501B and GU202) were considered for constraining the *P-T* conditions of metamorphic evolution. Petrographic studies helped in sorting seven samples (KY201A, UM501B, GU102A, 12/3A, U204, U208 and U210) identified for in-situ monazite and xenotime chemical dating. These prospective samples were

observed under scanning electron microscope (SEM) for back-scattered electron (BSE) images to identify and understand the textural associations of monazite and xenotime. Petrographic descriptions with emphasis on textural setting of monazite and xenotime in all the studied samples are provided below. Chatterjee *et al.* (2007, 2011) conducted a detailed petrological study of the rocks in the western and central SMGC. In the present study, similar mineral assemblages and textural associations in most of the rocks from the central SMGC is reported. Thus, the following petrographic description of the samples is provided in context of the deformation/metamorphic sequence established by Chatterjee *et al.* (2007, 2011). All mineral EPMA data used in P – T estimation are provided in supplementary table S1.

4.1 Sample KY201A and KY201B

Samples KY201A and KY201B are coarse- to medium-grained garnet–biotite gneiss comprising garnet, cordierite, biotite, sillimanite, K-feldspar, plagioclase, spinel and quartz. Accessory phases include monazite, zircon, ilmenite, magnetite and pyrite. Inclusion trails of sillimanite, relict biotite, quartz and ilmenite within garnet and cordierite porphyroblasts define S_1 fabric (figure 2a) and M_1 metamorphic assemblage. The post- S_1 /pre- S_2 garnet and cordierite porphyroblasts represent the M_2 metamorphic assemblage. Coarse-grained biotite and sillimanite align in the matrix to define the dominant metamorphic fabric S_2 in the rock representing M_3 metamorphic assemblage. The post- S_1 /pre- S_2 garnet porphyroblasts are almandine-pyrope in composition with minor Fe enrichment towards inclusion free rims. The core-to-rim variation in composition ranges in Alm_{69–75}Pyp_{25–18}Sps_{2.7–4.7}Grs_{2.6–2.9}. The cordierite compositions range from X_{Mg} value of 0.67–0.73. The X_{Mg} in matrix biotite (syn- S_2) is 0.57–0.72. Spinel (ZnO = 3.9–8.2 wt%) occurs as inclusion within cordierite (figure 2a and b).

Monazite grains in these samples are mostly xenoblastic in shape and size ranges from 20 to 80 μ m. Some grains are fractured. Monazite grains were found to occur as inclusions (20–40 μ m) within garnet and cordierite (figure 3a through c) as well as in the matrix along the grain boundaries of K-feldspar, biotite, plagioclase and quartz (figure 3d). In addition to its occurrence as inclusions (figure 3a), monazites are also observed

to share grain boundaries with the metamorphic phases (figure 3b).

4.2 Sample UM501B

The sample UM501B is a garnetiferous metapelite constituting of garnet, cordierite, biotite, sillimanite, plagioclase, K-feldspar, quartz and muscovite. Monazite, zircon and pyrite occur as accessory phases. The penetrative foliation (S_2) in the rock is defined by coarse-grained biotite, sillimanite and elongated quartz grains (figure 2c). Post- S_1 /pre- S_2 garnet and cordierite porphyroblasts often contain syn- S_1 biotite and sillimanite inclusions (figure 2c). Garnet composition ranges from Alm₇₅Pyp₉Sps_{9.9}Grs_{2.8} to Alm₇₇Pyp₁₁Sps_{11.3}Grs_{4.1}. Cordierite composition ranges between X_{Mg} values of 0.56 and 0.64. The X_{Mg} in biotite is 0.46–0.52.

Monazite grains in this sample are xenoblastic and elongated in shape with relatively larger grain size (~70–150 μ m along their long axis). Elongated highly fractured monazites with skeletal irregular grain boundaries are seen to align parallel to the biotite defined foliation wherein monazites occur within or along the grain boundaries of biotite (figure 3g). Matrix monazites are observed along the grain boundaries of K-feldspar, quartz, cordierite and plagioclase, sometimes as inclusions within these phases (figure 3e and f).

4.3 Sample GU102A and GU202

Samples GU102A and GU202 are garnet-free biotite–sillimanite–cordierite gneisses comprising sillimanite, biotite, cordierite, quartz and plagioclase. Monazite, zircon and hematite occur as accessory phases. Sillimanite occurs as fibrolites as well as coarse grains (up to 1 cm in length). Sillimanite and biotite define the pervasive metamorphic foliation (S_2) which warps around pre- S_2 /post- S_1 cordierite porphyroblasts (figure 2d). Cordierite is Mg-rich with average X_{Mg} of ~0.71. Biotite has X_{Mg} values of 0.53–0.56. Monazites occur mostly as sub-rounded to irregular shaped, fractured relatively small grains (15–40 μ m) excepting a few grains (80–100 μ m). Monazites are found to occur in close association with sillimanite, plagioclase, biotite and quartz (figure 3h and i).

4.4 Samples 12/3A, U204, U208 and U210

These samples represent medium-grained garnet-free metapelite rock comprising dominantly

Figure 2. Textural features of different mineral assemblages in the metapelite samples from different localities of central SMGC. Photomicrographs (a) and SEM-BSE image (b) of sample KY201B show post-S₁/pre-S₂ garnet and cordierite porphyroblast with inclusion trails of sillimanite, relict biotite, quartz and ilmenite preserving S₁ fabric within garnet core. Note spinel inclusions within cordierite. (c) Photomicrographs of sample UM501B illustrate post-S₁/pre-S₂ cordierite porphyroblasts and often contain syn-S₁ biotite and sillimanite inclusions which are wrapped by the S₂ pervasive foliation defined by coarse-grained biotite, sillimanite and elongated quartz grains. (d) SEM-BSE image of sample GU102A showing sillimanite and biotite defined pervasive metamorphic fabric (S₂), which warps around pre-S₂/post-S₁ cordierite porphyroblasts. Plane-polarised transmitted light photomicrograph (e) and crossed polarised light image (f) of sample U210 shows warping of porphyroblastic cordierite (post-S₁/pre-S₂) by biotite + sillimanite + quartz defined S₂ schistosity. The inclusion trails of sillimanite + biotite ± quartz (S₁ foliation) within cordierite are orthogonal to external foliation. Monazites within cordierite which are aligned to S₁ foliation.

Figure 3. SEM-BSE images of textural occurrence of monazites in the metapelites from different localities of central SMGC. Occurrence of monazites as inclusions within post-S₁/pre-S₂ garnet and cordierite porphyroblasts, as well as along the grain boundaries of garnet in sample KY201A and KY201B (a–c). Matrix monazites occur along the grain boundaries of plagioclase and quartz in sample KY201A (d). Monazite at the margin of K-feldspar, quartz and plagioclase in sample UM501B (e and f). Monazite grain overgrowing S₂ pervasive metamorphic fabric defined by biotite, quartz and cordierite in sample UM501B (g). Monazite grain occurring as inclusion within sillimanite in sample GU102A (h). Monazite occurring as inclusion within quartz and hematite, and at the grain boundaries of hematite in GU202 (i).

sillimanite, cordierite, biotite, plagioclase, antiperthite, K-feldspar, quartz and muscovite. Accessory phases include zircon, monazite and xenotime (only in sample U204). Inclusions of sillimanite $\pm$ biotite $\pm$ quartz (S_1/M_1) occur within cordierite porphyroblasts (pre- S_2 /post- S_1 ; M_2 assemblage). Pre- S_2 /

post- S_1 cordierites are warped by S_2 biotite $\pm$ sillimanite $\pm$ quartz fabrics which define pervasive foliation in the rock (figure 2e and f). Later biotite and muscovite at places crosscut the penetrative biotite foliation.

Monazites occur mostly as idioblastic to subidioblastic elongated grains of ~ 20 – $100\ \mu\text{m}$ in size. Monazites also occur as inclusions as well as along the boundaries of cordierite and biotite (figure 4d). Elongated grains of monazite are aligned parallel to the biotite defined foliation.

In all the studied samples, only U204 contains xenotime. Biotite and sillimanite are aligned parallel to define the fabric in the rock (figure 4a). Muscovite–quartz symplectites occur adjacent to K-feldspar and biotite (figure 4b and c). Cordierite often contains sillimanite and elongated quartz grains aligned parallel to the matrix foliation (figure 4d and e). Cordierite is Mg-rich with average X_{Mg} of ~ 0.71 . Biotite has X_{Mg} of 0.56 (supplementary table S1). The sample contains numerous hypidioblastic xenotime grains of varying sizes ($\leq 100\ \mu\text{m}$ in diameter) occurring in clusters. Xenotime shares grain boundary with biotite, K-feldspar, quartz, plagioclase and cordierite (figure 4a–c and f). Xenotime is also seen as included phase within quartz, plagioclase, biotite, muscovite and K-feldspar (figure 4b, c and f). Monazite in the sample occurs as inclusion or share grain boundary with biotite and quartz (figure 4d and g).

5. Results

5.1 P – T conditions of metamorphism

The pressure–temperature estimation of metapelitic rocks was carried out using the various conventional mineral geothermobarometers on stable mineral assemblages. The thermometers used in the present study are garnet–biotite thermometer (Ferry and Spear 1978; Bhattacharya *et al.* 1992) and garnet–cordierite thermometer (Bhattacharya *et al.* 1988) in metapelitic rocks. Pressure estimations were made using garnet–cordierite–sillimanite–quartz (GCSQ) barometer (Holdaway

and Lee 1977; Wells and Richardson 1980), garnet–aluminosilicate–quartz–plagioclase (GASP) barometer (Holdaway 2001) and garnet–biotite–plagioclase–quartz (GBPQ) barometer (Wu *et al.* 2004) in the metapelitic rocks. The P – T estimates calculated using various mineral thermobarometers are provided in supplementary table S2.

The garnet–cordierite thermometer (Bhattacharya *et al.* 1988) applied in the metapelitic rocks (KY201A, KY201B and UM501B) provided an average temperature of $715 \pm 23^\circ\text{C}$ with peak temperature values of up to 794°C . The garnet–biotite thermometric pair consistently provided lower temperature values of $533 \pm 55^\circ\text{C}$ (Ferry and Spear 1978), and $576 \pm 25^\circ\text{C}$ (Bhattacharya *et al.* 1992) in all the samples (supplementary table S2). Such low- T estimates most likely indicate re-equilibration of garnet–biotite pairs (Spear 1993). Garnet in the samples KY201A and KY201B does not preserve any compositional zoning, which possibly is because of the high temperature of metamorphism.

The GCSQ and GASP barometers provided average pressure values of 6.2 ± 0.66 and 6.0 ± 0.15 kbar (Holdaway and Lee 1977; Wells and Richardson 1980, respectively) and 5.8 ± 0.67 kbar (Holdaway 2001), respectively (supplementary table S2). In spite of presence of the assemblage garnet, biotite and plagioclase, the GBPQ barometer provided unusual pressure values (0.9 – 1.6 kbar), possibly because of the very low X_{Grss} content (< 0.020) (Wu *et al.* 2004). Application of GBPQ barometry in sample KY201B furnished low-pressure estimates of 4.4 ± 0.13 kbar, plausibly for re-equilibration of garnet and biotite (Spear 1993). For the same reason, application of garnet–biotite–muscovite–quartz and garnet–biotite–muscovite–aluminosilicate–quartz barometric formulations remains ambiguous.

5.2 Monazite geochronology

The chemical compositions of monazite and xenotime, their calculated spot ages along with respective uncertainties for each spot analyses are provided in supplementary tables S3 and S4, respectively.

5.2.1 Sample KY201A

Monazites in the sample occur as inclusions within garnet that show lack of any internal zoning and preserve high Th, Y and U contents (Th = 5.44–5.47

Figure 4. Photomicrographs (a–e) and SEM-BSE images (f–g) showing textural settings of mineral assemblages in sample U204 from Umpyrtha–Patharkhammah area (central SMGC). Occurrence of xenotime as clusters in a matrix of biotite, K-feldspar, plagioclase, muscovite, cordierite and quartz (a–c and f). Note that sillimanite and biotite defined the pervasive foliation in the sample. Inclusion trails of sillimanite and elongated quartz grains within cordierite parallel to the pervasive foliation (d–e). Monazite within as well as along the grain boundaries of biotite and quartz defined external foliation (d and g).

Figure 5. SEM-BSE images of monazite grains in metapelite samples of central SMGC illustrating compositional zoning. The white circles indicate analysed spots (in Ma) which preserve indistinguishable Edicaran–Cambrian ages.

wt%, Y = 1.64–1.96 wt%, U = 0.45–0.95 wt%). Monazites at the margins of garnet rims contain low Y and U contents (Y = 0–0.11 and 0.19–0.26 wt%), whereas high Th content (5.89–6.76 wt%). On the other hand, monazites associated with cordierites (grain contact or inclusion) are poor in Y but rich in Th and U contents (avg. 6.11 and 0.39 wt%, respectively). The cores in zoned monazites are rich in Th, U and Y contents (avg. 5.98, 0.67, 1.04 wt%, respectively) and are surrounded by high-Th (avg 7.63 wt%) and low-U, Y (avg 0.32 and 0.11 wt%, respectively) mantle separated by sharp boundaries (figure 5a and d). Spot ages ($n = 45$) from core and rim of several monazite grains irrespective of their textural setting display a range from 488 to 552 Ma and yield a well-constrained age of 518 ± 5 Ma (MSWD = 0.54) (figure 6a and b). The compositional variation in monazites can be explained due to cheralite $[\text{Ca}, (\text{Th}, \text{U})(\text{Y}, \text{REE})_{-2}]$ and huttonite $[\text{Si}(\text{Th}, \text{U})(\text{Y}, \text{REE})_{-1}\text{P}_{-1}]$ substitutions (figure 8a).

5.2.2 Sample UM501B

Unlike sample KY201A, monazites in this sample, irrespective of their textural setting, do not preserve any distinct zonation except for a few grains (figure 5b, c and e). Grain in figure 5g displays complex zoning wherein Y-rich (2.24 wt%)

core is overgrown by Y-poor (0.87 wt%) mantle. Thorium and uranium concentrations of the matrix monazites range in 3.20–7.10 and 0.10–0.76 wt%, respectively. Chemical ages from 36 spot analyses of monazite grains range from 469 to 552 Ma yield a single probable age peak at 513 ± 7 Ma (MSWD = 1.07) (figure 6c and d). The Th+U +Si vs. P+Y+REE compositional plot for monazite spot analyses illustrates more restricted scatter towards cheralite substitution vector (figure 8a).

5.2.3 Sample GU102A

Monazite in this garnet-free metapelite rock is found mostly in association with foliation parallel phases such as biotite and sillimanite. Cordierite in the sample does not preserve any inclusions of monazite. SEM-BSE images of monazite grains in this sample do not display any compositional zoning, except a few grains showing two compositional zones with irregular boundaries (figure 5j and k). While the darker core preserves low Th content (2.74 wt%) the outer zone is Th-rich (4.27–6.90 wt%), and both zones are Y-poor (2.96–3.19 wt%). The U content in these monazites ranges from 0.08 to 0.14 wt%. Thirty-one individual spot analyses of monazite grains display chemical ages ranging from 416 to 529 Ma indicating a statistically significant age peak at 476 ± 12 Ma (MSWD = 0.72) (figure 6e and f). Similar to sample UM501B, the Th+U+Si vs. P+Y+REE compositional plot in this sample illustrates more restricted scatter towards cheralite substitution vector (figure 8a).

5.2.4 Samples 12/3A, U204, U208 and U210

Monazites in these four garnet-free metapelites exhibit similarity in their chemical compositions with a minor variation in sample 12/3A. Such chemical similarity can be well related to the similar mineral assemblage across these samples. Monazite grains in these samples do not display any internal zonation in SEM-BSE images (figure 5f and h). However, a few grains show indistinct patchy zoning with irregular outlines (figure 5i and l). From all four samples, it is perceived that the Th/U ratios in monazite show a wide range variation from 2.58 to 126, irrespective of their textural settings wherein the Th-content ranges from 0.78 to 8.0 wt%. The highly variable Th/U ratio of 6.90–47.6 in sample U210 is

Figure 6. Age probability plots with histograms (a, c and e), and plots showing weighted mean ages (b, d and f) of monazites from Kynshi (a and b), Umling (c and d) and Guwahati (e and f).

yielded in response to high Th-content (2.26–5.79 wt%). In the context of sample 12/3A, chemical spot analyses reveal that a few grains having low Th-content (0.78–2.1 wt%) show low Th/U ratios (2.58–7.99) while the other analysed spots are rich in Th-content (5.57–6.85 wt%) and exhibit high values of Th/U ratios (35.17–47.32). In sample 12/3A, EPMA spot ages ($n = 26$) from analysed monazite range between 490 and 675 Ma yield poorly constrained ages of 521 ± 10 Ma (MSWD = 0.84) and 619 ± 36 Ma (MSWD = 0.31) (figure 7a–c). The statistically significant ages peak at 531 ± 6 Ma (MSWD = 0.68; figure 7d and g), 536 ± 5 Ma (MSWD = 0.80; figure 7e and h) and 535 ± 7 Ma (MSWD = 0.68; figure 7f and i) defined by chemical spot ages of analysed monazite, irrespective of their textural occurrence, from U204 ($n = 46$), U208 ($n = 55$) and U210 ($n = 42$), respectively, are presented in relative probability plot. The P+Y+REE *vs.* Th+U+Si plot of monazite compositions in these samples display clustering along cheralite substitution vector with some scattering towards huttonite substitution vector. In addition to it, a number of spot analyses from sample 12/3A display a well constrained cheralite substitution whereas the remaining spot analyses exhibit huttonite substitution vector with higher values of P+Y+REE and Th+U+Si (figure 8b).

5.3 Xenotime geochronology

Xenotime grains occur as clusters in sample U204 in a matrix of biotite, plagioclase, cordierite and quartz (figure 4a–c). Back-scattered electron images of xenotime display compositional zoning comprising multiple zones (figure 9a–g). Grain ‘b’ in figure 9 preserves high-Th and low-U (0.07 and 0.46 wt%) relict core as compared to a low-Th and high-U (0.06 and 0.51 wt%) rim, which is further rimmed by higher-Th and U (0.07 and 0.58 wt%) containing zone. Relict core in grain ‘c’ (in figure 9) retains low-Th and U (0.03 and 0.41 wt%) content, rimmed by high-Th, high-U (0.06 and 0.54 wt%) mantle. On the contrary, grain ‘f’ in figure 9 preserves U-rich (0.54 wt%) and Th-poor (0.06 wt%) core, surrounded by a U-poor (0.39 wt%) and Th-rich (0.50 wt%) mantle. The rims of the zoned xenotime grains are Th-rich (avg. 0.36 wt%). There is no major chemical variation in Y-content (avg. 33.80 wt%) wherein xenotime grains preserve U-content ranges from 0.51 to 2.22 wt%. Since the xenotime crystals show compositional zoning, a total of 96 spot analyses were performed in distinct zones. Spot analyses yielded individual ages ranging from 445 to 1359 Ma with associated 2σ errors of 31–208 Ma. All the calculated ages from spot analyses were analysed using Isoplot (ver. 4.15, Ludwig 2012) computational software, which

Figure 7. Age probability plots with histograms of obtained ages for monazite (a and d–f), with plots showing respective weighted mean ages from sample 12/3A (a–c), U204 (d and g) U208 (e and h) and U210 (f and i) of Umpyrtha–Patharkhammah area.

furnished statistically significant age probability peaks at 490 ± 11 , 823 ± 41 , 930 ± 36 and 1153 ± 29 Ma presented in relative probability plot (figures 10 and 11). The Th/U *vs.* age plot (figure 12) reveals that xenotime preserving ages of 734–1359 Ma have a very narrow range of Th/U (0.03–0.32), whereas those preserving ages of ~ 500 Ma display a wide range of Th/U ratios (0.05–2.20).

6. Discussion

6.1 Metamorphic evolution

The metamorphic *P–T* estimates of this study corroborate well with the findings of Chatterjee *et al.* (2007, 2011). The spinel inclusions within cordierite most likely indicate the result of the prograde transformation of syn-*S*₁ assemblage Sill + Bt + Qtz = Cord + Kfs + Spinel + melt as an incongruent melting reaction (Chatterjee *et al.*

2007). Syn-*S*₂ symplectitic intergrowth of biotite, sillimanite and quartz (*M*₃ assemblage) at the contact of pre-*S*₂/post-*S*₁ cordierite and K-feldspar indicate hydration reaction at a relatively lower temperature during retrogression stage. This reaction is responsible for dominant fabric forming stage in an intense deformational episode (Chatterjee *et al.* 2007). The garnet–cordierite temperature estimates of $715 \pm 23^\circ\text{C}$ most likely indicate the *M*₄ metamorphic assemblage where cordierite grew at the expense of Grt + Sill + Qtz during decompression reaction.

6.2 Age implications

Monazite in the sample collected from Umpyrtha–Patharkhammah area (U208) provided statistically significant oldest age of 536 ± 5 Ma while monazite in Guwahati area (sample GU102A) yielded the youngest age of 476 ± 12 Ma. Xenotime from Umpyrtha–Patharkhammah area (U204) on the

Figure 8. P + Y + REE (apfu) vs. Th + U + Si (apfu) plots of monazite (a, Kynshi–Umling–Guwahati; b, Umpyrtha–Patharkhammah) showing operation of cheralite–huttonite substitution resulting in their compositional heterogeneity. Note that most of the analysed monazites belong to the cheralite type substitution with a minor huttonite component.

other hand preserves statistically significant ages at 1153 ± 29 , 930 ± 36 , 823 ± 41 and 490 ± 11 Ma. Monazite in the same sample (U204) provided statistically significant age peak at 531 ± 6 Ma. Earlier studies have obtained ubiquitous Pan-African age records (494 ± 6 to 500 ± 14 Ma) in monazite in the basement metapelitic sequence from Sonapahar area in the SMGC (Chatterjee *et al.* 2007, 2011). The predominant Pan-African age records were found to be preserved in monazite grains irrespective of their textural occurrence in the metapelites. The authors obtained scarce older age records of 1472 ± 38 and 1078 ± 31 Ma in monazite cores (Chatterjee *et al.* 2007). Because of annealed nature of the rocks which was possibly caused by the Pan-African high-grade tectonothermal event, as observed during this study also, it is very difficult to ascertain any geological event to the scanty older age records found in monazite. Chatterjee *et al.* (2011) have obtained chemical ages at 1609 ± 9 , 1146 – 946 , 820 ± 21 and 649 – 524 Ma in monazite grains within metapelites in

Figure 9. SEM-BSE images (a–g) of xenotime grains in sample U204 from Umpyrtha–Patharkhammah metapelites illustrating compositional zoning. White circles indicate analysed spots (in Ma). Note the distinct ages preserved by discrete domains within xenotime grains.

Figure 10. Plot showing unmixing ages of xenotime in metapelite sample U204 from Umpyrtha–Patharkhammah area. Four distinct ages (in Ma) were obtained.

the Garo–Goalpara Hills area (western SMGC). While the 1609 ± 9 to 1596 ± 15 Ma age records in the Garo–Goalpara Hills were suggested to correspond to the Palaeo-Mesoproterozoic high-grade metamorphism, the relevance of the younger Neoproterozoic age records preserved in monazite rims is not clear. The preservation of older Neoproterozoic age records at 823 ± 41 , 930 ± 36 and 1153 ± 29 Ma in xenotime in addition to the dominant late

Figure 11. Plots showing weighted mean ages and 2σ errors (for data plotted in figure 10) of xenotime in sample U204 from Umpyrtha–Patharkhammah area.

Figure 12. Th/U *vs.* Age plot for sample U204. Xenotime preserving ages between 734 and 1359 Ma have a very narrow range of Th/U compared to the wide range of Th/U ratio for ~ 500 Ma xenotime.

Cambrian age (490 ± 11 Ma) obtained in the present study indicate episodic growth of xenotime during successive tectonothermal events. The high-grade

late Cambrian (490 ± 11 Ma) metamorphic event reached a peak P – T of ~ 6.5 kb and $\sim 750^\circ\text{C}$, which is similar to the closure temperature for Pb in monazite (Parrish 1990). This high-grade event might have obliterated most of the older age records in monazite in the central SMGC thereby preserving only the latest event. Diffusion experimental studies have suggested that Pb diffusion in xenotime is slower than that in monazite, making xenotime a more Pb retentive mineral (Cherniak 2006). However, it is worth mentioning that the authors have noted that because of the lower activation energy for Pb diffusion in xenotime than monazite, Pb diffusion in xenotime may be faster at temperatures of geologic interest. In a study by Copeland *et al.* (1988), the authors suggest that monazites have remarkably high Pb retention capacity to the extent that even they are found to contain inherited radiogenic Pb from previous sources which were partially dissolved during melting. Thus, the possibility of Pb loss from the monazite, during the Pan-African (~ 500 Ma) high-grade event in

the central SMGC is unlikely. Hence, monazites in the studied samples were most likely formed at only ~ 500 Ma, while xenotimes have formed at successive events. Metapelites in the western SMGC preserve older monazite ages (as shown in figure 1). The textural evidences such as preservation of core and rim in BSE images, patchy zonation and serrated grain boundary preserved in monazite (figure 5) in the central SMGC may indicate recrystallisation of monazite by dissolution–reprecipitation (Putnis 2002). Thus, the absence of the older ages in monazites from the study area may alternatively indicate recrystallisation of the older monazite grains during Pan-African high-grade (granulite) tectonothermal event. Another possibility is that zoning in monazite may have been caused by compositional variation during single metamorphic event at ca. 500 Ma.

The Prydz Bay area in the East Antarctica witnessed a widespread crustal growth episode during the period 1170–910 Ma with associated granulite facies metamorphism (Kinny *et al.* 1993; Wang *et al.* 2005; Carson and Grew 2007; Carson *et al.* 2007; Liu *et al.* 2007b, a). Neoproterozoic sedimentation cover over the ca. 1170–910 Ma basement in the Larsemann Hills (Brattstrand Paragneiss of Fitzsimons 1997), Bolingen Islands and McKaskle Hills (Hensen and Zhou 1995; Zhao *et al.* 1995; Carson *et al.* 2007; Liu *et al.* 2007b) resulted in pelitic and calc-silicate cover sequence, which were later metamorphosed to garnet + sillimanite + cordierite $\pm$ spinel $\pm$ quartz metapelites and wollastonite + scapolite + grossular calc-silicates (e.g., Fitzsimons and Harley 1991; Dirks and Hand 1995). These rocks are similar in mineral assemblage to the Precambrian basement covering most parts of central and western SMGC. The Prydz Bay belt witnessed its latest high-grade event during Ediacaran–Cambrian (ca. 570–510 Ma) recorded as pervasive granulite facies metamorphism (Motoyoshi *et al.* 1991; Nichols and Berry 1991; Zhao *et al.* 1992, 1995; Kinny *et al.* 1993; Hensen and Zhou 1995, 1997; Carson *et al.* 1996; Fitzsimons 1997; Fitzsimons *et al.* 1997; Kelsey *et al.* 2003, 2007; Wang *et al.* 2007; Liu *et al.* 2007b, a). The dominance of Late Cambrian monazite ages in the central SMGC have been suggested to represent the global Pan-African collision event between India and Australia–Antarctica during the East Gondwana assembly (Chatterjee *et al.* 2011). The preservation of 930 ± 36 and 1153 ± 29 Ma age records in xenotime may suggest that India (SMGC) was adjacent to East Antarctica (Prydz

Bay) during the Rodinia amalgamation and associated crustal growth. The rounded nature of the xenotime cores, as observed in BSE image, may indicate their detrital origin which were deposited as cover sediments over the ~ 1170 –910 Ma basement, and were later subjected to multiple metamorphic events at ca. 800 and 500 Ma.

Chatterjee *et al.* (2011) have correlated the 820 ± 21 Ma age preserved in monazite rim from Garo–Goalpara Hills area (western SMGC) to the 876–784 Ma high-grade metamorphism recorded in the N–S oriented EITZ. The preservation of the 823 ± 41 Ma age in xenotime from Umpyrtha–Patharkhammah area indicates the influence of the 876–784 Ma high-grade metamorphic event to further east in the central SMGC. The preservation of multiple ages within xenotime in a single sample furnishing single monazite age (only the latest event) further suggests that xenotime in metapelitic rocks may act as a useful chronometer, especially in poly-metamorphosed terranes.

7. Conclusions

The central SMGC has been affected by several tectonothermal events at ca. 1150, 930, 820 and 500 Ma. While xenotime preserves all of these events, monazite records only the latest suggesting periodic xenotime growth during successive metamorphic events. Monazite in the studied samples merely formed during the latest Pan-African metamorphic (~ 500 Ma) event. However, it may be possible that monazites that had formed in the earlier events recrystallised during ~ 500 Ma high-grade metamorphism. The preservation of 1150–930 Ma age in xenotime within central SMGC indicates its proximity to East Antarctica during Rodinia amalgamation. The preservation of ca. 820 Ma ages within xenotime from central SMGC further indicates the eastward extension of the 820 ± 21 Ma high-grade EITZ metamorphism which has affected the western SMGC (Chatterjee *et al.* 2011). The present study endorses the application of xenotime chemical dating in complexly evolved metamorphic terranes.

Acknowledgements

ACM acknowledges the partial financial support of this work from the University Grant Commission through Major Research Project (MRP) number MRP-MAJOR-GEOL-2013-36821. PB greatly

acknowledges the financial support from the UGC in the form of a research fellowship. All the authors thank Prof Biswajit Mishra for facilitating EPMA analyses in the DST-IIT National EPMA facility, IIT Kharagpur. Dr M K Ozha, Ashim Patel and Saptarshi Sinha are acknowledged for their help during EPMA and SEM analyses. The optical photomicrographs were obtained using microscope-imaging facility established through DST-FIST funding (SR/FST/ESI-152/2016) to the Department of Geological Sciences, Gauhati University. We acknowledge the Editor-in-Chief Prof N V Chalapathi Rao and three anonymous reviewers for their constructive comments, which helped to greatly improve the paper.

References

- Bardoloi A, Mazumdar A C and Chowdhary P K 1994 Polyphase deformation and fold geometry study of the Precambrian Gneissic Complex around Nalanga hill, Goalpara district, Assam; *Indian J. Earth Sci.* **21** 236–246.
- Barooah B C and Goswami I D 1972 Precambrian stratigraphy of the Assam plateau; *J. Mines Metals Fuels.* **20** 368–373.
- Bea R 1996 Residence of REE, Y, Th and U in granites and crustal protoliths; Implications for the chemistry of crustal melts; *J. Petrol.* **37**(3) 521–552.
- Bhattacharjee C C and Baruah N C 1973 The study of joints in relation to the folding episodes in the Pre-Cambrian rocks of the Hahim area; *J. Assam Sci. Soc.* **16** 54–62.
- Bhattacharya A, Mazumdar A C and Sen S K 1988 Fe–Mg mixing in cordierite: Constraints from natural data and implications for cordierite–garnet thermometry in granulites; *Am. Mineral.* **73** 338–344.
- Bhattacharya A, Mohanty L, Maji A K, Sen S K and Raith M 1992 Non-ideal mixing in phlogopite–annite binary; constraints from experimental data on Mg–Fe partitioning and a reformulation of the biotite–garnet geothermometer; *Contrib. Mineral. Petrol.* **111** 87–93.
- Bidyananda M and Deomurari M P 2007 Geochronological constraints on the evolution of Meghalaya massif, north eastern India: An ion microprobe study; *Curr. Sci.* **93** 1620–1623.
- Boger S D, Wilson C J L and Fanning C M 2001 Early Palaeozoic tectonism within the East Antarctic craton: The final suture between east and west Gondwana?; *Geology* **29** 463–466.
- Boniface N, Schenk V and Appel P 2012 Paleoproterozoic eclogites of MORB-type chemistry and three Proterozoic orogenic cycles in the Ubendian Belt (Tanzania): Evidence from monazite and zircon geochronology, and geochemistry; *Precamb. Res.* **192** 16–33.
- Carson C J and Grew E S 2007 Geology of the Larsemann Hills Region Antarctica (1:25000 scale map) (1st edn), Geoscience, Canberra, Australia.
- Carson C J, Fanning C M and Wilson C J L 1996 Timing of the progress granite Larsemann hills: Additional evidence for early Palaeozoic orogenesis within the east Antarctic shield and implications for Gondwana assembly; *Aust. J. Earth Sci.* **43**(5) 539–553.
- Carson C J, Grew E S, Boger S D, Fanning C M and Christy A G 2007 Age of boron- and phosphorus-rich paragneisses and associated orthogneisses, Larsemann Hills: New constraints from SHRIMP U–Pb zircon geochronology; In: *A keystone in a changing world – Online proceedings of the 10th ISAES* (eds) Cooper A K and Raymond C R *et al.*, USGS Open File Report 2007-1047, Extended Abstract **003** 4.
- Chatterjee N 2017 Constraints from monazite and xenotime growth modelling in the MnCKFMASH-PYCe system on the *P–T* path of a metapelite from Shillong–Meghalaya Plateau: Implications for the Indian shield assembly; *J. Metamor. Geol.* **35** 393–412.
- Chatterjee N, Mazumdar A C, Bhattacharya A and Saikia R R 2007 Mesoproterozoic granulites of the Shillong–Meghalaya Plateau: Evidence of westward continuation of the Prydz Bay Pan-African suture into Northeastern India; *Precamb. Res.* **152** 1–26.
- Chatterjee N, Banerjee M, Bhattacharya A and Maji A K 2010 Monazite chronology, metamorphism anatexis and tectonic relevance of the mid-Neoproterozoic Eastern Indian Tectonic Zone; *Precamb. Res.* **179** 99–120.
- Chatterjee N, Bhattacharya A, Duarah B P and Mazumdar A C 2011 Late Cambrian reworking of Palaeo-Mesoproterozoic granulites in Shillong–Meghalaya Gneissic Complex (Northeast India): Evidence from PT pseudosection analysis and monazite chronology and implications for East Gondwana assembly; *J. Geol.* **119** 311–330.
- Cherniak D J 2006 Pb and rare earth element diffusion in xenotime; *Lithos* **88** 1–14.
- Chimote J S, Pandey B K, Bagchi A K, Basu A N, Gupta J N and Saraswat A C 1988 Rb–Sr whole rock isochron age from the Myllem granite, Khasi Hills, Meghalaya; In: *4th National symposium of mass spectrometry*, Bangalore.
- Collins A S and Pisarevsky S A 2005 Amalgamating Eastern Gondwana: The evolution of the Circum-Indian orogens; *Earth Sci. Rev.* **71** 229–270.
- Copeland P, Parrish R R and Harrison T M 1988 Identification of inherited radiogenic Pb in monazite and its implication for U–Pb systematics; *Nature* **333** 760–763.
- Crawford A R 1969 India, Ceylon and Pakistan: New age data in comparison with Australia; *Nature* **233** 380–382.
- Crawford A R 1974 Indo-Antarctica, Gondwana Land and pattern of the distortion of a granulite belt; *Tectonophysics.* **22** 141–157.
- Crowley J L, Chatterjee N, Bowring S A, Sylvester P J, Myers J S and Searle M P 2005 U–(Th)–Pb dating of monazite and xenotime by EMPA, LAICPMS, and IDTIMS: Examples from the Yilgarn Craton and Himalayas; In: *Proceedings of the 15th annual Goldschmidt conference*, Vol. **A19** (Abstracts).
- Dash C R and Chatterjee B 1992 Geology of the Patharkhammah–Umpyrtha, East Khasi Hills district Meghalaya; *Geol. Surv. India Publ.* **125**(4) 24–26.

- Desikachar S V 1974 A review of the tectonic and geological history of eastern India in terms of plate tectonic theory; *J. Geol. Soc. India* **15** 137–149.
- Dirks P and Hand M 1995 Clarifying temperature–pressure paths via structures in granulite from the Bolingen Islands Antarctica; *Aust. J. Earth Sci.* **42**(2) 157–172.
- Dutch R A, Hand M and Clark C 2005 Cambrian reworking of the southern Australian Proterozoic Curnamona Province: Constraints from regional shear-zone systems; *J. Geol. Soc. London* **162** 763–775.
- Evans P 1964 The tectonic framework of Assam; *J. Geol. Soc. India* **5** 80–96.
- Ferry J M and Spear F S 1978 Experimental calibration of the partitioning of Fe and between biotite and garnet; *Contrib. Mineral. Petrol.* **66** 113–117.
- Fitzsimons I C W 1997 The Brattstrand paragneiss and the Sostrene orthogneiss: A review of Pan-African metamorphism and Grenvillian relics in southern Prydz Bay; In: *The Antarctic region, geological evolution and processes* (ed.) Ricci C A, Terra Antarctica Publication, Siena, pp. 121–130.
- Fitzsimons I C W 2000 A review of tectonic events in the East Antarctic shield, and their implications for Gondwana and earlier supercontinents; *J. Afr. Earth Sci.* **31** 3–23.
- Fitzsimons I C W 2003 Proterozoic basement provinces of southern and southwestern Australia, and their correlation with Antarctica; In: *Proterozoic East Gondwana: Supercontinent assembly and breakup* 206 (eds) Yoshida M, Windley B F and Dasgupta S; *Geol. Soc. London Spec. Publ.* **206** 93–130.
- Fitzsimons I C W and Harley S L 1991 Geological relationships in high-grade gneiss of the Brattstrand Bluffs Coastline, Prydz Bay East Antarctica; *Aust. J. Earth Sci.* **38**(5) 497–519.
- Fitzsimons I C W, Kinny P D and Harley S L 1997 Two stages of zircon and monazite growth in anatectic leucogneiss: SHRIMP constraints on the duration and intensity of Pan-African metamorphism in Prydz Bay East Antarctica; *Terra Nova* **9**(1) 47–51.
- Förster H J 1998 The chemical composition of REE–Y–Th–U-rich accessory minerals in peraluminous granites of the Erzgebirge–Fichtelgebirge region, Germany, Part II: Xenotime; *Am. Mineral.* **83** 1302–1315.
- Ghosh S, Chakraborty S, Bhalla J K, Paul D K, Sarkar A, Bishui P K and Gupta S N 1991 Geochronology and geochemistry of granite plutons from East Khasi Hills, Meghalaya; *J. Geol. Soc. India* **37** 331–342.
- Ghosh S, Chakraborty S, Paul D K, Bhalla J K, Bishui P K and Gupta S N 1994 New Rb–Sr isotopic ages and geochemistry of granitoids from Meghalaya and their significance in middle to late Proterozoic crustal evolution; *Ind. Miner.* **48** 33–44.
- Ghosh S, Fallick A E, Paul D K and Potts P J 2005 Geochemistry and origin of Neoproterozoic granitoids of Meghalaya, Northeast India: Implications for linkage with amalgamation of Gondwana Supercontinent; *Gondwana Res.* **8** 421–432.
- Gogoi K 1963 The geology of parts of the Khasi Hills along the southwestern and southeastern extension of the Sonapahar and structure of the main Sonapahar belt, Assam; Unpublished report of Geol. Surv. Intl. Prog.
- Harlov D E, Wirth R and Hetherington C J 2007 The relative stability of monazite and huttonite at 300–900°C and 200–1000 MPa: Metasomatism and the propagation of metastable mineral phases; *Am. Mineral.* **92** 1652–1664.
- Hazarika P, Mishra B and Pruseth K L 2015 Diverse tourmaline compositions from orogenic gold deposits in the Hutti–Maski greenstone belt, India: Implications for sources of ore-forming fluids; *Econ. Geol.* **110** 337–353.
- Hazarika P, Mishra B, Ozha M K and Pruseth K L 2017 An improved EPMA analytical protocol for U–Th–Pb_{total} dating in xenotime: Age constraints from polygenetic Mangalwar Complex, Northwestern India; *Chem. Erde.-Geochem.* **77** 69–79.
- Heinrich W, Andrehs G and Franz G 1997 Monazite–xenotime miscibility gap thermometry. I. An empirical calibration; *J. Metamor. Geol.* **15** 3–16.
- Hensen B J and Zhou B 1995 A Pan-African Granulite-facies metamorphic episode in Prydz Bay Antarctica – Evidence from Sm–Nd garnet dating; *Aust. J. Earth Sci.* **42**(3) 249–258.
- Hensen B J and Zhou B 1997 East Gondwana amalgamation by Pan-African collision? Evidence in the Prydz Bay region, East Antarctica; In: *The Antarctic region, geological evolution and processes* (ed.) Ricci C A, Terra Antarctica Publication, Siena, pp. 115–119.
- Hetherington C J, Jercinovic M J, Williams M L and Mahan K 2008 Understanding geologic processes with xenotime: Composition, chronology, and a protocol for electron probe microanalysis; *Chem. Geol.* **254** 133–147.
- Holdaway M J 2001 Recalibration of the GASP geobarometer in light of recent garnet and plagioclase activity models and versions of the garnet–biotite geothermometer; *Am. Mineral.* **86** 1117–1129.
- Holdaway M J and Lee S M 1977 Fe–Mg cordierite stability in high grade pelitic rocks based on experimental, theoretical and natural observations; *Contrib. Mineral. Petrol.* **63** 175–198.
- Holdsworth R E, Handa M, Miller J A and Buick I S 2001 Continental reactivation and reworking: An introduction; *Geol. Soc. London Spec. Publ.* **184** 1–12.
- Kelly N M, Clarke G L and Fanning C M 2002 A two-stage evolution of the Neoproterozoic Rayner structural episode: New U–Pb sensitive high resolution ion microprobe constraints from the Oygarden Group, Kemp Land, East Antarctica; *Precamb. Res.* **116** 307–330.
- Kelsey D E, Powell R, Wilson C J L and Steele D A 2003 (Th + U)–Pb monazite ages from Al–Mg-rich metapelites, Rauer Group East Antarctica; *Contrib. Mineral. Petrol.* **146**(3) 326–340.
- Kelsey D E, Hand M, Clark C and Wilson C J L 2007 On the application of in-situ monazite chemical geochronology to constraining *P–T–t* histories in high-temperature (>850°C) polymetamorphic granulites from Prydz Bay, east Antarctica; *J. Geol. Soc. London* **164** 667–683.
- Kelsey D E, Wade B P, Collins A S, Hand M, Sealing C R and Netting A 2008 Discovery of a Neoproterozoic basin in the Prydz belt in East Antarctica and its implications for Gondwana assembly and ultrahigh temperature metamorphism; *Precamb. Res.* **161** 355–388.

- Kinny P D, Black L P and Sheraton J W 1993 Zircon ages and the distribution of Archean and Proterozoic rocks in the Rauer Islands; *Antarctic Sci.* **5**(2) 193–206.
- Kretz R 1983 Symbols for rock-forming minerals; *Am. Mineral.* **68** 277–279.
- Kumar S, Rino V, Hayasaka Y, Kimura K, Raju S, Terada K and Pathak M 2017 Contribution of Columbia and Gondwana supercontinent assembly and growth-related magmatism in the evolution of the Meghalaya Plateau and the Mikir Hills, Northeast India: Constraints from U–Pb SHRIMP zircon geochronology and geochemistry; *Lithos* **277** 356–377.
- Lal R K, Ackermann D, Seifert F and Haldar S K 1978 Chemographic relationships in sapphirine-bearing rocks from Sonapahar, Assam, India; *Contrib. Mineral. Petrol.* **67** 169–187.
- Li Z X, Bogdanova S V, Collins A S, Davidson A, De Waele B, Ernst R E, Fitzsimons I C W, Fuck R A, Gladkochub D P, Jacobs J, Karlstrom K E, Lu S, Natapov L M, Pease V, Pisarevsky S A, Thrane K and Vernikovsky V 2008 Assembly, configuration, and break-up history of Rodinia: A synthesis; *Precamb. Res.* **160** 179–210.
- Liu X C, Jahn B M, Zhao Y, Zhao G and Liu X H 2007a Geochemistry and geochronology of high-grade rocks from the Grove Mountains, East Antarctica: Evidence for an Early Neoproterozoic basement metamorphosed during a single Late Neoproterozoic/Cambrian tectonic cycle; *Precamb. Res.* **158** 93–118.
- Liu X C, Zhao Y, Zhao G, Jian P and Xu G 2007b Petrology and geochronology of granulites from the McKaskle Hills, eastern Amery Ice Shelf, Antarctica, and implications for the evolution of the Prydz Belt; *J. Petrol.* **48** 1443–1470.
- Ludwig K R 2012 *Isoplot 4.15: A geochronological toolkit for microsoft excel*; Berkeley Chronological Center, Special Publication, Berkeley, California, Vol. 5.
- Mazumdar S K 1976 A summary of the Precambrian Geology of Khasi Hills, Meghalaya; *Geol. Surv. India Misc. Publ.* **23**(2) 311–334.
- Mitra S K 1998 Structural history of the rocks of the Shillong group around Sohiong, east Khasi hills, Meghalaya; *Indian J. Geol.* **70** 123–131.
- Motoyoshi Y, Thost D E and Hensen B J 1991 Reaction textures in calc-silicate granulites from the Bolingen Islands, Prydz Bay, East Antarctica; implications for the retrograde *P–T* path; *J. Metamor. Geol.* **9**(3) 293–300.
- Nichols G T and Berry R F 1991 A decompressional *P–T* path, Reinbolt Hills, East Antarctica. *J. Metamor. Geol.* **9** 257–266.
- Parrish R R 1990 U–Pb dating of monazite and its application to geological problems; *Can. J. Earth Sci.* **27** 1431–1450.
- Pouchou J L and Pichoir F 1984 A new model for quantitative X-ray microanalyses, Part I: Application to the analyses of homogenous samples; *Recherche Aerosp.* **3** 13–36.
- Powell C M and Pisarevsky S A 2002 Late Neoproterozoic assembly of East Gondwana; *Geology* **30** 3–6.
- Putnis A 2002 Mineral replacement reactions: From macroscopic observations to microscopic mechanisms; *Mineral Mag.* **66** 689–708.
- Rasmussen B 1996 Early-diagenetic REE-phosphate minerals (florencite, gorceixite, crandallite, and xenotime) in marine sandstones: A major sink for oceanic phosphorus; *Am. J. Sci.* **296** 601–632.
- Schenk V, Appel P, Jöns N, Loose D, Schumann A and Wegner H 2005 Pan-African reworking of the northeastern corner of the Congo Craton in Uganda; In: *Supercontinents and earth evolution symposium* (eds) Wingate M T D and Pisarevsky S A, *Geol. Soc. Australia* **100** 81.
- Spear F S 1993 *Metamorphic phase equilibria and pressure-temperature-time paths*; Mineralogical Society of America, Washington DC, 799p.
- Spear F and Pyle J 2002 Apatite, monazite, and xenotime in metamorphic rocks; In: *Phosphates: Geochemical, geobiological, and materials importance. Reviews in mineralogy and geochemistry* (eds) Kohn M L, Rakovan J and Hughes J M, Mineralogical Society of America, Washington, pp. 293–335.
- Spear F S, Pyle J M and Cherniak D 2009 Limitations of chemical dating of monazite; *Chem. Geol.* **266** 218–230.
- Suzuki K and Adachi M 1991 Precambrian provenance and Silurian metamorphism of the Tsubonosawa paragneiss in the South Kitakami terrane, Northeast Japan, revealed by the chemical Th–U–total Pb isochron ages of monazite, zircon and xenotime; *Geochem. J.* **25** 357–376.
- Suzuki K and Kato T 2008 CHIME dating of monazite, xenotime, zircon and polycrase: Protocol, pitfalls and chemical criterion of possibly discordant age data; *Gondwana Res.* **14** 569–586.
- Torsvik T H, Carter L M, Ashwal L D, Bhushan S K, Pandit M K and Jamtveit B 2001 Rodinia refined or obscured; palaeomagnetism of the Malani igneous suite; *Precamb. Res.* **108** 319–333.
- Van Breemen O, Bowes D R, Bhattacharjee C C and Chowdhary P K 1989 Late Proterozoic–Early Paleozoic Rb–Sr whole rock and mineral ages for granite and pegmatite, Goalpara, Assam, India; *J. Geol. Soc. India* **34** 89–92.
- Wang Y, Liu D, Ren L and Williams I S 2005 Geochemical characteristics and ion microprobe age of the mafic granulites from the Larsemann Hills, east Antarctica; *Geochim. Cosmochim. Acta* **69**(10) A292 (Suppl.).
- Wang Y, Tong L and Liu D 2007 Zircon U–Pb ages from an ultra-high temperature metapelite, Rauer Group, east Antarctica: Implications for overprints by Grenvillian and Pan-African events. In: *A keystone in a changing world – Online proceedings of the 10th ISAES, USGS Open File Report 2007-1047* (eds) Cooper A K and Raymond C R, Short Research Paper **023** 4.
- Wark D A and Miller C F 1993 Accessory mineral behavior during differentiation of a granite suite: Monazite, xenotime, and zircon in the Sweetwater Wash pluton, southwestern California, USA; *Chem. Geol.* **110**(1–3) 49–67.
- Wells P R A and Richardson S W 1980 Thermal evolution of metamorphic rocks in the Central Highlands of Scotland; In: *Caledonides of the British Isles – Reviewed* (eds) Harris A L, Holland C H and Leake B E, *Geol. Soc. London Spec. Publ.* **8** 339–344.
- Williams M L, Jercinovic M J and Hetherington C J 2007 Microprobe monazite geochronology: Understanding geologic processes by integrating composition and chronology; *Ann. Rev. Earth Planet. Sci.* **35** 137–175.

- Wu C M, Zhang J and Ren L D 2004 Empirical garnet–biotite–plagioclase–quartz (GBPQ) geobarometry in medium- to high-grade metapelites; *J. Petrol.* **45** 1907–1921.
- Yin A, Dubey C S, Webb A A G, Kelty T K, Grove M, Gehrels G E and Burgess W P 2010 Geologic correlation of the Himalayan orogen and Indian Craton: Part I. Structural geology, U–Pb zircon geochronology, and tectonic evolution of the Shillong Plateau and its neighbouring regions in Northeast India; *Geol. Soc. Am. Bull.* **122** 336–359.
- Zhao Y, Song B, Wang Y, Ren L and Chen T 1992 Geochronology of the late granite in the Larsemann Hills, east Antarctica; In: *Recent progress in Antarctic Earth Science* (eds) Yoshida Y, Kaminuma K and Shiraishi K, Terra Scientific Publishing Company, Tokyo, pp. 155–161
- Zhao Y, Liu X H, Song B, Zhang Z Q, Li J L, Yao Y P and Wang Y B 1995 Constraints on the stratigraphic age of metasedimentary rocks from the Larsemann Hills, East Antarctica: Possible implications for Neoproterozoic tectonics; *Precamb. Res.* **75**(3/4) 175–188.

Corresponding editor: N V CHALAPATHI RAO