CHAPTER 9

GEOCHRONOLOGY

U-Pb radiometric dating of zircon was carried out from the representative samples of the aluminous granulite, migmatitic felsic gneiss, felsic augen gneiss, coarse-grained charnockite and the fine-grained charnockite gneiss of the study area using Sensitive High-Resolution Ion Microprobe (SHRIMP). Additionally, U-Th-total Pb chemical dating of monazite was also carried out on samples of the aluminous granulite, migmatitic felsic gneiss and the felsic augen gneiss using Electron Microprobe (EPMA). The obtained dates and ages in relation to the respective monazite and zircon domains are discussed below in detail.

9.1 Sample description

Samples used for geochronological analyses have been collected from outcrop locations around the Phulbani town (Figs. 9.1, 9.2). The salient petrographical characteristics of all the samples are presented in Table 9.1. All the analyzed samples are briefly described in the following sections.

9.1.1 Aluminous granulite (Samples PH 10A1, PH 10A3, PH 35A2)

These samples were collected from the central part of the study area (Fig. 9.2) where the N-S trending mylonitic foliation (S_{4S}) is conspicuous in aluminous granulite and associated migmatitic felsic gneiss. The rock contains spinel, garnet, corundum, sillimanite, quartz, K-feldspar, plagioclase and biotite with zircon, monazite and apatite as accessory minerals. The peak UHT mineral assemblage is present in this rock and defined by garnet + spinel + sillimanite + quartz that stabilized from a garnet- and corundum-bearing mineral assemblage at about

1000ºC at 8 kbar pressure (Table 9.1). Skeletal intergrowth of spinel and quartz replacing garnet and sillimanite occurs along the composite S_2/S_3 gneissic fabric in the aluminous granulite (Fig. 9.3a) and marks the onset of UHT metamorphism (M_2). A double-layer corona of sillimanite and garnet separating spinel from the matrix quartz possibly developed during near isobaric cooling (M_{2R}) following the peak-M_2 stage of metamorphism at 917–964°C (Table 9.1). Such coronal sillimanite and garnet show stretching along the S_{4S} mylonitic foliation forming thread-like structure (Fig. 9.3b). Matrix biotite appeared at a later stage of retrogression (M_{2R}: 643–679°C). Quartz and K-feldspar grains of the mylonitized aluminous granulite are recrystallized. The K-feldspar grains are additionally stretched and surrounded by recrystallized grains. The aluminous granulite samples contain primary fluid inclusions which are present within garnet, sillimanite and quartz. Raman spectral characters indicate that these inclusions are dominantly composed of CO_2 (Table 9.1).

9.1.2 Migmatitic felsic gneiss

The sample PH 10GM4 was collected from the same location of the aluminous granulite described above. This rock occurs as host to the aluminous granulite and the latter rock is present as small to big lenses or bands within the former. Apart from these, detached lenses and layers of mafic granulite are present within the migmatitic felsic gneiss. The strong N–S trending mylonitic foliation (S_{4S}) is developed in this rock too. This rock contains K-feldspar, plagioclase, garnet, sillimanite and biotite as major minerals while zircon, monazite and apatite occur as accessory phases. The mylonitic foliation (S_{4S}) of this rock is defined by alternate quartzofeldspathic and biotite-sillimanite±quartz-rich layers (Fig. 9.3c). This biotite-bearing assemblage was formed at 468−713ºC leading to breakdown of garnet during retrograde metamorphism (late M_{2R}; Table 9.1). The quartzofeldspathic layers are characterized by dynamically recrystallized K-feldspar grains showing elongation along S_{4S} with the development of core-mantle microstructure (Fig. 9.3d). Garnet, quartz and K-feldspar contain high density (up to 1.02 gm/cm^3) CO_2-rich fluid inclusions (Table 9.1).

The sample PLB69A/1 was collected from western part of the RSZ (Fig. 9.1).This rock is composed of garnet, K-feldspar, quartz with minor amount of biotite and ilmenite and has a conspicuous mylonitic foliation (S_{5S}). In this rock, the mylonitic foliation is defined by deformed K-feldspar and quartz grains (Fig. 9.3e). The K-feldspar grains are recrystallized and the mutual boundaries of the recrystallized grains appear to be straight. Quartz grains dominantly form ribbons which are parallel to the mylonitic foliation. Ilmenite grains typically mimic the grain boundaries of the recrystallized K-feldspar grains. The amount of biotite is low in this rock and usually occurs around garnet.

9.1.3 Felsic augen gneiss (Sample RP 11)

The sample RP 11 was collected from eastern segment of the RSZ. This rock contains porphyroblasts of perthitic K-feldspar that occur as augen within a recrystallized quartzofeldspathic matrix (Fig. 9.3f) where biotite is occasionally present. Garnet grains are sporadic in appearance and are dominantly brecciated. Apatite, zircon and monazite occur as accessory minerals. This rock has the appearance of porphyritic granite when it occurs away from the RSZ. While within the shear zone, it shows pervasive deformation with the development of a broadly E–W trending mylonite foliation (S_{5S}).

9.1.4 Coarse-grained charnockite (Samples PH 9 and PH 10C)

The coarse-grained charnockite samples were collected from two locations. Sample PH 10C was collected from the same location of the aluminous granulite and the migmatitic felsic gneiss samples, while the sample PH 9 was collected 5 km away from the ductile shear zone (Fig. 9.1). The rock contains K-feldspar, plagioclase, orthopyroxene, garnet, ilmenite and biotite with zircon and apatite as accessory minerals and has a crude gneissic foliation (S_4) which is defined by orthopyroxene and elongated K-feldspar grains. The felsic layers are constituted of dynamically recrystallized quartz and K-feldspar while mafic layers are composed of garnet, orthopyroxene, hornblende and biotite. Plagioclase shows oscillatory zoning indicating the igneous origin of this rock (Fig. 9.3g). Orthopyroxene and ilmenite grains are surrounded by corona and intergrowth of garnet and quartz at the contacts of plagioclase (Fig. 9.3h) which resulted during near isobaric cooling at 681–693°C at 6.2 kbar pressure (Table 9.1). Garnet, quartz, K-feldspar and plagioclase contain CO_2-rich high density (up to 1.02 gm/cm^3) primary fluid inclusions (Table 9.1).

9.1.5 Fine-grained charnockite gneiss (Sample PH 46B)

This sample was collected from a river section situated at the north of Phulbani town where this rock is found to be deformed along with the associated migmatitic felsic gneiss (Fig. 9.1). The gneissic foliation (S_3) in both the rocks shows broadly E–W trend. This rock is composed of K-feldspar, plagioclase, orthopyroxene, ilmenite, quartz, hornblende, biotite and/or garnet as major minerals while zircon and apatite as accessory minerals. The gneissic foliation of this rock is defined by alternate mafic and felsic layers. Stretched orthopyroxene and ilmenite grains constitute the mafic layers while the felsic layers are composed of quartz, K-feldspar and plagioclase. An intergrowth of garnet and quartz occurs around orthopyroxene and ilmenite at their contact with plagioclase (Fig. 9.3i) which possibly developed during cooling (M_{2R}) at 735−770ºC at 6.4−6.8 kbar (Table 9.1).

9.2 Methodology

For zircon analysis, samples were prepared by crushing and milling followed by water separation, sieving, heavy liquid separation and Franz magnetic barrier separation at Presidency University following the processes detailed in Saha et al. (2016). Utmost care was taken to avoid cross contamination during sample preparation. Zircon grains were selected and handpicked for mounting at Hiroshima University. Epoxy mounts were prepared with sample zircon grains and standard Duluth gabbroic anorthosite zircon (FC1) having an age of 1099±0.6 Ma (Paces and Miller, 1993). Subsequently, the mounts were polished and gold coated for observation under the JEOL Scanning Electron Microscope (SEM) at the Hiroshima University. Backscatter electron (BSE) and Cathodoluminescence (CL) imaging was done for each zircon grain to study the internal morphology as well as to assess fractures and metamictized zones in analyzed grains. SEM-CL images of selected zircon grains are shown in figures 9.4a-r. Zircon analysis for U-Pb dating was done at the Hiroshima University with the SHRIMP-IIe facility in two analytical sessions. A combination of backscattered electron and Cathodoluminescence images were used to select the sites for SHRIMP analysis. The experimental conditions and the procedures followed for the measurements were based on Williams (1998) and also detailed in Das et al. (2017c). The spot size of the primary ion beam was approximately 20 µm. The common Pb correction was made on the basis of the measured ^{204}Pb and the model for common Pb compositions proposed by Stacey and Kramers (1975). External zircon standard (SL13) was used to measure U contents. This standard material is reported to contain 238 ppm (U-Pb age 572 Ma; Claue-Long et al., 1995). Obtained U-Pb data were reduced in a manner similar to that described by Williams (1998) using CONCH software (Nelson, 2006). The measured value of the FC1 standard for the analytical session is 1097±5 Ma (n=7; MSWD = 0.50). Each of the seven mass scan cycles were used following the standard procedure for SHRIMP analysis as detailed in Williams (1998). The CONCH generated data for all the samples are quoted in the Table 9.2 with 1σ uncertainty and plotted in Wetherill diagram to obtain group ages. A value of 0.5 was taken as correlation coefficient for all the plots.^{206}Pb/^{238}U, ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb spot dates in the data table are corrected for ^{204}Pb as mentioned above. For calculating group ages, a ±5% discordancy cut-off was considered from the processed data. In the result section (section 9.3), all the weighted mean ages obtained from different samples are quoted as ^{207}Pb/^{206}Pb ages. Group ages could not be calculated from some samples, and in such cases, only the individual ^{207}Pb/^{206}Pb dates are reported.

Texturally constrained monazite grains were analyzed from the aluminous granulite (samples PH10A1, PH10A3, PH35A2), migmatitic felsic gneiss (sample PH10GM4, PLB 69A/1) and felsic augen gneiss (RP 11) to determine the ages of tectonothermal imprints including the peak UHT metamorphism. All the grains were analyzed for U-Th-total Pb concentrations by JEOL JXA 8200 Superprobe at the Natural Science Center for Basic Research and Development (N-BARD), Hiroshima University. The operating conditions were 15 kV accelerating voltage, 200 nA beam current and 2-3μm beam diameter. The following 16 lines Al-K$_\alpha$, Si-K$_\alpha$, P-K$_\alpha$, S-K$_\alpha$, Ca-K$_\alpha$, Y-L$_\alpha$, La-L$_\alpha$, Ce-L$_\alpha$, Pr-L$_\beta$, Nd-L$_\beta$, Sm-M$_\beta$, Gd-M$_\beta$, Dy-M$_\beta$, Pb-M$_\beta$, Th-M$_\alpha$, and U-M$_\beta$ were measured, and then quantified as oxide by ZAF correction. The measurements of Pb-M$_\beta$ were carried out by a high-sensitive detector (R = 100 mm). The interferences of Th-M$_{\gamma}$ on U-M$_{\beta}$ and U-M$_{\zeta}$ on Pb-M$_{\beta}$ were corrected. Correction for Nd-L$_{\beta 1}$ due to Ce-L$_{\beta 2}$ has also been done. Standard materials are ThO$_2$ compound silicate glass and natural thorianite for Th, U$_3$O$_8$ compound silicate glass and natural uraninite for U and Pb–Te for Pb. The peak intensities of Th, U, and Pb were integrated for 60, 120, and 440 s, respectively. The detection limit of Pb at the 2σ confidence level is of the order of 45 ppm, and the measurement errors of PbO are 55 ppm for 0.05 wt.% level, and 66 ppm for 0.5 wt.% level, respectively. Details of the followed procedures are described in Fujii et al. (2008) and Das et al. (2015). Basic principle of age dating using the U-Th-total Pb technique was developed by Suzuki and Adachi (1991). However, the age calculation was carried out by employing improved method of Cocherie and Albarede (2001) and plotted by Isoplot/Ex version 3.7 (Ludwig, 2012). The consistency of age data was checked using a standard monazite having ID-TIMS age of 1033 Ma (cited in Hokada and Motoyoshi, 2006). During analysis, this standard monazite yielded a weighted mean age of 1036±12 Ma (MSWD=1.02; n=6). Results of all the analyses are presented in Table 9.3. Uncertainties in the individual analysis and weighted mean ages are quoted at 95% confidence level. BSE images of the analyzed monazite were checked to study the zoning pattern and spot selection. X-ray maps were generated for elements U, Th and Y for representative monazite grains.

The uncertainties of weighted-mean SHRIMP zircon and EPMA monazite dates presented here are 1σ and 2σ error of the weighted means respectively. These uncertainties reflect the precision to which the weighted means can be calculated as a function of analytical uncertainties and the number of analyses used to calculate the means, but should not be considered the absolute accuracy to which the dates are known. It is important for comparing dates from different minerals in different rocks-measured in different analytical sessions, in different laboratories, or by different techniques (EPMA vs SHRIMP in this study). This has been demonstrated by many workers (Schmitt and Vasquez, 2017 for SHRIMP, Spear et al., 2009 and Williams et al., 2017 for EPMA). Based on these studies, the accuracy of SHRIMP and EPMA dates presented in this study should be considered to be ca. 1–2%. The important dates and ages obtained from the zircon and the monazite grains are summarized in Table 9.4.

9.3 Results

9.3.1 Zircon morphology

The analyzed zircon grains of the present study are characterized by interior domains and overgrowth domains. Textural variations exist within the interior domains. Conspicuous oscillatory zoning is present within such domains in zircons of coarse-grained charnockite and felsic augen gneiss. Apart from this, interior or core domains of some grains are xenocrystic. The xenocrystic zircon domains are characterized on the basis of the structures revealed in CL images. Generally, a xenocrystic zircon is distinguished by the presence of irregular surfaces around it or internal zoning which is truncated by overgrowth. The overgrowth domains either have CL characters different than the xenocrystic interior domains or have growth bands which are clearly visible in CL images. Oval shaped zircon cores in some samples are interpreted as detrital in origin. Some zircon grains of aluminous granulite and fine-grained charnockite gneiss samples do not contain core-rim structure and their interior domains appear to be homogenous without any morphological contrasts. The overgrowth domains of zircon grains of the analyzed samples occasionally occur surrounding the interior domains mentioned above. These overgrowth domains mantle the interior domains and are characterized by planar zoning and inwardly curved boundaries. In some zircon grains, convolute zones also occur within the overgrowth domains. Zircon morphologies of the individual samples are described in details below.

Most of the zircon grains of coarse-grained charnockite (sample PH 10C) are euhedral, elongated in shape with high aspect ratio. Grains have interior domains with moderate- to dark-CL characters followed by bright-CL thin (up to 30 µm) overgrowth (Figs. 9.4a-d). Faint oscillatory zoning is often present at the edge of these interior domains (Fig. 9.4c). Occasionally, bright-CL overgrowth domains are projected inward into these regions as irregular convolute zones. Zircon grains of the sample PH 9 are also elongated with high aspect ratio like zircon grains of the sample PH 10C. All the grains have low- to moderate-CL weakly oscillatory zoned interior (Figs. 9.4e, f) surrounded by a thin (up to 20 µm) highly luminescent overgrowth. Spots and patches of the luminescent zircon are also present at the low-CL interior part in some grains. The overgrowth domain locally forms inwardly curved convolute zones.

Zircon grains of fine-grained charnockite gneiss (sample PH 46B) are prismatic in shape (Figs. 9.4g-i). Few elliptical grains are also present. Most of the grains are characterized by bright-CL xenocrystic cores (Figs. 9.4g, h) which are surrounded by dark-CL featureless overgrowths. Relics of moderate-CL zircon interior are present within some zircon grains (Fig. 9.4i). These moderate-CL domains are mostly unzoned and occasionally surrounded by thin bright-CL overgrowths.

Zircon grains of aluminous granulite (samples PH 10A1 and PH 35A2) are elliptical to circular in shape and up to 60 µm along the maximum dimension. Most of the grains are characterized by moderate- to dark- CL homogeneous interior domains, which in few cases, are overgrown by narrow bright-CL overgrowths (Figs. 9.4j, k). Zircon grains with bright-CL detrital cores are also present (Fig. 9.4j).

Most of the zircon grains of the felsic augen gneiss (sample RP11) are euhedral and characterized by prominent oscillatory zoning (Figs. 9.4l-n). These oscillatory-zoned domains are occasionally surrounded by a thin dark-CL featureless overgrowth zone that appears as a transgressive front into the oscillatory zoned domains (arrow in figure 9.4m). Due to very low luminescence, these zones hardly reveal any structure. However, faint traces of oscillatory zoning are locally preserved within these domains (arrowhead in figure 9.4m). Most of the grains have an outermost bright-CL narrow (up to 25 µm) overgrowth zone with characteristic inward moving boundaries. Zircon grain having dark-CL interior is also present in this sample which possibly formed due to partial replacement of the core (arrow in figure 9.4o).

Zircon grains of migmatitic felsic gneiss (sample PH 10GM4) are short- or long-prismatic in shape (Figs. 9.4p-r). Few grains contain xenocrystic cores (Figs. 9.4p, q) with a surrounding dark-CL featureless overgrowth. The latter is often flanked by a thin (up to 10µm) bright-CL overgrowth with planar zoning (white arrow in figure 9.4p). Grains can be grouped in two major morphological types depending upon the CL response. Some contain bright-CL interiors successively surrounded by thin dark-CL and bright-CL overgrowths. It is important to note that the width of these bright-CL and dark-CL overgrowths altogether are smaller than the beam diameter hence analytical spots from these overgrowths always overlapped both of these zones. The other grains have dark-CL prismatic cores with a bright-CL overgrowth (Fig. 9.4r). However, the structure of this prismatic core is obscured because of the low-CL response.

9.3.2 Zircon U-Pb analytical data

Coarse-grained charnockite

Sample PH 10C: Out of 16 points analyzed from 13 grains, 12 points were selected from the dark-CL interior domains and the rest were selected from the bright-CL overgrowths. U and Th contents in the moderate- to dark- CL domains vary widely between 189–2509 ppm and 105–543 ppm respectively (Th/U = 0.13–0.79). Data from this group yield a weighted mean age of 970±6 Ma (n= 7, MSWD=0.33; Fig. 9.5a). A single point (analysis no. 4) from the same dark-CL oscillatory-zoned interior with convolutions projected from overgrowth yields much younger date of 912 ± 5 Ma with high reverse discordance (>10%), and not considered for group age calculation. U and Th contents of the bright-CL overgrowth domains vary within the range of 291–1321 ppm and 86–215 ppm respectively with Th/U ratio 0.13–0.67. Four points were analyzed from such domains and yield spot dates of 919±22 Ma, 915±10 Ma, 956±14 Ma and 960±7 Ma.

Sample PH 9: A total of 9 points were analyzed only from the weakly oscillatory zoned interior domains of the same number of zircon grains. U and Th contents vary widely in the range of 63–1065 ppm and 164–609 ppm, respectively (Th/U = 0.15–3.01). Out of these, 7 spot dates spanning 994±11 Ma to 944±12 Ma yield a weighted mean age of 973±19 Ma (n=7; Fig. 9.5b). It is worth noting that the MSWD of the weighted mean age of 973±19 Ma is calculated to be 2.6 which is greater than the maximum permissible value (Wendt and Carl, 1991). Because of this, the age is henceforth described as ca. 973 Ma. One single spot having date of 969±95 Ma from the oscillatory-zoned core was not considered during calculation of the ca. 973 Ma age because of high error (Table 9.2). Additionally, spot date of 950±15 Ma from the same interior domain was also not considered during calculation of the group age because of slight discordancy (92%) of the same.

Fine-grained charnockite gneiss

Sample PH 46B: Out of the 11 points analyzed from 10 grains, 2 spots (analysis nos. 3 and 6; Table 9.2) from the bright-CL xenocrystic cores have 166 and 189 ppm U and 74 and 100 ppm Th with Th/U ratios of 0.44 and 0.52 respectively. Spot dates calculated from these two points are 1190±18 Ma and 1165±25 Ma respectively (Fig. 9.5c). The rest of the points belong to the moderate-CL interior domains and dark-CL overgrowths surrounding the bright-CL xenocrystic cores. U and Th contents of the moderate-CL interior domains vary in the range of 799–2127 ppm and 197–311 ppm respectively (Th/U=0.14–0.37). Two spots (analysis nos. 5 and 7; Table 9.2) from the moderate-CL domain are nearly concordant and yield spot dates of 1016±14 Ma and 1024±6 Ma. Three other spots from the similar zircon domain yield 958±10 Ma, 966±10 Ma and 960±9 Ma dates. U and Th contents of the dark-CL overgrowths surrounding the bright- CL xenocrystic cores vary within the range 1314–2460 ppm and 197–274 ppm respectively (Th/U= 0.11–0.19). Out of the 4 spots analyzed from this domain, 2 spots yield 1113±9 and 1156±6 Ma dates. The other 2 spots yield spot dates of 947±9 and 1012±8 Ma. No group age could be calculated from the core or overgrowth zircon since the analyses show high scatter. It appears that the xenocrystic cores formed at ca. 1190–1165 Ma, while moderate-CL interior domains and overgrowth formed by metamorphic processes in the time frame of ca. 1024–947 Ma.

Aluminous granulite

Samples PH 10A1 and PH 35A2: The analyzed zircon grains from these two samples of aluminous granulite are described together as these samples have same mineralogy and reaction texture and interpreted to have same evolutionary history. Out of 11 points analyzed from the same number of grains, 10 points belong to the moderate- to dark-CL interior domains which have U and Th contents within the range 568–1338 ppm and 68–139 ppm respectively (Th/U=0.05–0.17). Such domains have dates in the range of 1026±10 to 900±9 Ma (Fig. 9.5d). However, a much older highly discordant date of 1765±5 Ma was also calculated from this domain. A single zircon grain having bright-CL detrital core is also analyzed which has U and Th contents 209 and 85 ppm respectively with much higher Th/U ratio of 0.40. This detrital core yields concordant date of 1136±14 Ma. Although no group age has been calculated from the analyzed zircon grains of this sample, the spread of dates suggests that major zircon growth occurred during ca. 1026–900 Ma, possibly during metamorphism.

Felsic augen gneiss

Sample RP 11: 15 points were analyzed from 13 grains from this sample. Out of these, 10 spots are located at the oscillatory zoned domains yielding spot dates within the range of 1192±10 Ma to 1154±10 Ma with a weighted mean age of 1173±12 Ma (n=9; Fig. 9.5e). U and Th contents of the spots vary within the range of 310–4939 ppm and 59–307 ppm respectively (Th/U=0.06–0.27). It is important to note that the MSWD of the weighted mean age of 1173±12 Ma is calculated to be 2.8 which is greater than the maximum permissible value (Wendt and Carl, 1991) and thus described as ca. 1173 Ma. Additionally, two relatively younger spot dates of 1097±18 Ma and 1095±12 Ma were measured from the same oscillatory zoned domains with U content 314 ppm and 515 ppm and Th content 79 ppm and 81 ppm respectively. A single spot analysis from an overgrowth which surrounds an oscillatory zoned interior has U and Th contents 175 ppm and 67 ppm respectively. The measured spot date is concordant with the value of 1104±25 Ma. Another spot that overlaps the oscillatory-zoned domain and the bright-CL overgrowth yields slightly discordant ^{207}Pb/^{206}Pb date of 1038±13 Ma with U and Th content 560 ppm and 61 ppm (Th/U=0.10). A much younger spot date of 977±11 Ma is also calculated from the dark-CL interior part of a zircon grain with U and Th content 2096 and 13 ppm (Th/U=0.006). Ca. 1173 Ma age calculated from the oscillatory zoned zircon domains best reflects the crystallization age of the granitic protolith. Spot dates in the range ca. 1104–977 Ma possibly indicate variable resetting of older zircon by later metamorphism.

Migmatitic felsic gneiss

Sample PH 10 GM4: Excepting two, all the analyzed spots show weak to moderate reverse discordance (105%–121%; Table 9.2). Given the scenario, only the spot dates are reported from this sample. Out of 12 spots from 10 grains, 3 spots (spots 4, 8, 11) were analyzed from the bright-CL interior domains. Of these, 2 spots (spots 4, 8) are xenocrystic in nature and have similar U (207–214 ppm) and Th (138–158 ppm) contents with spot dates 1117±24 Ma and 1133±22 Ma (Fig. 9.5f). The other spot from the same domain shows similar U (238 ppm) and Th contents (114 ppm) with a younger date of 983±20 Ma. One dark-CL prismatic core shows the spot date of 976±7 Ma. The overgrowth zones have both dark- and bright-CL responses with U and Th contents in the range of 640–1277 ppm and 5-234 ppm respectively (Th/U = 0.005–0.28). Spot dates from these zones lie within the range of 863±13 Ma to 987±14 Ma with a weighted mean age of 949±15 Ma (n=7, MSWD=2.2; Fig. 6f). The results show that the xenocrystic cores have spot dates in the frame of ca. 1133−1117 Ma, while the overgrowth was formed at 949±15 Ma, possibly due to metamorphism.

9.3.3 Monazite U-Th-total Pb data

Aluminous granulite

Samples PH10A1, PH10A3 and PH35A2: A total of 19 grains were analyzed from these three samples. Analyzed monazites grains show two broad textural modes; e.g. (1) as inclusions within porphyroblastic garnet and (2) part of the matrix composed of sillimanite, K-feldspar, quartz, plagioclase and/or biotite. Monazite grains which are included within porphyroblastic garnet are very small (up to 30 µm long) rounded to oblate in shape while the matrix monazite grains are bigger (up to 50µm long) showing elongate shape with occasional irregular outer boundaries. Although the matrix monazite grains show complex zoning, the included ones are mostly unzoned. The zoning pattern in the latter is broadly concentric with Th-rich cores followed by gradual depletion of this element (Fig. 9.6a). The peripheral part shows enrichment of Y. Spot dates of monazite grains from both the matrix and the inclusions vary within the range of ca. 700 to 1000 Ma (Fig. 9.6b). Spot dates from the included monazite grains and the Th-rich core of the matrix monazite grains constitute a population with a weighted mean age of 987±6 Ma (n=19, MSWD=0.29) (Fig. 9.6c). Another group of data yields a weighted mean age of 966±4 Ma (n=37, MSWD=0.60) from the Th-rich cores of the matrix monazite grains. Out of a total of 29 points analyzed from the overgrowth domains of the matrix monazite grains, three distinct populations were identified with weighted mean ages of 939±10 Ma (n=11, MSWD=0.13), 894±13 Ma (n=10, MSWD=1.18) and 781±15 Ma (n=8, MSWD=1.3) (Figs. 9.6d, e, f). Although spot data for each of these populations show similar U and Th contents, the 894±13 Ma and

781±15 age domains are located only at the Y-rich rims of the matrix monazite grains. A single spot from the exterior part of matrix monazite gives 701±39 Ma date.

Felsic augen gneiss

Sample RP 11: Monazite grains of this sample measure 50-150 µm along their maximum dimension. Three monazite grains which occur within the mylonitic matrix composed of recrystallized quartz, K-feldspar and plagioclase were analyzed. Additionally a single monazite included within a brecciated garnet was also analyzed. X-ray mapping of one matrix monazite (Fig. 9.6g) shows that the interior of the grain is homogenous in Th, but there are patches of high-U, Th and Y at the grain interior as well as at the margins. A total of 19 points were analyzed that yield dates between 535±17 Ma and 899±14 Ma (Fig. 9.6h). The dominant mean age recorded from these monazite is 831±11 Ma (n=9, MSWD= 2.4) (Fig. 9.6i). Apart from an older date of 899±14 Ma, rest of the spot dates from matrix monazite lie between 658 ±18 Ma and 790±18 Ma. A small matrix monazite grain has spot dates from 535±17 to 551±17 Ma. A spot date of 558±19 Ma is also recorded from the periphery of a monazite grain with ca. 831 Ma core.

BSE image of the included monazite (Fig. 9.6j) indicate presence of vein-like features which cross-cut the grain in a random fashion. X-ray mapping of the same monazite (Fig. 9.6k) reveals that the interior is depleted in U and Y but enriched in Th content and the veins are Th-rich (arrow in figure 9.6k). Because of the presence of such veins, the grain appears to have polygonal domains which are otherwise unaffected. Micro-pores are invariably present along such Th-rich veins and locally connected with each other to produce larger pores. A total of 14 points were analyzed from the included monazite out of which 9 spots belong to the polygonal domains and 5 spots belong to the Th-rich veins. In the former case, spot dates vary within the range of 960±20 Ma to 748±18 Ma (Fig. 9.6l). A much younger spot date of 595±13 Ma was also obtained from the same domain. In the latter case spot dates lie within the range of 907±19 Ma to 619±17 Ma (Fig. 9.6l).

Migmatitic felsic gneiss

Sample PH10GM4: Two monazite grains set in the quartzofeldspathic matrix of the migmatitic felsic gneiss were analyzed (Figs. 9.6m, n). These grains are larger in size (up to 200 µm; Figs. 9.6o, p) compared to the monazite grains of the aluminous granulite and are characterized by Th and Y zoning (Figs. 9.6q, r). Some grains even show traces of oscillatory zoning of Th at the core (Fig. 9.6q). The core regions of these monazite grains are Th-rich and Y-poor and are surrounded by a Th-poor overgrowth. Y-rich patches at the rim regions are also noteworthy. Out of a total of 36 points analyzed from these monazite grains, two distinct age populations were noted. An older age of 968±4 Ma (n=30, MSWD=0.51) (Fig. 9.6s) was calculated from data points dominantly from the Th-rich, Y-depleted cores. However, the Y-rich patches also yield spot dates of ca. 968 Ma. Spot dates that define a younger age of 942±10 Ma (n=5, MSWD=0.42) are only present at the Y-rich patches. No younger population was noted except a single spot date of 885±24 Ma.

Sample PLB69A/1: Seven monazite grains of this sample were analyzed. Out of the analyzed monazite grains, two grains are included within the porphyroblastic garnet and rest of the grains occurs within the quartzofeldspathic matrix. The included monazite grains are smaller in size (maximum length is up to 150 µm) with respect to the matrix monazite (up to 300 µm along the maximum length). Interior domains of the matrix monazite grains are characterized by patchy zoning (Fig. 9.6t). Such zoning pattern is defined by differences in Y content. Interior domains having such zoning pattern are commonly surrounded by Th-rich overgrowth. It is important to mention that the included monazite grains do not have the zoning pattern mentioned above (Fig. 9.6u, v). A total of 26 points were analyzed from these monazite grains and the spot dates lie within the range of 791±33 Ma to 970±28 Ma (Fig. 9.6w) with a weighted mean age of 931±6 Ma (n=23, MSWD=1.10; Fig. 9.6x). A much younger spot date of 791±33 Ma was also calculated from exterior part of a matrix monazite grain.

9.4 Summary

The major outcomes of the geochronological study of Phulbani domain is summarized below:

1. Data from oscillatory zoned zircon from felsic augen gneiss suggest that in Phulbani domain, crystallization of a granitic protolith occurred at ca. 1173 Ma.
2. Texturally constrained monazite data suggest maximum age of garnet growth vis-à-vis commencement of peak metamorphism at ca. 987 Ma.
3. Data from oscillatory zoned zircon of coarse-grained charnockite suggest that charnockite magmatism took place at ca. 970 Ma.
4. Oscillatory zoned monazite domains of migmatitic felsic gneiss which yield Ca. 968 Ma age possibly signifying cooling after the peak metamorphism.
5. Ca. 949 Ma zircon age from migmatitic felsic gneiss, ca. 939 Ma and ca. 931 Ma ages respectively from monazite of aluminous granulite and migmatitic felsic gneiss indicates a major stage of monazite and zircon growth during this time. These ages could be linked to a high-grade metamorphism subsequent to UHT metamorphism in the Phulbani domain.

6. Weighted mean age of ca. 781 Ma from aluminous granulite located at the N-S trending ductile shear zone possibly reflects the age of the shearing activity. Additionally, spot dates within the range of ca. 558–535 Ma from a matrix monazite of felsic augen gneiss indicate the timing of shearing along RSZ.