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Evidence for a Paleoproterozoic event of metamorphism in the Bastar craton, Central India: P-T-t constraints from mineral chemistry and U-Pb geochronology of mafic dykes

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The Bastar craton largely consists of Mesoarchaeoan orthogneisses with vestiges of supracrustal rocks that have been intruded by Proterozoic granites and mafic dykes. Many regions in the Bastar craton have been subjected to medium or high grade metamorphic conditions but the nature and timing of regional metamorphism is poorly understood. In this study, metamorphosed mafic igneous rocks collected from two different dyke swarms from the southern part of the Central Indian Bastar craton have been studied to evaluate the timing and conditions of metamorphism. In this region, two distinct metamorphosed dyke swarms are recognized based on differences in petrology and geochemistry: the Meso-Neoarchaeoan sub-alkaline BD1 swarm and the Neoarchaeoan boninite-norite (BN) swarm.

The BD1 dykes are characterized by magnesio- and ferro-hornblende and sodic plagioclase (andesine to labradorite) whereas the BN dykes contain magnesio-hornblende and sodic-calcic amphiboles (barroisite and winchite types) with more calcic plagioclase. Temperatures calculated using the amphibole-plagioclase thermometer range from ~575°C (BN dykes) to ~700°C (BD1 dykes). Due to the absence of garnet in the studied rocks, metamorphic pressures were estimated based on the Al-content in amphibole barometer (~4 kbar for the BD1 dykes). Together these data indicate the metamorphic grade in this region is medium amphibolite facies. U-Pb age results for metamorphic rutile from a BN dyke yielded a Palaeoproterozoic date of 2118 ± 2 Ma, interpreted to indicate the time of exsolution of retrograde rutile from Ti-rich actinolite. This represents a robust minimum age constraint for the timing of emplacement of the BN, and by inference the BD1 dyke swarm.

Introduction

Metamorphosed mafic rocks have been increasingly used to provide constraints on the timing of high grade metamorphism because they commonly contain U-bearing accessory minerals such as zircon, titanite, rutile and occasionally monazite that formed during metamorphic transformation. These minerals are amenable to high precision U-Pb dating (Bussy et al., 1995; Fraser et al., 1997; Heaman et al., 2002) and can place rigid constraints on the timing of peak metamorphism. Although pressure and temperature conditions can be gleaned from mafic rocks, it is considerably less quantitative compared to the information obtained from pelites or calc-silicates. However, there are many regions where these are the only rocks available to provide some constraints on the evolution and P-T history of a geologic terrane (Spear, 1993). In contrast to pelitic systems, there are a limited number of diagnostic mineral assemblages available in metamorphosed mafic rocks and this situation is even more challenging if the mafic rocks do not contain garnet. Indeed, most of the methods available for estimating the P-T conditions of metamorphosed mafic igneous rocks (or for any metamorphic rocks) essentially require the presence of garnet.

The Bastar craton in central India is a relatively poorly understood part of the Indian Shield but records a protracted geological history from the Mesoarchaeoan TTG basement to the emplacement of extensive Paleoproterozoic mafic dyke swarms to the development of large Mesoproterozoic sedimentary basins, such as the Chattisgarh Basin (Crookshank, 1963; Mishra et al., 1988; Ramakrishnan, 1990; Chaudhuri et al., 2002; Srivastava, 2006a, b, 2008; Srivastava and Gautam, 2007). Although a general outline of the geologic history for the craton has been established, there is very little known about its tectonic evolution, despite the fact that large parts of the craton have experienced medium to high grade metamorphism. Observations made in these earlier studies demonstrated the presence of cordierite and andalusite/sillimanite in metapelites, and the absence of garnet in amphibolites, indicating low-pressure metamorphism in the southern Bastar craton. Narayanaswami et al. (1963) observed that the metamorphic grade consistently increases from south to north in the Bastar craton. However, Santosh et al. (2004, 2006) have documented the existence of the Bhopalpatnam granulites in the southwestern part the Bastar craton. This is ~150 km west of the

study area. These authors have suggested that the granulites preserve a record of metamorphism at high pressure (up to 8.0–9.5 kbar) with a temperature range of 720–800°C.

The samples investigated in this study were collected from two metamorphosed mafic dyke swarms exposed in the southern part of the central Indian Bastar craton (CIBC); the Meso-Neoproterozoic BD1 and the Neoproterozoic-Paleoproterozoic BN swarms (Srivastava and Singh, 2004; Srivastava, 2006a, b, 2008; French et al., 2008). The petrological and geochemical characteristics of these mafic dykes have already been studied in order to understand their magmatic history (Srivastava and Singh, 2004; Srivastava, 2006a, b, 2008; Srivastava and Gautam, 2007) but very little is known about their metamorphic history, the regional metamorphic conditions, or the timing of metamorphism (Crookshank, 1963; Narayanaswami et al., 1963; Chatterjee, 1970; Venkatesh and Ramakrishnan, 1985; Mishra et al., 1988; Ramakrishnan, 1990). In this study we report the petrography and mineral chemistry for samples from these two metamorphosed dyke swarms and an isotope dilution thermal ionization mass spectrometry (IDTIMS) U-Pb metamorphic rutile date for a BN dyke. These results provide the first constraints on the timing and metamorphic pressure-temperature conditions of mafic dyke swarms of the southern Bastar craton.

Geological setting

The rectangular-shaped central Indian Bastar craton (also known as Bhandara or central Indian craton) is separated from the surrounding Archaean blocks of India, the Bundelkhand, the Dharwar and the Singhbhum cratons by three prominent rifts; the Godavari in the southwest, the Narmada in the northwest and the Mahanadi in the northeast. It is bounded by the Eastern Ghats Belt (EGB) to the southeast (Fig. 1). The study area is situated in the southern part of

Figure 1. Major cratons and structural features of India (modified after Naqvi and Rogers, 1987). Major structural features are: 1. Small thrusts in western Dharwar craton; 2. Eastern Ghats Belt (EGB); 3. Sukinda; 4. Singhbhum; 5. Son Valley; and 6. Great Boundary fault. NSRZ: Narmada-Son Rift Zone.

the Bastar craton, which comprises a vast tract of granitoids with inliers of supracrustal rocks. The supracrustal rocks include different types of metamorphic rocks (including metamorphosed mafic igneous rocks), a variety of mafic igneous rocks and unmetamorphosed late Proterozoic sedimentary rocks (Crookshank, 1963; Ramakrishnan, 1990).

Figure 2 presents geology, tectonic setting and field-relationships of different mafic rocks with the other rock types from the southern Bastar craton (Crookshank, 1963; Ramakrishnan, 1990; Srivastava and Singh, 2004; Srivastava, 2006a, b, 2008; Srivastava and Gautam, 2007). In the southern Bastar craton two sets of sub-alkaline mafic dyke swarms and one set of boninite-norite mafic dykes are identified. Field relationships of the different mafic units are already described in different publications whereas emplacement ages are constrained mainly indirectly from structural relationships with previously dated lithologies (Ramakrishnan, 1990; Srivastava and Singh, 2004; Srivastava, 2006, 2008; Srivastava and Gautam, 2007; French et al., 2008). The important field-observations made by these authors are (i) in general, all three dyke swarms are emplaced in the Archaean granite gneisses, (ii) the dyke trends vary between NW-SE to WNW-ESE, (iii) tongues of 2.3 Ga granite (Ramakrishnan, 1990) cut the BD1 swarm indicating emplacement of BD1 dykes before 2.3 Ga, (iv) BD2 dykes cut all the formations including Proterozoic granite (2.3 Ga), which is consistent with U-Pb zircon/baddeleyite dates of 1.88–1.89 Ga (French et al., 2008), (v) none of the BN dykes are known to cut the 2.3 Ga granites, (vi) a BN dyke is reported to cut a dyke of BD1 swarm, (vii) veins of younger granite (2.3 Ga) are reported to cut a dyke of BN dyke swarm, and (viii) none of the dyke swarms are reported to cut unmetamorphosed Neoproterozoic sedimentary rocks. On the basis of these field observations it is suggested that the BD1 swarm was probably emplaced in the Meso-Neoproterozoic, the BD2 swarm was emplaced in the Paleoproterozoic (1.88–1.89 Ga; French et al., 2008) and the BN swarm was emplaced during the Paleoproterozoic-Neoproterozoic (Srivastava, 2008).

Petrography

The BD1 samples are characterized by granoblastic textures and consist of hornblende, plagioclase, chlorite, quartz, epidote, apatite, titanite, and iron oxides (Figs. 3a and b). Some samples show a poorly developed schistose texture defined by oriented hornblende grains. In a few samples plagioclase shows mild-saussuritization. Porphyroblastic hornblende shows poikiloblastic textures, defined by abundant inclusions of quartz, epidote, and plagioclase (Fig. 3a). Smaller amphibole grains generally lack sieve texture and exhibit a preferred orientation. Larger grains show elongate prismatic habits, with a sieved texture defined by inclusions of quartz, epidote, apatite, titanite, and iron oxides. The observed mineral assemblages and textures in the BD1 samples suggest amphibolite facies metamorphic conditions.

The BN dykes show either acicular or decussate texture and consist of hornblende, actinolite, chlorite, plagioclase, minor epidote, quartz, rutile, and iron oxides (Figs. 3c and d). Late quartz ± epidote stringers also occur. Plagioclase has polysynthetic albite twinning with no saussuritization. Hornblende occurs as greenish subhedral elongate blades and exhibits a decussate texture over a range of grain sizes from medium grained blades (~5 mm) to very tiny needles (<100 mm). Chlorite occurs as fine-grained radiating arrays enveloping or

Figure 2. Geological maps of the southern Bastar craton. Locations of mafic dykes sampled for electron microprobe analysis and U-Pb dating are also marked. Geological maps modified after Crookshank (1963), Srivastava (2006a, b).

grading into hornblende, usually associated with fine-grained actinolite. Relict plagioclase and late quartz pockets are surrounded and penetrated by randomly oriented fine-grained needles of actinolite. Rutile exhibits two distinct morphologies: (i) trails and aggregates of equant to somewhat elongate rods (up to ~5:1 aspect ratio) that are yellow-orange to dark red-brown in colour, heavily striated, subhedral grains (Fig. 4a); and (ii) highly elongate (as high as 20:1 aspect ratio observed), perfectly euhedral, isolated, randomly oriented needles and thin blades, ranging in colour from light orange to dark brown (Fig. 4b). The second type of rutile grains commonly show elbow-shaped contact twins and are typically fully enveloped by the largest hornblende crystals. Granoblastic textures only occur very locally and along grain boundaries between rutile aggregates, hornblende, and quartz. On the basis of these granoblastic textures between granular aggregates of rutile and actinolite we interpret the rutile to be metamorphic in origin, and suggest that it was probably formed by the breakdown of primary magmatic Fe-Ti oxides (titanite or ilmenite).

Whole rock chemistry

All three mafic dyke swarms have distinct geochemical traits that were interpreted to indicate derivation from three distinct magma compositions (Srivastava and Singh, 2004; Srivastava, 2006a, b; Srivastava and Gautam, 2007). Some important geochemical observations are:

1. Concentrations of TiO_2 , P_2O_5 and Y are relatively higher in the

BD2 dyke samples and lower in the BN dyke samples, whereas the BD1 dyke samples show intermediate concentration.

2. BD1 and BD2 samples have different incompatible element concentration at similar MgO concentration suggesting that these two swarms are derived from two different sub-alkaline tholeiitic magmas. In general, incompatible trace element concentrations increase with decreasing MgO. Higher MgO concentrations in BD1 samples in comparison to BD2 samples probably indicate that these are derived from a magma generated by a higher percentage of melting, probably at deeper depths than magma for the BD2 swarm.
3. The BD1 and BN mafic dyke samples have almost similar Zr concentrations at different MgO concentrations, again suggesting that these two were not derived from a single melt.
4. The BD1 and BD2 samples have distinct differences in Ti and Zr concentrations observed at similar Cr contents. Similar MgO and Cr contents with distinctly different incompatible trace element concentrations cannot be derived from differentiation of the same type of magma. Two distinct parental magmas or mantle sources are required.
5. Figure 5 presents primordial mantle-normalized incompatible trace elements, including all rare-earth elements for the three swarms. Each group clearly shows different patterns. Although BD1 and BN dykes are metamorphosed and altered, incompatible trace elements show very limited variation and do not show any obvious effect of alteration or contamination. Distinct trace element concentrations in different mafic dykes corroborate

Figure 3. (a and b) Photomicrographs of metamorphosed BD1 mafic dykes showing granoblastic texture. Hornblende grains (in Fig. 2a) show porphyroblastic and poikiloblastic textures, the latter containing inclusions of quartz, epidote, and plagioclase. (c and d) Photomicrographs of metamorphosed BN mafic dykes showing acicular and decussate textures. All photographs are taken under plane-polarized light. The field of view is 3.5 mm across. Fe-Hb – Ferro-hornblende; Mg-Hb – Magnesio-hornblende; Pl – Plagioclase.

involvement of different petrogenetic processes in the genesis of BD1, BD2, and BN mafic dykes. REE concentrations are also distinctly different in these three groups. BN samples show more enrichment in LREE than BD1 and BD2 samples; LREE enrichment in BD1 is lowest in comparison to other two.

Thus, based on whole rock geochemistry it is likely that the BD1, BD2, and BN dyke swarms were derived from different batches of

basaltic magma. It is suggested that BD1 dykes are derived from a sub-alkaline basaltic magma that characteristically had comparatively high MgO and low Ti, P, and incompatible trace element concentrations than the sub-alkaline basaltic magma responsible for genesis of BD2 dykes. BN dykes, in contrast, are suggested to have been derived from a boninitic magma (Srivastava, 2006a). In addition to these distinct geochemical characteristics, compatible-incompatible

Figure 4. Photomicrographs of a sample from BN dyke showing (a) Type 1 'prograde' rutile. (b) Type 2 'retrograde' rutile. Abbreviations: Pl – plagioclase; Ac – actinolite; Qz – quartz; R – rutile; Sa – saussurite; Ur – uraltite.

Figure 5. *Primordial mantle-normalized multi-element and chondrite-normalized rare-earth elements patterns for metamorphosed BD1 and BN swarms and un-metamorphosed BD2 swarm from the southern Bastar craton (after Srivastava, 2006a, b).*

trace element modelling suggest that the BD1 dykes were derived from ~15-20% batch melting of a partially depleted lherzolite mantle source. In contrast, the Paleoproterozoic BD2 dykes were derived from ~7-10% batch melting of a metasomatized enriched mantle source. The Neoarchaeon BN dykes are products of different pulses of high-Mg boninitic magma that was produced by ~20% melting of a refractory mantle source.

Mineral chemistry

Analytical method

Three of BD1 dykes and two samples of BN dykes were selected for electron microprobe mineral analysis. All mineral analyses were performed on polished thin sections using a fully automated Cameca SX-50 Electron Microprobe at the Instituto de Geociencias, Universidade de Brasília (Brazil). The wavelength dispersive (WDS) analyses were performed at an accelerating voltage of 15 kV and a beam current of 25 nA. Background counting time was set to half of the peak counting time. Both synthetic and natural mineral standards were used for the analyses and the same standards and procedure were retained throughout. Representative probe data of minerals are presented in Tables 1 to 3. Representative samples from BD1 and BN dyke swarms were chosen for detailed analysis in order to evaluate mineral compositions to be used for P-T calculations.

Results

Amphibole

Amphibole analyses (ca 40 analyses) were performed on the core of crystals in domains where textural features indicate equilibrium of the metamorphic assemblage. These analyses have been normalized to the 13ex CNK scheme of Robinson et al. (1982). The Fe^{3+} -content were calculated from the equation proposed by Droop (1987). All the analysed amphiboles are classified on the basis of 'Si' and " X_{Mg} " (Fig. 5), following the nomenclature of Leake et al. (1997).

The brownish to greenish amphiboles analysed from the BD1 mafic dykes show variation from magnesio-hornblende to ferro-hornblende (see Table 1 and Fig. 6), whereas greenish amphiboles analysed from the BN dykes are strictly magnesio-hornblende, with X_{Mg} ranging from 0.843 to 0.996 (see Table 2 and Fig. 6). When compared to BN amphiboles those from BD1 dykes have lower MgO and Cr_2O_3 content, and higher FeO , Al_2O_3 , Na_2O , K_2O and TiO_2 contents. The composition of amphiboles from BN and BD1 are nevertheless typical of amphibolite facies rocks (Evans, 1982). Compositional constraints, including the contents of alkalis, Al and TiO_2 , suggest that amphiboles from BD1 mafic dykes crystallized at higher temperature than amphiboles from BN dykes (Stein and Dietl, 2001; Leake, 1971; Ferreira Filho et al., 1998).

Plagioclase

Plagioclase analyses (ca 30 analyses) were performed on the core of crystals in domains where textural features indicate equilibrium of the metamorphic assemblage. Plagioclase shows significant compositional variation with respect to anorthite content. 'An' content $\{= 100 [\text{Ca}/(\text{Ca}+\text{Na}+\text{K})]\}$ ranges from andesine to labradorite (Table 3). Plagioclase with low temperature metabasites (BN) is more calcic than the high temperature metabasites (BD1) (see Table 3).

Geothermobarometric calculations

For a characterization of the P-T regime during metamorphism, garnetiferous lithologies are the most suitable, since a set of reasonably well-calibrated geothermobarometers based on Fe-Mg exchange equilibria and pressure-sensitive net-transfer reactions are available. In this study, the equilibration temperatures for selected BD1 and BN dykes were determined using the compositions of coexisting amphibole-plagioclase pairs (after Blundy and Holland, 1990; Table 4a). It has been suggested that the Al-content of amphibole is largely controlled by pressure and, therefore, in appropriate assemblages it can be used as a reliable barometer (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Stein and Dietl, 2001). Aluminum contents in amphiboles were determined, and pressures estimated, for the BD1 dykes using a variety of these geobarometers (Table 4b). The barometric models of Hammarstrom and Zen (1986) and Hollister et al. (1987) provide a pressure range roughly between 3.3 and 5.5 kbar for the studied rocks. The Johnson and Rutherford (1989) calibration gives 1 kbar lower P estimates. Such variation in absolute pressure values could be related to the uncertainties associated with thermochemical data in locating the end-member reactions. The plagioclase-amphibole thermometer of Blundy and Holland (1990) suggests average temperatures of ~575°C and ~700°C for BN and BD1 dykes, respectively (see Table 4).

Table 1. Representative electron microprobe analyses of amphiboles from the BD1 dykes

Sample Number Points	9				10					317						
	1	2	3	4	1	2	3	4	5	1	2	3	4	5	6	7
SiO ₂	45.93	45.91	45.65	46.16	46.60	46.24	47.09	47.20	46.64	43.27	43.58	43.70	43.76	42.92	43.46	44.18
TiO ₂	0.81	0.87	0.84	0.93	0.76	0.78	0.80	0.68	0.77	0.87	0.94	0.99	0.97	0.82	0.71	0.79
Al ₂ O ₃	8.61	8.92	8.93	8.70	8.55	8.34	8.20	8.02	8.61	9.89	10.17	9.87	9.80	9.86	9.89	9.83
Cr ₂ O ₃	0.02	0.02	0.01	0.00	0.05	0.00	0.02	0.03	0.00	0.00	0.03	0.00	0.02	0.05	0.00	0.00
FeO	18.56	19.21	19.01	18.72	17.49	17.85	17.47	18.24	18.16	22.09	21.71	21.23	21.72	21.84	21.25	21.55
MnO	0.25	0.29	0.23	0.31	0.25	0.24	0.23	0.25	0.20	0.29	0.24	0.27	0.24	0.28	0.19	0.22
MgO	9.58	9.32	9.21	9.32	9.82	9.78	10.13	10.10	9.99	7.09	7.13	7.39	7.24	6.75	7.12	7.20
CaO	11.36	11.20	11.33	11.27	11.64	11.55	11.56	11.67	11.66	11.39	11.35	11.30	11.42	11.19	11.35	11.40
Na ₂ O	0.97	0.98	0.93	0.92	0.88	0.80	0.86	0.81	0.91	1.23	1.33	1.23	1.19	1.30	1.21	1.20
K ₂ O	0.54	0.62	0.59	0.63	0.47	0.48	0.49	0.39	0.50	0.69	0.74	0.73	0.68	0.68	0.64	0.60
H ₂ O	1.97	1.98	1.98	1.82	1.92	1.98	1.79	2.00	2.00	1.93	1.94	1.85	1.94	1.91	1.92	1.95
Total	98.61	99.33	98.71	98.78	98.41	98.03	98.63	99.39	99.43	98.74	99.17	98.57	98.98	97.59	97.74	98.91
Si	6.886	6.837	6.849	6.904	6.983	6.961	7.015	6.996	6.920	6.628	6.643	6.677	6.667	6.662	6.711	6.734
Al ^{IV}	1.114	1.163	1.151	1.096	1.017	1.039	0.985	1.004	1.080	1.372	1.357	1.323	1.323	1.338	1.289	1.266
Al ^{VI}	0.407	0.402	0.429	0.437	0.493	0.440	0.454	0.397	0.426	0.413	0.471	0.455	0.439	0.466	0.511	0.500
Fe ³⁺	0.488	0.588	0.502	0.451	0.266	0.373	0.320	0.439	0.420	0.523	0.421	0.433	0.443	0.430	0.371	0.393
Ti	0.091	0.097	0.095	0.104	0.085	0.088	0.089	0.076	0.086	0.100	0.108	0.114	0.111	0.095	0.082	0.090
Cr	0.002	0.003	0.002	0.000	0.006	0.000	0.003	0.004	0.000	0.000	0.004	0.000	0.002	0.006	0.000	0.000
Fe ²⁺	1.838	1.804	1.883	1.891	1.925	1.874	1.855	1.822	1.833	2.306	2.346	2.279	2.328	2.404	2.737	2.354
Mn	0.032	0.036	0.029	0.040	0.031	0.031	0.029	0.032	0.025	0.038	0.031	0.035	0.031	0.036	0.025	0.029
Mg	2.141	2.069	2.060	2.078	2.194	2.195	2.250	2.231	2.211	1.620	1.620	1.684	1.646	1.563	1.638	1.635
Ca	1.824	1.787	1.822	1.806	1.868	1.863	1.844	1.853	1.853	1.869	1.854	1.850	1.866	1.860	1.877	1.861
Na	0.283	0.282	0.271	0.267	0.256	0.232	0.249	0.233	0.261	0.364	0.394	0.365	0.352	0.391	0.362	0.353
K	0.104	0.118	0.113	0.121	0.090	0.092	0.092	0.074	0.095	0.134	0.144	0.141	0.133	0.135	0.125	0.117
X _{Mg}	0.538	0.534	0.522	0.523	0.533	0.539	0.548	0.550	0.547	0.413	0.408	0.425	0.414	0.394	0.408	0.410
Class	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Fe-Hb	Fe-Hb	Fe-Hb	Fe-Hb	Fe-Hb	Fe-Hb	Fe-Hb

Mg-Hb – Magnesio-hornblende; Fe-Hb – Ferro-hornblende

Table 2. Representative electron microprobe analyses of amphiboles from the BN dykes

Sample Number Points	304										369							
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8
SiO ₂	52.90	52.92	51.97	52.59	52.40	52.44	52.65	52.43	52.74	53.71	52.50	51.46	52.03	52.39	52.54	52.23	51.94	52.07
TiO ₂	0.33	0.29	0.38	0.36	0.38	0.26	0.26	0.28	0.26	0.19	0.28	0.34	0.39	0.35	0.37	0.34	0.36	0.35
Al ₂ O ₃	5.31	5.47	5.58	5.69	5.44	5.58	5.20	5.58	4.58	3.42	6.04	6.35	5.60	5.81	5.77	5.25	5.81	5.75
Cr ₂ O ₃	0.34	0.23	0.37	0.27	0.30	0.43	0.30	0.33	0.20	0.11	0.47	0.60	0.46	0.42	0.37	0.30	0.39	0.46
FeO	10.17	10.81	10.55	10.31	10.33	9.96	10.61	10.16	10.53	11.17	9.26	9.74	9.69	9.45	9.12	8.64	9.48	9.55
MnO	0.14	0.21	0.12	0.14	0.19	0.13	0.23	0.00	0.14	0.11	0.14	0.23	0.15	0.11	0.13	0.05	0.09	0.09
MgO	16.43	16.25	15.94	16.18	16.12	16.22	16.24	16.28	16.43	17.07	16.87	16.39	16.76	16.61	16.81	17.25	16.71	16.78
CaO	11.09	10.82	10.83	11.02	11.22	10.92	10.55	11.20	10.71	9.79	11.45	11.22	11.33	11.33	11.48	12.04	11.30	11.45
Na ₂ O	0.43	0.54	0.53	0.54	0.54	0.62	0.62	0.59	0.55	0.39	0.60	0.60	0.52	0.62	0.58	0.64	0.55	0.66
K ₂ O	0.05	0.06	0.07	0.08	0.06	0.09	0.06	0.06	0.09	0.06	0.09	0.08	0.06	0.07	0.05	0.06	0.06	0.07
H ₂ O	1.93	2.09	2.08	2.10	2.10	2.09	2.09	1.93	2.01	2.08	2.12	2.09	2.09	1.95	2.11	2.05	2.09	1.90
Total	99.11	99.69	98.42	99.27	99.07	98.73	98.80	98.83	98.23	98.09	98.81	99.09	99.10	99.12	99.32	99.83	98.77	99.13
Si	7.412	7.381	7.359	7.379	7.391	7.397	7.401	7.388	7.461	7.519	7.322	7.237	7.311	7.355	7.368	7.450	7.317	7.314
Al ^{IV}	0.588	0.619	0.641	0.621	0.609	0.603	0.599	0.612	0.539	0.481	0.678	0.763	0.689	0.645	0.632	0.550	0.683	0.686
Al ^{VI}	0.289	0.280	0.291	0.321	0.295	0.324	0.261	0.315	0.224	0.084	0.315	0.289	0.239	0.317	0.322	0.315	0.281	0.266
Fe ³⁺	0.737	0.860	0.786	0.722	0.651	0.689	0.894	0.649	0.824	1.293	0.653	0.776	0.752	0.614	0.577	0.339	0.711	0.657
Ti	0.034	0.031	0.040	0.038	0.041	0.028	0.027	0.030	0.027	0.020	0.029	0.036	0.042	0.037	0.039	0.035	0.038	0.037
Cr	0.037	0.026	0.041	0.030	0.033	0.048	0.033	0.037	0.023	0.013	0.052	0.067	0.051	0.047	0.041	0.033	0.043	0.051
Fe ²⁺	0.454	0.401	0.464	0.488	0.568	0.486	0.354	0.549	0.422	0.014	0.427	0.370	0.387	0.496	0.492	0.672	0.406	0.464
Mn	0.016	0.025	0.014	0.017	0.023	0.015	0.027	0.000	0.017	0.013	0.016	0.027	0.018	0.013	0.016	0.006	0.010	0.010
Mg	3.431	3.379	3.364	3.385	3.389	3.410	3.403	3.420	3.464	3.564	3.508	3.436	3.512	3.476	3.514	3.600	3.510	3.514
Ca	1.664	1.617	1.642	1.656	1.696	1.650	1.589	1.690	1.623	1.468	1.711	1.691	1.706	1.705	1.724	1.805	1.705	1.723
Na	0.118	0.146	0.146	0.147	0.147	0.171	0.168	0.160	0.151	0.105	0.162	0.164	0.141	0.170	0.158	0.172	0.150	0.180
K	0.009	0.011	0.013	0.013	0.010	0.015	0.010	0.010	0.016	0.010	0.016	0.014	0.011	0.012	0.009	0.010	0.010	0.013
X _{Mg}	0.883	0.894	0.879	0.874	0.856	0.875	0.906	0.862	0.891	0.996	0.891	0.903	0.901	0.875	0.877	0.843	0.896	0.883
Class	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb	Mg-Hb

Mg-Hb – Magnesio-hornblende

Figure 6. A plot of X_{Mg} vs Si in formula for calcic amphiboles (after Leake et al., 1997). Solid squares and solid stars correspond to BN and BD1 samples, respectively.

U-Pb Geochronology

Mineral separation

Mineral separation and isotope dilution thermal ionization mass spectrometry (ID-TIMS) U-Pb analyses were carried out at the University of Alberta Radiogenic Isotope Facility. One sample (JEF00-14) from a BN dyke was chosen for U-Pb IDTIMS dating study, in an initial attempt to isolate any relict baddeleyite grains that might have survived metamorphism. A ~2 kg sample was pulverized with a Bico Disk Mill, and a heavy mineral concentrate was obtained using the water-based mineral separation procedure outlined by Söderlund and Johansson (2002). Many thousands of euhedral, equant to very elongated and bladed; orange, red and brown rutile crystals were recovered, but unfortunately no baddeleyite or zircon was identified. The occurrence of large quantities of rutile in the concentrate demonstrates that the simple water-based method used for baddeleyite separation also works exceptionally well for isolating rutile crystals from mafic dykes. In some cases, for example the Great Dyke of Zimbabwe (Oberthür et al, 2002; Mukasa et al, 1998), rutile has been used as a reliable geochronometer for determining the age of crystallization of mafic dykes, and so dykes that are known to contain primary rutile are amenable to this simple method of mineral

Table 3. Representative electron microprobe analyses of plagioclases from the Bastar dykes

Sample Number	BD1 dykes																	
	9					10					317							
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	6	7	8
SiO ₂	57.63	57.57	58.44	56.81	57.07	56.90	57.12	57.12	56.86	57.17	58.65	60.76	61.31	60.84	59.54	60.40	59.69	60.32
Al ₂ O ₃	27.31	26.99	26.67	27.74	27.45	27.65	27.39	27.71	27.48	27.45	26.34	25.19	25.23	25.91	24.61	24.79	25.47	24.99
FeO	0.12	0.12	0.16	0.04	0.03	0.00	0.06	0.09	0.01	0.07	0.14	0.12	0.17	0.15	1.44	0.43	0.29	0.32
CaO	8.91	8.78	8.48	9.57	9.48	9.49	9.22	9.64	9.53	9.38	7.93	6.68	6.56	6.89	6.14	6.23	7.15	6.74
Na ₂ O	6.74	6.69	7.19	6.28	6.29	6.41	6.53	6.44	6.46	6.40	7.36	8.34	8.30	8.01	7.87	8.36	7.84	8.08
K ₂ O	0.06	0.05	0.03	0.12	0.10	0.08	0.05	0.05	0.07	0.12	0.06	0.05	0.04	0.06	0.46	0.10	0.09	0.20
Total	100.77	100.19	100.97	100.55	100.41	100.53	100.37	101.05	100.41	100.58	100.49	101.13	101.61	101.86	100.06	100.29	100.54	100.64
Si	2.565	2.574	2.594	2.537	2.550	2.541	2.554	2.540	2.544	2.551	2.612	2.679	2.688	2.662	2.672	2.687	2.653	2.675
Al	1.432	1.422	1.395	1.460	1.446	1.455	1.443	1.452	1.449	1.444	1.382	1.309	1.303	1.336	1.301	1.300	1.334	1.306
Fe	0.005	0.004	0.006	0.001	0.001	0.000	0.002	0.003	0.001	0.002	0.005	0.004	0.006	0.005	0.054	0.016	0.011	0.012
Ca	0.425	0.421	0.403	0.458	0.454	0.454	0.442	0.459	0.457	0.449	0.378	0.315	0.308	0.323	0.295	0.297	0.341	0.320
Na	0.581	0.580	0.619	0.544	0.545	0.555	0.566	0.555	0.560	0.554	0.636	0.713	0.706	0.680	0.684	0.721	0.676	0.694
K	0.003	0.003	0.002	0.007	0.006	0.004	0.003	0.003	0.004	0.007	0.003	0.003	0.002	0.003	0.026	0.006	0.005	0.011
Ab	57.57	57.78	60.45	53.93	54.26	54.77	56.01	54.57	54.87	54.87	62.48	69.14	69.47	67.54	68.04	70.45	66.17	67.70
Or	0.34	0.28	0.17	0.66	0.56	0.44	0.29	0.27	0.39	0.65	0.32	0.28	0.21	0.34	2.63	0.54	0.49	1.10
An	42.09	41.94	39.38	45.40	45.18	44.80	43.71	45.15	44.74	44.48	37.19	30.58	30.32	32.12	29.33	29.01	33.35	31.20

Sample Number	BN dykes											
	304											
	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	53.28	53.59	53.87	53.63	53.01	55.10	53.30	55.39	56.96	57.39	56.56	62.42
Al ₂ O ₃	29.11	29.53	30.02	29.66	29.71	29.11	28.55	29.39	27.73	27.00	27.62	24.15
FeO	0.20	0.19	0.23	0.24	0.22	0.16	0.10	0.12	0.14	0.52	0.16	0.14
CaO	11.39	11.62	11.63	11.55	11.80	10.61	10.60	10.23	9.59	8.19	9.25	8.31
Na ₂ O	4.82	4.52	4.78	4.79	4.67	5.40	5.74	5.84	6.27	6.68	6.38	6.19
K ₂ O	0.04	0.06	0.10	0.12	0.09	0.06	0.05	0.05	0.03	0.32	0.03	0.04
Total	98.85	99.51	100.63	99.99	99.50	100.43	100.34	100.01	100.71	100.09	99.99	101.25
Si	2.433	2.430	2.419	2.424	2.409	2.470	2.484	2.493	2.540	2.574	2.538	2.735
Al	1.567	1.578	1.588	1.580	1.591	1.538	1.511	1.506	1.457	1.427	1.461	1.247
Fe	0.008	0.007	0.009	0.009	0.008	0.006	0.004	0.004	0.005	0.019	0.006	0.005
Ca	0.557	0.565	0.559	0.559	0.575	0.510	0.510	0.493	0.458	0.393	0.445	0.390
Na	0.427	0.398	0.416	0.420	0.412	0.469	0.499	0.509	0.542	0.581	0.555	0.526
K	0.002	0.003	0.006	0.007	0.005	0.004	0.003	0.003	0.001	0.018	0.002	0.002
Ab	43.29	41.19	42.44	42.56	41.50	47.76	49.31	50.65	54.11	58.52	55.42	57.28
Or	0.23	0.33	0.56	0.71	0.54	0.36	0.31	0.28	0.15	1.84	0.17	0.21
An	56.48	58.49	57.00	56.73	57.96	51.89	50.38	49.06	45.74	39.64	44.41	42.51

Table 4a. Thermometry of studied metabasites calculated on the basis of coexisting amphibole-plagioclase pairs (after Blundy and Holland, 1990)

Sample Number	BD1 dykes							BN dyke			
	9			10			Mean±σ	304			Mean±σ
Amphibole point in Table 1	3	4	3	1	3	5		10	10	9	
Plagioclase point in Table 3	1	3	2	2	4	5		1	5	10	
ln Kd	0.035	0.471	0.358	0.496	0.518	0.394		1.153	1.111	1.325	
Temp (°C)	707	686	706	682	678	700	693±13	580	576	560	572±11

Table 4b. Barometry of studied BD1 dykes, calculated on the basis of 'Al' contents in amphiboles

Sample Number	9		Mean±σ	10				Mean±σ	317					Mean±σ
	3	4		1	2	3	5		1	2	6	7	5	
Amphibole point in Table 1	3	4		1	2	3	5		1	2	6	7	5	
Barometer used ↓														
Hammarstrom and Zen (1986)	4.03	3.79	3.91±0.17	3.68	3.52	3.32	3.66	3.55±0.17	5.06	5.27	5.13	4.96	5.15	5.11±0.11
Hollister et al. (1987)	4.15	3.89	4.02±0.18	3.76	3.58	3.36	3.73	3.61±0.18	5.31	5.55	5.39	5.20	5.41	5.37±0.13
Johnson and Rutherford (1989)	3.22	3.02	3.12±0.14	2.93	2.80	2.63	2.91	2.82±0.14	4.09	4.27	4.15	4.01	4.17	4.14±0.10

separation. In the case of the sample investigated here, our interpretation is that all of the rutile present is metamorphic in origin, and so the technique may also have wide applicability in terms of concentrating rutile from a potentially large diversity of rutile-bearing metamorphic rocks, especially those that are known to contain elongate, bladed rutile (e.g. Möller et al., 2000; Zack et al., 2004). The primary advantages of the water-based rutile mineral separation over conventional techniques are that it is less costly, more time efficient, involves fewer steps and therefore reduces loss of delicate blades, and avoids the use of toxic heavy liquids (Söderlund and Johansson, 2002).

U-Pb ID-TIMS analysis

Pure rutile fractions were selected using a binocular microscope, avoiding grains with visible fractures, inclusions and alteration. The mineral fractions were weighed with a Mettler UTM-2 ultra-microbalance; uncertainty in the weights is generally ±0.5–1.0 µg. All samples were spiked with a measured amount of a mixed ²⁰⁵Pb-²³⁵U tracer solution, and the samples were dissolved in TFE Teflon bombs at 215°C over a 4–5 day period in a mixture of distilled acids, comprising a 5:1 ratio of 48% HF and 7N HNO₃.

After digestion, the samples were visually inspected to ensure that complete dissolution of the grains had taken place, and then allowed to dry down in an ultra-clean environment to form a precipitate. The precipitates were then dissolved in 3.1N HCl over a

24 hour period at 215°C. Uranium and Pb were purified using ion exchange chromatography employing Dowex AG1 X8, 200–400 mesh, chloride form resin, similar to the HBr procedure outlined in Heaman and Machado (1992). These purified sample solutions were combined together with 0.15N H₃PO₄ to facilitate locating the samples after evaporation to dryness.

For isotopic analysis, the samples were mixed with 2.5–4.0 µL of silica gel and 2.5–4.0 µL of 0.15N H₃PO₄ and loaded onto outgassed Re-filaments. All isotopic analyses were carried out on a VG354 mass spectrometer operating in analogue Daly photomultiplier detector peak-hopping mode. The empirically determined Faraday-Daly conversion factors used in this study for all Daly measurements were 0.086%/atomic mass unit (amu) Pb and 0.0052%/amu U. The isotopic composition of Pb in excess of blank Pb was calculated using the two-stage Pb evolution model of Stacey and Kramers (1975). The one-sigma errors listed in Table 5 were calculated using an in-house algorithm that numerically propagates all known sources of uncertainty (Heaman et al. 1992). The Isoplot/Ex3 (Ludwig, 2003) program was used for all age calculations. The decay constants for ²³⁸U (1.55125 × 10⁻¹⁰a⁻¹) and ²³⁵U (9.8485 × 10⁻¹⁰a⁻¹) and the present day ²³⁸U/²³⁵U ratio of 137.88 are those determined by Jaffey et al. (1971). The age uncertainty is reported at two-sigma.

Results

The U-Pb isotopic data for five fractions of elongate, weakly to

Table 5. U-Pb ID-TIMS rutile data for a BN dyke sample JEF00-14 (Loc. Gatam, Southern Bastar craton; 18°49.37'N, 81°34.71'E)

	Description*	Weight	Concentrations (ppm)				TCPb	Isotopic ratios				Apparent ages (Ma)			
		(µg)	U	Model Th	Pb	Th/U	(pg)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	%Disc
1	7 euh, tan, str	3.7	16	1.9	6.5	0.12	7.3	222	0.40175±212	7.377±55	0.13318±67	2177.1±9.7	2158.2±7.1	2140.3±8.7	-2.02
2	13 euh, tan, str	4.8	18	1.4	6.7	0.08	9.6	228	0.38465±156	6.918±42	0.13044±61	2097.9±7.3	2100.9±5.8	2103.8±8.2	0.33
3	125 thin elongate, or	16.1	14	0.9	5.9	0.07	17	325	0.36845±81	6.583±30	0.12957±49	2022.1±3.8	2057.0±4.0	2092.2±6.7	3.90
4	32 larger red frags	63.9	30	2.2	11.9	0.07	55	841	0.37640±45	6.815±10	0.13131±14	2059.5±2.1	2087.6±1.3	2115.5±1.8	3.09
5	75 red equant	52.4	30	1.4	11.8	0.05	31	1236	0.38108±44	6.911±9	0.13153±9	2081.3±2.1	2100.1±1.2	2118.5±1.1	2.05

Notes: Th concentration estimated from abundance of ²⁰⁸Pb and corresponding ²⁰⁷Pb/²⁰⁶Pb ages. TCPb refers to the total amount of common Pb in picograms measured in the analysis. The values used in this study for the decay constants for ²³⁸U (1.55125 × 10⁻¹⁰a⁻¹) and ²³⁵U (9.8485 × 10⁻¹⁰a⁻¹) and the present day ²³⁸U/²³⁵U ratio of 137.88, are those determined by Jaffey et al. (1971). Atomic ratios are corrected for fractionation, blank, spike and common Pb (Stacey and Kramers, 1975), except ²⁰⁶Pb/²⁰⁴Pb ratios which are corrected for fractionation and spike only. All errors quoted in this table are 1 sigma uncertainties. All analyses determined using a VG354 thermal ionization mass spectrometer.

*Abbreviations: euh - euhedral, str - striated, tan - tan brown in colour, or - orange, frags - fragments (number corresponds to the number of crystals analysed)

Figure 7. Concordia diagram showing U-Pb isotopic data for rutile from the metamorphosed BN mafic dyke of the southern Bastar craton. Error ellipses are shown at the 2s level and the data point labels are keyed to Table 5. Shaded ellipse, labelled with larger lettering in boxes represent the data points used in the final age calculation.

non-striated, orange to red rutile blades are presented in Table 5 and shown on a concordia diagram in Figure 7. Rutile in this sample has low uranium (14-30 ppm) and Th (0.9-2.2 ppm) contents and low Th/U (0.05-0.12). The uranium content correlates with colour intensity, the darkest red rutile fractions (#4, #5) have the highest uranium contents. One analysis (#1) shows slight reverse discordance, which may be attributed to either incomplete equilibration between the sample and spike, or an incorrect common Pb correction (small sample size and low Pb concentration). The other four analyses are between 0.3 and 3.9% discordant with $^{207}\text{Pb}/^{206}\text{Pb}$ dates that vary between 2092 and 2119 Ma. The two most precise analyses (#4, #5) correspond to both the largest fractions of red rutile and those that have the highest U and Pb concentrations and the highest $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. They yield identical $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 2115.5 ± 3.6 and 2118.5 ± 2.2 Ma (2 σ), respectively and the weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ date of 2117.7 ± 1.9 Ma (MSWD=1.9) is interpreted as a good estimate for the timing of rutile exsolution from Ti-rich amphibole. It is likely however, that this exsolution took place above the closure temperature of rutile (380-420°C; Mezger et al., 1989), and so more accurately, this date represents the timing of cooling below the closure temperature of Pb-diffusion in rutile after the exsolution.

Discussion

The metamorphosed mafic igneous rocks (metabasites) from the southern part of the Bastar craton contain hornblende, plagioclase, chlorite, quartz, epidote and iron oxide but no garnet. In contrast, metabasites in the northern block do contain garnet. Narayanaswami et al. (1963) suggested that the metamorphic grade increases consistently from south to north in the Bastar craton. It is unclear at this point whether the presence or absence of garnet in these metabasites is due to bulk composition, differing P-T conditions or both.

The presence of garnet is indicative of medium to high pressure

metamorphic conditions. In many cases garnet may be absent in basic rocks metamorphosed under low pressure conditions such as in most thermal aureoles (Yardley, 1993). De Waard (1967) found that garnet-bearing metabasites are rich in Al_2O_3 -content compared to garnet-free varieties and their bulk compositions plot above the ideal hornblende-plagioclase join in the ACF. The bulk chemical compositions of the studied samples, presented by Srivastava and co-workers (Srivastava and Singh, 2004; Srivastava, 2006a, b, 2008; Srivastava and Gautam, 2007), reflect low concentration of Al_2O_3 , as a result they lie below the hornblende-plagioclase join in the ACF. This is very likely the reason for the lack of garnet in the studied metabasites. Manna and Sen (1974) proposed that garnetiferous types have lower X_{Mg} (0.4). The metabasites of the study area have X_{Mg} higher than 0.4 (Srivastava, 2006b), thus suggesting that bulk composition is, at least, partly responsible for the absence of garnet in metabasites of the study area.

The experimental data of Green and Ringwood (1967, 1972) on quartz tholeiite with $X_{\text{Mg}} = 0.61$, indicate that garnet is formed at 700-800°C/8 kbars. Geothermobarometric estimates for metabasites from the study area indicate temperatures of ~575°C and ~700°C for BN and BD1 dykes, respectively (based on the hornblende-plagioclase thermometer of Blundy and Holland, 1990). The simplified barometer proposed by Hammarstrom and Zen (1986) and Hollister et al. (1987) based on the Al-contents in the amphibole, when applied to BD1 samples yielded a pressure range between 3.3 and 5.5 kbar (see Table 4). It is not possible to calculate pressure conditions for BN dyke samples as they have very low Al-contents (< 1). Here it is important to mention that because of the small distance (sometimes adjacent to each other) between samples, and no post-metamorphic tectonic activity between sample sites, we argue that both mafic dyke swarms were metamorphosed under similar P-T conditions.

Figure 8 presents the chemographic relationships between different mineral phases present in metamorphosed mafic igneous rocks (Bucher and Frey, 2002). The mineral assemblages observed in the Bastar metabasites have close similarities with the chemographies 1 and 2 but it is more close to the chemography 2 as these are biotite free. These two chemographies are representative of metabasites in

Figure 8. Chemographic relationship between different mineral phases present in metamorphosed mafic igneous rocks represented by ACF diagrams (based on Bucher and Frey, 2002). Star shows presumed assemblages and P-T condition of studied metabasites.

the middle to upper amphibolite facies at low pressures (Bucher and Frey, 2002). Chemography 3 contains garnet and two pyroxenes in their mineral assemblages, not hornblende, therefore the observed mineral assemblage is not corroborated with this chemography. It is also important to note that most of the amphiboles of chemographies 1 and 2 contain ferro-magnesian amphiboles in addition to a calcic-amphibole (Bucher and Frey, 2002). The Bastar metabasite dykes also contain ferro-magnesian amphiboles. Estimated P-T values for the studied rocks are also plotted on this diagram which fall between chemographies 1 and 2. Thus, we conclude that the studied dykes have mineral assemblage somewhere between chemographies 1 and 2. On this basis we presume these samples, which are representative for both dyke swarms, were metamorphosed under moderate temperature (600-700°C) and pressure (3.5-5.5 kbar) conditions and may be classified as medium-grade metabasites. This also suggests that the lack of appropriate pressure conditions (i.e. above 8 kbar) and lack of suitable bulk composition inhibited formation of garnet-bearing assemblages of metabasites in the study area.

U-Pb ID-TIMS results for rutile in a BN metamorphosed mafic dyke from the southern Bastar craton (sample JEF00-14) indicates that the timing of exsolution of retrograde rutile from Ti-rich hornblende may have occurred at 2118 ± 2 Ma, which represents a robust minimum age constraint for the timing of emplacement of the BN dyke, and by inference the BD1 dyke swarm since BN dykes cross-cut the BD1 swarm.

Although some authors have studied metabasites from the central India Bastar craton and adjoining Eastern Ghats belt (Mishra et al., 1988; Ramakrishnan, 1990; Dasgupta et al., 1993; Bhowmik and Roy, 2003; Santosh et al., 2004, 2006), a 2.1 Ga metamorphic event in the Bastar craton has not been reported previously. Ramachandra et al. (2001) have presented a critical review of the tectonothermal evolution of the Bastar craton on the basis of geological features observed by different authors and available geochronological data on different granitoids. These authors have suggested that during the Neoarchean to Paleoproterozoic period (2.7 to 2.1 Ga) the Bastar craton experienced extensive magmatism, tectonic reworking and uplift/erosion. Yedekar et al. (1990) documented 2.1 Ga volcanic activity in the northern Bastar craton. However, there is no dyke swarm dated at ca. 2.1 Ga in the Bastar craton, ca. 2180 Ma mafic dykes are reported from the adjoining Dharwar (Pandey et al., 1997; French and Heaman, 2010) and Bundelkhand (Rao, 2004) cratons. Although precise dates are not available for many granitic intrusions in the Bastar craton, a number of ca. 2.1 Ga granites, mainly exposed within the study area, have been reported (Sarkar et al., 1981, 1990; Sarkar and Gupta, 1990). The Bijli rhyolites exposed in the northern Bastar craton also have a similar age (Sarkar et al., 1981). Sarkar et al. (1990) pointed out that 2.1 Ga corresponds to the timing of late- to post-tectonic I-type granite plutonism followed by crustal anatexis and generation of S-type granites and migmatization, marking final cratonization of Bastar craton. Similar events are also reported from the adjoining Singhbhum craton (Sarkar et al., 1990; Ericksson et al., 1999). It is significant to mention that on the basis of a Paleoproterozoic compilation of lithostratigraphic, tectonothermal, geochronological and paleomagnetic data Zhao et al. (2002) documented a global period of 2.1–1.8 Ga collisional orogens and established Precambrian geological kinship between South America and West Africa; Western Australia and South Africa; Laurentia and Baltica; Siberia and Laurentia; Laurentia and Central Australia; East Antarctica and Laurentia, and North China and India. The 2.1 Ga U-Pb rutile age

obtained here adds further evidence that that Bastar craton may have been part of this global crustal amalgamation beginning at about 2.1 Ga.

Summary

Metamorphosed mafic igneous rocks from two dyke swarms exposed in the southern part of central Indian Bastar craton comprise garnet-free, medium-grade metabasites. Amphibole compositions from the Meso-Neoarchean BD1 swarm span the range from magnesio- to ferro-hornblende, whereas those from the Neoarchean-Paleoproterozoic BN swarm are distinctly high X_{Mg} magnesio-hornblendes. Amphibole compositions from the BN dykes also have distinctly higher Cr_2O_3 contents, and lower FeO, Al_2O_3 , Na_2O , K_2O and TiO_2 concentrations. Geothermobarometric estimates based on amphibole-plagioclase pairs indicate temperatures of $\sim 575^\circ C$ and $\sim 700^\circ C$ for BN and BD1 dykes, respectively. Al-contents in amphiboles suggest pressures of equilibrations around 3.7 to 5.5 kbar. This suggests medium amphibolite grade metamorphism of these dykes. U-Pb IDTIMS results for metamorphic rutile from a BN dyke yields an age of 2118 ± 2 Ma and, considering the low closure temperature to Pb diffusion in rutile, provides a minimum estimate for the timing of amphibolite grade metamorphism in these dykes. This date is interpreted to indicate the timing of exsolution of retrograde rutile from Ti-rich hornblende. This represents a robust minimum age constraint for the timing of emplacement of the BN, and by inference the BD1 dyke swarm.

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