Amphibolites in the rare metal- and tin-bearing Bastar–Malkangiri pegmatite belt in Chhattisgarh and Odisha, India

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Amphibolites and Abukuma-type low-grade and low-pressure meta-sedimentary rocks (MSR) host mineralised rare metal (Nb–Ta, Be and Li)- and Sn-bearing granite pegmatites and their parental, fertile S-type granites in the Bastar–Malkangiri Pegmatite Belt (BMPB) in the SE part of the Bastar craton in parts of Chhattisgarh and Odisha, India. Amphibolites, based on their field relationship (as sills in MSR), mineral assemblage and textural features, are broadly classified into three types: (i) tremolite-, (ii) hornblende–actinolite-, and (iii) hornblende-bearing amphibolites. Petrochemically, amphibolite types (i–iii) show a regular decrease in their Mg content and related trace elements such as Cr (81–1731 ppm), Ni (135–379 ppm) and Co (23–68 ppm) and, hence, are designated, respectively, as high-, intermediate- and low-Mg amphibolites. All the three types show slight enrichment in Si, Fe and P, reflected in their normative quartz, hypersthene and lesser diopside, magnetite, ilmenite and apatite, but *no* olivine. They are relatively enriched in incompatible elements such as Rb (16–526 ppm), Ba (15–538 ppm), Zr (56–147 ppm) and Nb (3–44 ppm), with relatively a higher concentration of these elements in those near to the contacts with pegmatites, thereby demonstrating some influence of the pegmatites on the chemistry of the host amphibolites. In spite of these, the three types of amphibolites show regular differentiation trends, reflected by their systematic decrease of Ni, Cr and Co with a decrease of Mg, and also show Fe-enrichment in their alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) – ($\text{FeO} + \text{Fe}_2\text{O}_3$) – MgO (AFM) plot. The field, petrography and major–minor trace elements petrochemistry, including rare earth elements with slight negative to no Eu-anomaly, and their chemical patterns cumulatively point out that these amphibolites are *ortho-type* and *sub-alkaline* in nature, with *quartz tholeiitic* magmatic affinity, and the formation due to more of fractional crystallisation and less of 5–25% partial melting of an enriched primordial mantle magma (enriched mid-oceanic ridge basalt – E-MORB), emplaced at a deduced shallow depth of 10–25 km, with the main controlling phases being olivine, plagioclase, clinopyroxene and apatite.

Keywords. Amphibolites; Bastar–Malkangiri Pegmatite Belt; Odisha–Chhattisgarh; India.

1. Introduction

The Bastar–Malkangiri Pegmatite Belt (BMPB), in parts of the Chhattisgarh and Odisha states of

India, is well known for primary and secondary commercial deposits of tin and rare metals (RMs), viz., lithium, beryllium, niobium and tantalum, manifested as cassiterite, lepidolite, amblygonite,

beryl and columbite–tantalite, with no commercial mica (Deshpande 1976; Ramaswamy *et al.* 1976; Murthy *et al.* 1979; Ramachar *et al.* 1979; Lamba and Khanna 1981; Ramesh Babu and Ramachar 1983; Lamba and Agarkar 1988; Acharya *et al.* 1989; Ramesh Babu 1993, 1999). Earlier, Crookshank (1963) and Bhola and Bhatnagar (1969) reported the occurrence of lepidolite and beryl from the pegmatites around Mundval. BMPB extends over 80 km in an NW–SE direction from Dantewada in the Bastar district of Chhattisgarh on the northwest to Salimi in the Malkangiri district of Odisha on the southeast and passes through the villages of Metapal, Katekalyan, Tongpal, Govindpal, Mundval, Mundaguda and Dammoguda (Ramesh Babu 1990). In BMPB, the pegmatites are intimately associated with granites that, in turn, were emplaced in the Precambrian Bengpal Group of rocks, comprising meta-sedimentary rocks and amphibolites. We present here the geological setting, structure, petrography and petrochemistry of the amphibolites in the study area, and discuss their implication on the petrogenetic aspects of these amphibolites, besides probing the bearing of these amphibolites on the pegmatitic RM mineralisation in the area.

2. Geological setting

The BMPB, in parts of Chhattisgarh and Odisha, forms the SE part of the Bastar craton in central India (figure 1). It extends over 80 km in length, with 15–20 km width, in a general NW–SE direction, starting from Dantewada in the Bastar district (Chhattisgarh) in NW to Salimi in the Malkangiri district (Odisha) in SE. It is bound by the Indravati basin in the north, Sukma basin in the south, Eastern Ghat complex in the east and Bailadila Iron Ore Group in the west. In the area under study, the oldest rocks exposed are the Archaean meta-sedimentary and meta-basic rocks (amphibolites) of the Bengpal Group, with a regional metamorphic event around 2530 ± 89 Ma, defined by their migmatitic leucosome (Bandyopadhyay *et al.* 1990; Ramakrishnan 1990). Palaeoproterozoic granitoids, known as Paliam and Darba granites in the SE part of BMPB (2308 ± 48 Ma, Ramesh Babu *et al.* 1993), pegmatites, quartz veins and dolerites emplaced/intruded into the Bengpal Group of rocks, and the entire sequence is unconformably overlain by the Neoproterozoic Indravati Group of sediments. The

meta-sedimentary rocks of the Bengpal Group are mainly argillaceous and arenaceous in bulk composition and comprise andalusite schist (with cordierite, at places), quartz-mica schist, sericite quartzite and quartzite. Thin bands and lenses of banded magnetite quartzite are common in the NW part of BMPB. Amphibolites occur mainly as sills in the meta-sedimentary rocks. In the NW part of the belt, these occur at the contact of meta-sedimentary rocks and granites. Paliam and Darba granites in the SE part as well as the granites around Pakanar and Metapal in the NW part of BMPB were emplaced into the Bengpal Group of rocks, with their contacts being fairly sharp at north of Hirapa Dongri and south of Arval Dongri (Ramesh Babu and Dhana Raju 2016). At places, the thin zone of granitised schist occurs in the contacts. The andalusite schist at the contact of granites is undulated and transformed into the coarse-grained muscovite schist. Granites, at the contact with the meta-sedimentary rocks, show flow banding/foliation, almost parallel to the margins and contain xenoliths of the latter. In the marginal parts of the Paliam granite, greisenisation (cf. Lamba and Agarkar 1988), marked by muscovite-rich (up to 13.5 vol%) zones and occurrence of fluorite and topaz, is recorded. Pegmatites occur intruding most of the earlier rock formations (Bengpal Group and granites) and show varied internal zoning, mineralogy and Sn–RM-mineralisation, based on which they are classified into five types, viz., type I: barren, simple, unzoned biotite or muscovite–microcline pegmatites; type II: partly differentiated muscovite–microcline pegmatites with beryl; type III: fully differentiated muscovite–microcline pegmatites with beryl, columbite–tantalite $\pm$ cassiterite; type IV: replaced lepidolite–albite–muscovite pegmatites with amblygonite, cassiterite, beryl $\pm$ columbite–tantalite; and type V: replaced muscovite–albite pegmatites with cassiterite and beryl (Ramesh Babu 1993, 1999).

Amphibolites occupy a large part of the study area. They are dark coloured, hard, massive and, being resistant to weathering, as compared to surrounding schists, stand out prominently and form hill ranges. Large bodies of these are exposed to the north of Churwada trending E–W, the south of Mundval and Tongpal trending E–W to NW–SE, and around Marjun. Comparatively thinner bands are also seen at Rangawada, Peramarasu, Mohpodoro and west of Kukri metta. Amphibolites have intruded all the

Figure 1. Generalised geological map of southern Bastar craton, showing BMPB and the Garda-Toyar area (Geology, after Ramakrishnan 1990).

meta-sedimentary rocks of the Bengpal Group, mostly as sills with sharp contacts, although the cross-cutting relationship is noticed, at places. They are of two distinct types: (i) large massive, thicker and medium-grained bodies such as those north of Churwada, south of Mundval and around Marjun, which do not show much contact effects and into which many pegmatites, including the mineralised tin- and RM-bearing ones, are emplaced; and (ii) relatively thinner and small bodies at Rangawada, Peramarasu, Mohpodoro and west of Kukri metta, which are devoid of any major pegmatite veins, including mineralised ones. Based on the specific phase of amphiboles, these amphibolites are classified into three types, viz., tremolite-, hornblende-actinolite- and hornblende-bearing amphibolites, corresponding, respectively, to high-Mg (9–16% MgO), intermediate-Mg (7–10% MgO) and low-Mg (4–7% MgO) amphibolites. They are mostly massive, with the first two types generally occurring together and the tremolite-bearing ones at lower levels compared to the other two, whereas hornblende-bearing amphibolites are of smaller dimensions and spatially separated from the first two types.

3. Structural aspects

A perusal of the geological map of southern Bastar and Jeypore by Crookshank (1963) suggests a closed regional structure west of Kukanar, extending in NW–SE direction between Gariapal and Muripal villages. From the disposition of rock formations, it is inferred that the major structure is a doubly plunging, overturned anticlinorium with the area having been subjected to a minimum of the following two cycles of folding: (i) due to compressional forces roughly from NNE–SSW (F_1), which have thrown the formations into overturned folds with E–W to WNW–ESE trends and NNE axial plane dipping; and (ii) second set of compressional forces from WNW–ESE have refolded the axes of the first-order folds, with trend of cross-fold (F_2) axes being NNE–SSW, sub-parallel to the F_1 compressional forces. The meta-sedimentary rocks in the study area show ENE–WSW to E–W and NW–SE regional trend with northerly dips. The longer axis of the amphibolites is aligned more or less parallel to the regional trend of the meta-sedimentary rocks. However, in the NW portion around Marjun, the discordant relationship

is noticed. Abundant emplacement of pegmatites had taken place along the shears. The amphibolites were subjected to profuse emplacement of pegmatites, especially near to their contact with meta-sedimentary rocks. The area was subjected to intense faulting, especially in the SE part. The major trend is NNE–SSW and sub-parallel to the major lineament along which the Sabari river flows. The straight course of the Bhimsen river and the steep scarps of the Kukri metta hill are also attributable to a major fault. The faulting appears to be post-pegmatitic, as has been observed north of Gurupada village, where a pegmatite of ~30–50 cm thickness was dislocated by five fault planes. Along the faults to the NE of the centre, the movement is sinistral, while those to SW of the centre have dextral movement. The lineament and drainage analysis, based on LANDSAT imagery and aerial photographs, indicates five major trends, viz., NW–SE, WNW–ESE, NNW–SSE, ENE–WSW and NNE–SSW, which appear to represent the deep-seated fractures in the crust (Chawla unpublished report 1988).

4. Methods of study

The methods of the study adopted are those of petrography and petrochemistry.

4.1 Petrography

This includes thin-section study in the transmitted light and a few sections in reflected light. Microscopic study for different aspects, such as rock nomenclature, texture, mineralogical alterations, determination of An-content of plagioclase by extinction angle method and mode, was carried out on a Leitz Orthoplan microscope having a facility for simultaneous study in both transmitted and reflected light. During the mineragraphic study, quantitative determinations of per cent reflectivity (R) at 546 nm and micro-hardness (Vicker's hardness number, VHN) of ore minerals were carried out using Leitz equipment. The modal analysis of 20 representative samples was done, after staining for feldspars, by point count method (with about 3000 counts for each sample) using a Swift automatic point counter. Photomicrography was done by the Leitz Variomat automatic photographic accessory, fitted to the above microscope.

4.2 Petrochemistry

The major and minor element analysis of rocks, in terms of oxides, was carried out using the rapid wet chemical methods, essentially after Shapiro and Brannock (1955). Details of various techniques used in this, involving sample and solution (I and II) preparations and instruments used such as (i) atomic absorption spectrophotometry for Al, Fe^t, Mg, Ca and Mn; (ii) spectrophotometry for Si, Ti and P; (c) flame photometry for alkalis; (d) titrimetry for Fe²⁺; and (e) gravimetry for H₂O, were given elsewhere (Satyanarayana 1986) and the same were adopted in this study. International Rock Standards (IRS) – AGV-1 and BCR-1 – were used as a check on the analysis. The per cent errors involved with reference to the value of these standards for different analysed radicals are as follows: SiO₂: ± 0.8, TiO₂: ± 3, Al₂O₃: ± 0.4, Fe₂O₃: ± 1, FeO: ± 2.5, MnO: ± 2, MgO: ± 1.3, CaO: ± 0.6, Na₂O and K₂O: ± 1.6 and P₂O₅: ± 6. Trace elements – Rb, Sr, Ba, Pb, Y, Zr, Ni, Co, Cr, V and Zn – in rock samples were determined by WDXRFS (Wavelength Dispersive X-ray Fluorescence), following the methods of determination given by Viswanathan (1989), using the K- α spectra of the above trace elements, except Pb for which L-beta spectra were used, with rhodium X-ray tube as the excitation source. The resultant secondary X-radiation was collimated (150 μ m) and dispersed, using a LiF 220 analysing crystal. The intensity of each radiation was measured with a scintillation counter. The data were calibrated using different appropriate IRS. The resultant regression equations of the form $y = a + bx$ (where y is the concentration of the element, a is the intercept, b is the slope and x is counts/second of the characteristic radiation of the element) were used to compute the element concentration in the samples for different determined values of ' x '. For each sample, at least three determinations were made and their arithmetic mean of the concentration of element was finally taken. For the elements analysed, a precision and accuracy of ±10–20% was obtained at their lowest level of concentration in the sample, with respect to IRS. Rare earth elements (REE: La, Ce, Sm, Eu, Tb, Yb and Lu) were determined by Instrumental Neutron Activation Analysis (INAA), following the methods of Reddy *et al.* (1975) and Gurna *et al.* (1988), using APSARA reactor, 45 cc Ge (Li) detector, 1024 channel analyser, 5 h time and 2.3 keV at 1332 keV system resolution. The statistical error at 1σ

level for the counts collected for the peak of interest of La, Ce, Sm, Yb and Lu is $<\pm 10\%$ and for Eu and Tb is $<\pm 15\%$.

5. Petrography

Amphibolites are medium grained and contain essentially one or two amphiboles (tremolite, actinolite and hornblende) and plagioclase as major minerals, with minor to accessory quartz, chlorite, zoisite, epidote, sphene, apatite, rutile, opaque ore minerals (ilmenite, magnetite and sulphides) and rarely microcline. Texturally, these rocks are massive with relict ophitic to sub-ophitic texture, defined by large laths of hornblende/actinolite–tremolite (after pyroxene) enclosing highly sericitised, idioblastic plagioclase laths, preserved in some samples. Occasionally, they are feebly foliated due to the rough orientation of chlorite at south of Mundval. Myremekitic and granophyric textures were noticed in some samples. *Hornblende* is mostly prismatic in habit, often clustering and with rugged terminations. Basal sections are euhedral prismatic with four or eight sides, and show perfect two sets of cleavage at an angle of 56° . It is in different shades of green and bluish green colour, and is pleochroic. Twinning is very common. Extinction angle ($Z\wedge C$) varies from 22° to 24° and rarely up to 31° . It alters to chlorite and zoisite. *Tremolite* is colourless and is either long, tabular prismatic crystal or columnar to aggregate fibrous in form. Many grains show simple twinning. Extinction angle varies from 18° to 21° , indicating that tremolite is Mg-rich. *Actinolite* is pale green, feebly pleochroic and similar to tremolite in habit, with extinction angle ranging from 10° to 15° . At places, two generations of amphiboles are seen – the earlier formed one as tabular prisms of tremolite/actinolite, enclosed by xenoblastic prisms of common hornblende. *Plagioclase* is mostly subhedral to euhedral in habit and is twinned after complex laws such as combined carlsbad and albite, and albite and pericline laws. Usually, it is much altered to sericite or fine aggregates of saussurite, with some grains showing less alteration. Although the alteration is intense, the majority of the grains retain twinning. Occasionally, two modes of plagioclase are seen, with larger xenoblastic grains completely sericitised and smaller relatively fresh grains showing lamellar twinning. Anorthite content (determined after Michel Levy's method) varies from 34% to

$42\% \pm 3\%$. Quartz occurs in minor amount as (i) medium- to coarse-grained xenoblasts, occupying the interstices and (ii) cuniform type in myrmekitic and granophyric intergrowths with plagioclase; it normally shows wavy extinction. Chlorite is an important accessory mineral, mostly occurring as an alteration product of the amphiboles. In tremolite-bearing rocks, it is Mg-rich showing anomalous brown interference colours and length-fast character, whereas in hornblende-rich rocks, it is Fe-rich with anomalous violet or blue interference colours and length-slow character. Usually, aggregates of chlorite are associated with sphene and opaque minerals. Zoisite occurs as an alteration product of amphiboles, while epidote occurs as an alteration product of both amphiboles and plagioclase. Sphene occurs in almost all the samples as wedge-shaped crystal and in clusters of drop-like granules. It occurs around ilmenite with nearby alteration of amphibole to chlorite, indicating its formation due to released Ti and Ca from ilmenite and amphiboles, respectively. Apatite occurs as columnar and clusters of radiating needles. Fresh microcline crystals, showing typical cross-hatched twinning, are seen rarely in smaller basic intrusive bodies containing relatively higher plagioclase content. Ilmenite occurs as tabular and prismatic crystal, replaced by anatase along margins. Rutile is deep brown in colour, with red internal reflections and occurs as prisms, either around grain margins or as fracture filling of amphibole grains. Minor irregular-shaped pyrrhotite, showing strong birefractance and anisotropism, occurs in some samples. Traces of ultrafine grains of other sulphides, with chalcopyrite replaced by bornite, are seen in a few sections. Based on the presence of a type of major amphibole, the amphibolites in the study area are broadly classified into three types, viz., (i) tremolite-, (ii) hornblende–actinolite- and (iii) hornblende-bearing amphibolites. A few textural features of the amphibolites are given in plate 1.

Modal composition (in vol.%) of these amphibolites is given in table 1. An examination of the modal composition reveals that the amphibolites intrusive in different parts of the area show variation both in type and content of amphiboles as well as plagioclase. Thus, those of Govindpal, Beikupli and Chintalnar (sl. nos. 1–6 in table 1) are light coloured comprising mainly tremolite, whereas those north of Churwada, Kudripal and Mindaguda (sl. nos. 7–14) comprise mainly hornblende with minor actinolite. It may be noted that the samples of massive amphibolites south of

Plate 1. (a) Amphibolite showing relict ophitic texture, with hornblende (H) enclosing highly sericitised plagioclase. PPL, + N, Bar: 0.26 mm. (b) Amphibolite with typical fibrous and columnar aggregate of tremolite. PPL, +N, Bar: 0.29 mm. (c) Two generations of amphiboles, the first formed as columnar actinolite (A), enclosed in xenoblastic prisms of chloritised hornblende (H). PPL, +N, Bar: 0.17 mm. (d) Intergrowth of cunifform quartz and saussuritised plagioclase. PPL, +N, Bar: 0.16 mm. (e) Sphene occurring around opaque grains (ilmenite), with nearby alteration of amphibole to chlorite. PPL, +N, Bar: 0.19 mm. (f) Ilmenite (I), occurring as tabular and prismatic crystals, replaced by anatase (A). RL, oil; 1 N, Bar: 0.09 mm.

Mundval (sl. nos. 3 and 8) contain both hornblende and tremolite, indicating probably a complex or multiple intrusions. Likewise, the amphibolites of Marjun and Churwada are also considered to be multiple intrusive bodies. In contrast to the presence of both hornblende- and tremolite-rich larger

bodies of amphibolites, the smaller bodies of Permarasu, Rangawada and Kukri metta comprise chiefly common hornblende. Anorthite content of plagioclase in larger bodies of amphibolites varies from 40% to 42%, whereas in the small bodies of amphibolites it varies from 34% to 36%. The lower

Table 1. *Modal analysis (in vol.%) of the amphibolites from BMPB.*

Sl. no.	Tremol.	Hornbl.	Actin.	Plag.	Zoisite	Chlorite	Quartz	Sphene	Apatite	Opaques
1. B-7	63.0	—	—	33.5	—	—	2.5	0.5	—	0.5
2. B-27	62.4	—	—	20.0	14.0	1.0	2.5	—	—	0.1
3. B-24	60.0	—	—	25.0	4.0	3.0	6.0	—	0.5	1.5
4. B-34	53.5	—	—	31.5	13.0	—	1.0	—	—	1.0
5. B-39	62.7	—	—	36.0	—	—	0.4	0.1	0.1	0.7
6. B-35	61.0	—	—	20.0	15.5	0.5	2.0	0.7	0.2	0.1
7. B-22	—	47.3	5.8	31.3	1.8	0.3	11.8	—	0.5	1.2
8. B-12	—	49.0	15.3	33.0	—	—	2.4	—	—	0.3
9. B-51	—	55.0	2.2	33.8	—	4.5	3.0	1.0	0.3	0.2
10. B-18	—	63.2	0.1	24.8	1.4	—	8.6	0.9	—	1.0
11. B-20	—	46.2	0.2	25.4	0.1	10.5	15.4	1.7	0.1	0.4
12. B-11	—	48.0	4.5	42.0	1.5	—	2.0	1.5	0.5	—
13. B-10	—	65.9	0.6	21.7	—	1.7	7.8	1.8	0.1	0.4
14. B-52	—	45.0	2.7	39.0	1.0	—	11.9	0.1	—	0.3
15. B-19	0.8	41.4	—	42.4	4.7	—	10.0	—	—	0.7
16. B-21	0.2	37.6	—	51.7	1.0	0.4	8.6	0.5	—	—
17. B-6	—	50.0	—	43.5	2.0	—	2.0	2.0	0.5	—
18. B-3	—	45.0	—	43.0	4.5	5.3	1.0	2.5	0.4	0.6
19. B-46	—	40.0	—	39.8	—	5.8	13.4	1.0	—	—
20. B-32	Tr/act0.2	40.2	—	41.2	0.7	—	13.8	3.5	0.4	—

N.B.: Sl. nos. 1–6: tremolite-bearing amphibolites; 7–14: hornblende–actinolite-bearing amphibolites; and 15–20: hornblende-bearing amphibolites.

Abbreviations used: Tremol.: Tremolite; Hornbl.: Hornblende; Actin.: Actinolite; Plag.: Plagioclase, Opaques: Ilmenite, magnetite and Cu–Fe sulphides.

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An-content and the presence of microcline in the smaller bodies of hornblende-bearing amphibolites indicate that they are more of alkaline than the larger bodies of tremolite-bearing and hornblende–actinolite-bearing amphibolites.

6. Petrochemistry

6.1 Results and petrochemical features

Chemical analyses of 20 samples of amphibolites, in terms of their major and minor oxides (table 2), CIPW norms (table 3), Niggli values (table 4) and trace elements, including REE for two samples (table 5), are presented.

An examination of the petrochemical data reveals the following main chemical features.

6.1.1 Classification of amphibolites

From the analyses of 20 amphibolites (table 2), three groups can be identified, based on their MgO content. Thus (i) the first six samples (at sl. nos. 1–6) represent *high-Mg type* with an MgO

content ranging from 9.38 to 15.95 wt.%, with an average of 13.64 wt.%; (ii) the samples at sl. nos. 7–14 represent *intermediate-Mg type* with an MgO content ranging from 7.30 to 10.56 wt.%, with an average of 8.30 wt.%; and (iii) the samples at sl. nos. 15–20 represent relatively *low-Mg type* with an MgO content varying from 4.36 to 7.05 wt.% with an average of 5.85 wt.%. This classification of amphibolites into high-, intermediate- and low-Mg types agrees well with their field and petrographic data in that the high-Mg type corresponds to the tremolite-bearing amphibolites, intermediate-Mg type to hornblende–actinolite-bearing amphibolites and low-Mg type agrees with the hornblende-bearing amphibolites.

6.1.2 Major and minor oxide patterns

The above Mg-based classification of the amphibolites is corroborated by their other important constituents such as CaO, Al₂O₃ and to some extent TiO₂. Thus, the high-Mg type containing tremolite is characterised by low CaO (5.47–7.29 wt.%, with an average of 6.20 wt.%), low Al₂O₃ (8.50–13.75 wt.% with an average of 10.61 wt.%)

Table 2. Major and minor element analysis (as wt.% oxide) of the amphibolites from BMPB.

Sl. No.	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	H ₂ O ⁺	H ₂ O ⁻	Mg*	D.I.
1. B-7	52.83	0.19	8.83	0.19	10.65	0.19	15.40	5.92	1.07	0.71	0.96	2.55	0.41	52.29	17.00
2. B-27	50.63	0.10	8.50	2.69	8.40	0.17	15.95	5.78	1.10	0.21	3.18	3.13	0.14	59.15	20.38
3. B-24	52.19	0.37	10.61	0.72	10.44	0.20	14.06	5.47	1.00	1.75	0.96	2.00	0.40	50.45	19.93
4. B-34	53.91	0.56	9.82		10.44	0.19	14.58	5.47	1.05	0.50	0.97	1.22	0.50	51.33	18.77
5. B-39	53.28	0.63	13.75	0.11	9.54	0.18	9.38	7.29	1.58	1.61	1.08	1.12	0.32	42.62	24.75
6. B-35	52.36	0.34	12.18	0.19	9.54	0.18	12.50	7.29	1.18	0.88	1.09	1.47	0.34	49.87	18.92
7. B-22	52.64	0.43	14.15	0.47	9.94	0.18	8.83	7.50	1.90	0.98	0.91	0.94	0.30	40.33	25.82
8. B-12	51.90	0.35	11.81	1.00	8.64	0.19	10.56	7.34	1.31	0.80	3.38	2.04	0.19	47.91	28.39
9. B-51	51.91	1.13	9.92	2.86	11.06	0.20	7.68	8.74	2.06	0.73	2.23	1.35	0.01	34.46	29.94
10. B-18	52.78	0.73	10.16	2.69	10.41	0.19	8.19	8.39	1.50	0.75	2.13	1.36	0.18	37.26	28.72
11. B-20	51.78	0.73	14.92	1.43	10.29	0.02	7.30	9.49	1.05	1.05	1.04	0.54	0.31	35.43	22.24
12. B-11	51.55	0.80	10.16	2.96	10.16	0.17	8.29	9.28	2.00	0.66	3.15	0.67	0.02	37.51	29.11
13. B-10	53.12	0.60	9.45	1.80	9.90	0.21	8.29	9.57	1.53	0.85	3.78	1.28	0.16	38.88	30.42
14. B-52	53.09	0.47	14.92	0.61	9.90	0.20	7.30	6.20	1.88	1.65	1.07	1.77	0.47	35.92	30.09
15. B-19	53.70	0.33	14.12	2.54	7.33	0.15	6.73	8.23	1.80	1.01	2.35	1.53	0.06	40.73	34.34
16. B-21	54.62	0.55	14.64	3.95	7.25	0.15	4.36	7.69	1.87	1.24	1.73	1.65	0.27	31.25	39.51
17. B-6	50.94	0.75	14.12	2.33	8.73	0.15	6.22	9.79	2.62	0.89	2.78	0.96	0.03	34.84	32.88
18. B-3	47.25	0.68	15.11	3.20	10.34	0.20	5.90	10.06	3.12	0.30	3.16	0.69	0.01	30.04	27.93
19. B-46	54.50	0.63	13.22	2.85	8.26	0.17	4.87	8.39	1.75	1.26	2.55	1.46	0.14	30.75	38.57
20. B-32	53.28	0.90	9.92	3.88	9.32	0.17	7.05	8.74	2.06	1.50	2.13	0.84	0.10	36.63	36.27

Note: Sl. nos. 1–6: high-Mg amphibolites; 7–14: intermediate-Mg amphibolites; and 15–20: low-Mg amphibolites.

Mg*: Mg-ratio; D.I.: Differentiation index.

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Table 3. *CIPW norms of the amphibolites from BMPB.*

Sl. No.	qz	or	ab	an	c	di	en	fs	mt	il	ap
1. B-7	4.2	3.9	8.9	17.0	—	5.2	36.0	18.2	0.2	0.3	2.0
2. B-27	9.8	1.1	9.4	8.3	3.6	—	39.9	13.3	3.9	0.2	7.7
3. B-24	1.5	10.0	8.4	19.5	—	1.6	34.6	18.5	—	0.8	2.0
4. B-34	7.1	2.8	8.9	20.6	—	—	36.4	18.1	0.7	1.1	2.3
5. B-39	5.0	6.7	13.1	27.2	—	5.7	21.8	15.6	—	1.2	2.3
6. B-35	4.0	5.0	10.0	25.3	—	3.7	30.1	16.4	0.2	0.6	2.3
7. B-22	4.0	5.6	16.2	27.2	—	3.7	21.0	16.6	0.7	0.8	2.0
8. B-12	12.9	4.5	11.0	14.5	3.6	—	26.4	14.8	1.4	0.9	8.1
9. B-51	8.8	3.9	17.3	15.8	—	11.2	16.2	13.9	4.2	2.1	5.0
10. B-18	11.7	4.5	12.6	18.9	—	7.3	18.5	14.3	4.0	1.4	5.0
11. B-20	7.7	6.1	8.4	33.1	—	6.2	16.6	15.1	2.1	1.4	2.4
12. B-11	8.5	3.9	16.8	16.7	—	8.5	18.2	13.3	4.2	1.3	7.4
13. B-10	12.8	5.0	12.6	16.4	—	5.9	19.1	14.8	2.6	1.2	8.7
14. B-52	4.9	9.5	15.7	27.5	—	1.2	17.9	17.7	—	0.8	2.4
15. B-19	13.0	6.1	15.2	26.1	0.4	—	16.8	11.0	3.7	0.6	5.4
16. B-21	16.6	7.2	15.7	27.2	0.2	—	10.9	9.4	5.8	1.1	4.0
17. B-6	5.9	5.0	22.0	23.9	—	6.6	13.7	11.4	3.2	1.4	6.4
18. B-3	0.1	1.7	26.2	26.4	—	2.8	11.4	18.5	4.6	1.2	7.4
19. B-46	16.7	7.2	14.7	24.5	—	0.4	11.5	11.8	4.2	1.2	6.1
20. B-32	10.1	8.9	17.3	13.3	—	13.1	13.8	10.0	5.6	1.7	5.0

Note: Sl. nos. 1–6: high-Mg amphibolites; 7–14: intermediate-Mg amphibolites; and 15–20: low-Mg amphibolites.

Table 4. *Niggli values for the amphibolites of BMPB.*

Sl. No.	q	al	fm	c	alk	si	ti	p	k	mg
1. B-7	10.0	12.0	71.0	14.0	3.0	122.0	0.33	0.90	0.30	0.71
2. B-27	−1.0	11.0	72.0	14.0	3.0	111.0	0.17	2.96	0.11	0.72
3. B-24	−3.0	14.0	68.0	13.0	5.0	117.0	0.62	0.92	0.54	0.69
4. B-34	12.0	13.0	71.0	13.0	3.0	126.0	0.95	0.93	0.24	0.70
5. B-39	10.0	20.0	55.0	19.0	6.0	134.0	1.16	1.06	0.31	0.63
6. B-35	6.0	16.0	62.0	18.0	4.0	122.0	0.59	1.06	0.33	0.69
7. B-22	7.0	20.0	54.0	20.0	6.0	131.0	0.79	0.94	0.25	0.60
8. B-12	14.0	17.0	59.0	20.0	4.0	130.0	0.66	3.57	0.29	0.67
9. B-51	3.0	14.0	57.0	23.0	6.0	127.0	2.08	2.32	0.19	0.50
10. B-18	13.0	15.0	58.0	22.0	5.0	133.0	1.37	2.25	0.25	0.53
11. B-20	11.0	21.0	50.0	25.0	4.0	127.0	1.33	1.06	0.40	0.53
12. B-11	0.0	14.0	56.0	24.0	6.0	124.0	1.45	3.21	0.18	0.53
13. B-10	13.0	14.0	55.0	26.0	5.0	133.0	1.13	4.01	0.27	0.56
14. B-52	10.0	23.0	52.0	17.0	8.0	142.0	0.93	1.18	0.37	0.55
15. B-19	14.0	22.0	48.0	23.0	7.0	142.0	0.65	2.64	0.27	0.55
16. B-21	27.0	25.0	45.0	23.0	7.0	155.0	1.18	2.09	0.30	0.41
17. B-6	−6.0	20.0	46.0	26.0	8.0	126.0	1.40	2.92	0.18	0.50
18. B-3	−18.0	21.0	47.0	25.0	7.0	110.0	1.19	3.11	0.06	0.44
19. B-46	24.0	22.0	46.0	25.0	7.0	12.0	1.33	3.03	0.32	0.44
20. B-32	7.0	15.0	54.0	24.0	7.0	135.0	1.72	2.28	0.33	0.49

Note. Sl. nos. 1–6: high-Mg amphibolites; 7–14: intermediate-Mg amphibolites; and 15–20: low-Mg amphibolites.

and low TiO₂ (0.10–0.63 wt.% with an average of 0.36%). In contrast, the low-Mg type having hornblende and plagioclase as its major constituents is marked by high CaO (7.69–10.06 wt.% with

an average of 8.82 wt.%), high Al₂O₃ (9.92–15.11 wt.% with an average of 13.52 wt.%) and relatively high TiO₂ (0.33–0.90 wt.% with an average of 0.64 wt.%). Compared to the above two types,

Table 5. Trace element contents, including REE for two samples, (in ppm) of the amphibolites of BMPB.

Sl. No.	Rb	Sr	Ba	Y	Zr	Nb	Zn	V	Cr	Co	Ni	Pb
1. B-7	215	61	39	68	74	19	115	143	1313	58	347	21
2. B-27	27	46	132	15	56	13	95	129	1731	68	379	20
3. B-24	136	31	538	44	74	44	113	145	1120	63	295	13
4. B-34	43	89	15	23	67	13	94	146	1329	59	339	15
5. B-39	79	99	189	36	81	17	86	147	529	50	219	18
6. B-35	87	92	222	36	67	18	83	145	999	54	285	16
7. B-22	67	117	271	35	92	15	102	161	550	50	230	20
8. B-12	54	103	102	39	73	3	77	174	997	50	249	6
9. B-51	20	84	187	26	108	9	89	325	580	58	218	13
10. B-18	36	131	166	24	143	15	82	259	581	54	222	3
11. B-20	526	215	109	40	99	18	84	168	253	49	198	17
12. B-11	43	108	99	34	142	6	80	235	780	52	250	10
13. B-10	45	11	184	29	137	19	91	204	413	68	197	25
14. B-52	233	92	87	75	99	18	90	180	301	34	174	20
15. B-19	63	75	204	35	122	13	69	242	313	42	173	13
16. B-21	59	97	206	37	147	16	103	152	81	35	135	16
17. B-6	35	173	180	18	112	8	82	171	320	32	171	12
18. B-3	16	106	133	20	86	3	87	266	334	36	153	34
19. B-46	54	104	283	32	139	11	79	210	120	23	143	24
20. B-32	46	136	392	31	173	22	121	234	394	32	181	100
Sl. No.	La	Ce	Sm	Eu	Tb	Yb	Lu	Total	(Ce/Yb) _{cn}	Eu/Eu*		
B-22	17	28	2.9	0.7	0.2	1.7	0.25	50.87	3.87	1.0		
B-19	14	24	3.7	0.8	0.4	2.0	0.3	45.2	2.89	0.68		

Note. Sl. nos. 1–6: high-Mg amphibolites; 7–14: intermediate-Mg amphibolites; and 15–20: low-Mg amphibolites.

Analyst: Dr. S Viswanathan, WDXRFS, AMD, Hyderabad.

B-22: Intermediate-Mg amphibolite; B-19: low-Mg amphibolite.

Analysts: Sher Singh Gurna and N. Satyanarayana, INAA Laboratory, AMD, Hyderabad.

the intermediate-Mg type, containing hornblende and actinolite, has patterns of CaO and Al₂O₃ of medium contents.

6.1.3 Critical trace element patterns

The Mg-based classification of the amphibolites is also corroborated by critical trace element contents (table 5) such as Cr, Ni, Co and Zr. Thus, the high-Mg type is characterised by high Cr (529–1731 ppm, average 1170 ppm), Ni (219–379 ppm, average 311 ppm) and Co (50–68 ppm, average 59 ppm), and low Zr (56–81 ppm, average 70 ppm). In contrast, the low-Mg type is marked by low Cr (81–394 ppm, average 260 ppm), Ni (135–181 ppm, average 159 ppm) and Co (23–42 ppm, average 33 ppm), and high Zr (86–173 ppm, average 130 ppm). The intermediate-Mg type is having patterns in between the above two contrasting patterns.

6.1.4 CIPW norm patterns

In respect of CIPW norms (table 3), the high-Mg-type amphibolites are characterised by high normative enstatite (21.8–39.9, average 33.1) and ferrosilite (13.3–18.5, average 16.7), and low normative diopside (0.0–5.7, average 2.7), ilmenite (0.2–1.2, average 0.7), magnetite (0.0–3.9, average 0.84) and apatite (2.0–7.7, average 3.1), whereas in the case of the low-Mg type it is *vice versa*, with the intermediate-Mg type having in-between values. Furthermore, the high-Mg type is marked by a higher value for normative an/ab ratio (0.88–2.5, average 2.0) in contrast to the lower value (0.77–1.7, average 1.3) for the low-Mg-type amphibolites.

6.1.5 Discriminatory plots

When the analysed amphibolites are plotted in relevant bi-linear diagrams with Niggli's mg as the abscissa against Niggli's ti (figure 2a) and alk

Figure 2. Bi-linear plots of Niggli's mg vs. Niggli's ti (a) and Niggli's alk (b); Niggli's mg vs. log Cr (c), log Ni (d), Co (e) and Zr (f) (after [Leake 1964](#)). Symbols used: *squares* – high-Mg/tremolite-bearing amphibolites; *triangles*: intermediate-Mg/hornblende-actinolite-bearing amphibolites; and *circles*: low-Mg/hornblende-bearing amphibolites.

Figure 3. Chondrite-normalised REE plot. B-22: intermediate-Mg amphibolite and B-19: low-Mg amphibolite (chondrite values after Nakamura 1974).

(figure 2b), and Cr (figure 2c), Ni (figure 2d), Co (figure 2e) and Zr (figure 2f) as ordinates (Niggli values in table 4), it is clearly seen in all these plots that the three types of amphibolites are clearly demarcated. Furthermore, in these plots a clear trend – either negative or positive, depending upon the geochemical relationship of the elements plotted on the ordinate against Niggli's mg – is seen.

6.1.6 Effect of intrusive pegmatite

The effect of intrusion of pegmatites into the amphibolites is reflected in the petrochemistry of the latter, particularly with respect to their K and related trace elements. Thus, the sample nos. B-7, B-24, B-39, B-20 and B-52, which are close to the pegmatite, the effect of pegmatitic intrusion is demonstrated in their relatively higher contents of K_2O (0.71–1.75 wt.%, table 2) and Rb (79–526 ppm, table 5), and to some extent Ba, highest in sample no. B-24 with 538 ppm (table 5). It is also interesting to note that the high- and intermediate-Mg amphibolites (samples at sl. nos. 1–14 in table 2) are having SiO_2 value varying from 50.63 to 53.91 wt.%, which is certainly higher than the one normally expected for an MgO content of 15.95–7.30 wt.%. This relatively higher SiO_2 content could also be ascribed to the pegmatites that are intrusive into the amphibolites.

6.1.7 REE patterns

Using the REE data on two samples, one each of intermediate-Mg-type amphibolites (sample no. B-22) and low-Mg-type amphibolites (sample no. B-19) (table 5), their chondrite-normalised patterns are shown in figure 3. From these data, it

is observed that there is not much difference in the total REE and LREE contents of these two types of amphibolites. However, the intermediate-Mg-type amphibolite (B-22) is marked by relatively higher $(Ce/Yb)_{cn}$ with no Eu-anomaly ($Eu/Eu^* = 1.0$), whereas the low-Mg-type amphibolite (B-19) is characterised by relatively lower $(Ce/Yb)_{cn}$ and small negative Eu-anomaly ($Eu/Eu^* = 0.68$) (figure 3).

7. Discussion

Data and information on the field setting, petrography and petrochemistry of the amphibolites in the area under study, presented heretofore, are critically examined in this section to arrive at their following four important aspects, viz., (i) type of the amphibolites – ortho or para; (ii) chemical nature of their precursor rock(s); (iii) petrogenetic implications; and (iv) bearing of the amphibolites on the pegmatitic RM mineralisation in the area.

7.1 Type of amphibolites

As per the field setting in the area under study, the three types of amphibolites, viz., high-Mg type with major tremolite, intermediate-Mg type with hornblende and actinolite, and low-Mg type with hornblende, are all essentially massive and were emplaced as sills, with sharp contacts, into their host, low-grade Abukuma-type meta-sedimentary rocks. Petrographically, the three types of amphibolites contain more or less equal amounts of amphiboles and twinned (on complex laws) plagioclase as major phases, with minor to accessory quartz, zoisite, chlorite, epidote, wedge-shaped crystals and clusters of sphene, columnar and clusters of radiating needles of apatite, and opaque minerals that comprise mostly ilmenite and

Figure 4. Bi-linear plot of Niggli's mg *vs.* Niggli's c. Trend line of the Karoo dolerites is shown with an arrow (after Leake 1964). Symbols as in figure 2.

magnetite (table 1). Diopside, a characteristic mineral of para-amphibolites, and almandine that is generally present in the ortho-type are conspicuously absent in these amphibolites, with the latter may be due to low-pressure and low-temperature Abukuma-type metamorphism in the area (Ramesh Babu and Dhana Raju 2018), in which almandine is absent. Petrochemically, the three types of amphibolites are characterised by (a) moderate to very high contents of Cr (81–1731 ppm) and Ni (135–379 ppm) (table 5) and lower values of Niggli's k (0.06–0.33) (table 4); (b) in Niggli's mg *vs.* c plot (figure 4) (after Leake 1964), the three types of amphibolites define a trend (from Niggli's mg of 0.7 to 0.4), which is more or less similar to that of Karoo dolerites (Walker and Poldervaart 1949) with the high-Mg tremolite-bearing amphibolites plot such as those of early differentiates and accumulates, whereas the intermediate- and low-Mg type plots in the field of middle stage differentiates, with none in the fields of either dolomite, pelite-dolomite or pelite-limestone mixtures; (c) in Niggli's 100 mg–c–(al-alk) plot (figure 5), the three types of amphibolites define a trend similar to that of the Karoo dolerites; and (d) in plots involving Niggli's mg *vs.* ti, alk and critical trace elements such as Cr, Ni, Co, Zr, (figure 2a–f), all the three types of amphibolites define a trend as also in the plot of Ni *vs.* Cr (figure 6), with positive trend in the plots with Cr, Ni and Co, and negative trend in the plots with ti, alk and Zr. Such regular trend distinctly corresponds to those normally expected in a magmatic differentiation sequence and almost impossible to expect in amphibolites having sedimentary parentage of

Figure 5. Tri-linear plot of Niggli's 100 mg–c–(al-alk). Trend line of the Karoo dolerites is shown with an arrow (after Leake 1964). Symbols as in figure 2.

Figure 6. Bi-linear plot of log Ni *vs.* log Cr (after Leake 1964). Symbols as in figure 2.

rocks such as pelite, semi-pelite and dolomite-limestone mixtures. Thus, the field, petrographic and petrochemical features cumulatively point out that the amphibolites in the area under study are of ortho-type; in the following section, the nature of their parental magma is discussed.

7.2 Nature of parental magma

Prior to using the geochemistry of these ortho-amphibolites to probe the nature and type of their parental magma, it is important to assess the effects of alteration on their chemistry.

Figure 7. Ternary system of $\text{CaO}/\text{Al}_2\text{O}_3$ – $\text{MgO}/10$ – $\text{SiO}_2/100$ to recognise alteration of the samples (after Davies *et al.* 1978). Symbols as in figure 2.

Petrographically, the important mineralogical alterations noted are chloritisation (Mg-rich chlorite from tremolite and Fe-rich from hornblende) and lesser degree epidotisation of amphiboles, chloritisation and saussuritisation of plagioclase, and formation of sphene from ilmenite and calcic plagioclase. These alterations took place during auto-hydrothermal processes at low temperatures. As these amphibolites are of ortho-type, it may be surmised that their amphiboles are the products derived from the original minerals such as olivine and pyroxene. It is significant to note that neither calcitisation nor serpentinisation is observed in the amphibolites. In order to recognise the extensively altered amphibolites, all the analysed samples were plotted in the ternary system, $\text{CaO}/\text{Al}_2\text{O}_3$ – $\text{MgO}/10$ – $\text{SiO}_2/100$ (after Davies *et al.* 1978; figure 7) in which all the low-Mg and most of the intermediate-Mg type plot in ‘Not altered field’. Most of the high-Mg type and a few of the intermediate-Mg-type amphibolites plot a little outside or in the border zone of this field towards the ‘Mg’ apex; indeed, these amphibolites contain either tremolite or actinolite, pointing to the possible relative enrichment of Mg during the formation of these amphiboles from their precursor olivine and/or pyroxene. $\text{FeO}/\text{Fe}_2\text{O}_3$ ratio, an indicator of the state of oxidation, is generally low (0.02–0.32) in the high- and intermediate-Mg-type amphibolites, whereas relatively higher (0.27–0.54) in the low-Mg-type amphibolites. This feature can be comparable with the field setting of these amphibolites, in that high- and intermediate-Mg types occur at relatively deeper levels as larger bodies, whereas the low-Mg type is confined to higher

Figure 8. Bi-linear plot of $\% \text{SiO}_2$ vs. $\% (\text{Na}_2\text{O} + \text{K}_2\text{O})$ to distinguish alkaline and sub-alkaline volcanic rocks (after Irvine and Baragar 1971). Symbols as in figure 2.

Figure 9. Bi-linear plot of Zr/TiO_2 vs. $\% \text{SiO}_2$ for separating 1 – andesites, 2 – sub-alkaline basalts, 3 – trachyandesites, 4 – alkali basalts, 5 – phonolites and 6 – basanite (after Floyd and Winchester 1978). Symbols as in figure 2.

levels as smaller bodies. In the bi-linear diagrams, viz., SiO_2 vs. alkalies (figure 8, after; MacDonald and Katsura 1964; Irvine and Baragar 1971) and Zr/TiO_2 vs. SiO_2 (figure 9; after Floyd and Winchester 1978), most of the amphibolites plot in the field of ‘sub-alkaline basalts’. To find out the true nature of these sub-alkaline rocks (tholeiitic or calc-alkaline), the samples were plotted in the bi-linear diagram of normative plagioclase vs. Al_2O_3 (figure 10, after Irvine and Baragar 1971), when it is noted that all of them plot in the

Figure 10. Bi-linear plot of normative plagioclase vs. $\%Al_2O_3$ to distinguish tholeiitic from calc-alkaline rocks (after Irvine and Baragar 1971). Symbols as in figure 2.

Figure 11. AFM diagram showing the fields of tholeiitic and calc-alkaline basalts (after Irvine and Baragar 1971). Symbols as in figure 2.

tholeiitic field. This is also corroborated by their plots in the alkalis ($Na_2O + K_2O$) – ($FeO + Fe_2O_3$) – MgO (AFM) diagram (figure 11, after Irvine and Baragar 1971) in which all the three types of amphibolites are in the tholeiitic field. Furthermore, in this diagram, all the amphibolites define a clear trend of Fe-enrichment from high-Mg- to low-Mg-type amphibolites. It is thus established that these ortho-amphibolites are sub-alkaline and tholeiitic in nature, with a well-defined Fe-enrichment from the high-Mg

through intermediate-Mg to low-Mg amphibolites. Of the three types of amphibolites, some of the tremolite-bearing ones (sample nos. B-7, B-27, B-24 and B-34) are marked by high MgO content (14–16 wt.%) and relatively low TiO_2 content (0.1–0.6 wt.%) (table 2), with high Ni (295–3379 ppm) and Cr (1120–1731 ppm) (table 5), resembling ‘komatiitic basalts’. The absence of characteristic features of komatiites such as field association with ultramafic rocks, petrographic features of spinifex texture with occasional magnesian pigeonite and usually sodic plagioclase, and diagnostic chemical feature of $CaO/Al_2O_3 > 0.8$ –1 (Arndt and Nesbitt 1982) point to the non-komatiitic nature of the amphibolites under study, in spite of their high Mg, Ni and Cr, and low TiO_2 contents. Also, the tremolite-bearing amphibolites may be considered as ‘cumulates’, but the absence of typical cumulate textures such as poikilitic texture (olivine/pyroxene within plagioclase) rules out their being cumulates. In the light of these observations and due to distinct linear trend from high-Mg- to low-Mg-type amphibolites in Niggli’s mg vs. c (figure 4) and AFM plots (figure 11), besides their field occurrence at relatively lower levels compared to low-Mg type, it appears most probably that the high-Mg type could be an early differentiate of the parental tholeiitic magma, possibly quartz tholeiitic magma, indicated by normative quartz (1.5–16.7) (table 3) in all the analysed samples.

7.3 Petrogenetic implications

(a) It was shown earlier that the three types of amphibolites belong to early to middle stage differentiates, as indicated in their Niggli’s mg vs. c diagram (figure 4), and the observed systematic variation between Niggli’s ti and alk , and Zr (figure 2a, b and f) and positive correlation with Cr, Ni and Co (figure 2c–e)] points out to the operation of high degree of *fractional crystallisation* during the petrogenesis of these amphibolites. (b) Plots of amphibolites in Zr vs. TiO_2 (figure 12) indicate distinct directions, which, when compared with theoretical fractionation vectors, the controlling crystallising phases appear to be plagioclase–apatite–olivine–clinopyroxene, which characterise the tholeiitic fractional trends (Pearce and Norry 1979). (c) When the analysed amphibolites are plotted in the covariance diagram of a compatible element, Cr with an incompatible and immobile

Figure 12. Bi-linear plot of Zr (ppm) vs. %TiO₂, with fractionation vectors (after Pearce and Norry 1979). Symbols as in figure 2.

Figure 13. Bi-linear plot of log Y vs. log Cr, showing variations within the amphibolites under study and the petrogenetic pathways that connect them to primordial mantle composition. 5%, 10%, 20% and 40% refer to the degree of partial melting of the primordial mantle material (after Pearce 1982). Symbols as in figure 2.

element, Y (figure 13, after Pearce 1982), it is observed that almost all the intermediate- and low-Mg-type amphibolites are showing the important role of fractional crystallisation, corroborating the earlier arrived inference. During fractional crystallisation, trends of these amphibolites are extended to meet the trend of partial melting in

this diagram, their intersections indicate ~5–25% partial melting of the primordial mantle of Wood (1979). It is interesting to note that most of the high-Mg-type amphibolites also fall in this range of partial melting with, however, a little enrichment of Cr than that expected due to partial melting of the primordial mantle. This is probably due to the early differentiated and early separation of high-Mg minerals such as olivine and clinopyroxene from the primordial magma. (d) The observed REE contents, both of LREE and HREE (table 5), and the chondrite-normalised patterns (figure 3) are more or less comparable to those of early Precambrian tholeiites of NE Minnesota (Arth and Hanson 1975). In this, attention is drawn to a very gentle slope of REE pattern from LREE to HREE with a small negative Eu-anomaly for tholeiite formed by 10% partial melting and no Eu-anomaly for tholeiite formed by 25% partial melting of peridotite at shallow depths (<30 km), leaving a residue composed predominantly of olivine and orthopyroxene (refer figure 5b on p. 337 of Arth and Hanson 1975). (e) It appears that the primordial mantle that gave rise to the melts leading ultimately to the formation of amphibolites under study is enriched, and such enrichment is indicated by high content of P₂O₅ (0.91–3.78%, table 2) and Rb (16–87 ppm, table 5) in samples comparatively not influenced by pegmatite emplacement, since enriched mantle components are mantle reservoirs, enriched in Rb, Sm, U (and Th) relative to Sr, Nd and Pb, respectively (Condie 1989). (f) Extrapolating the above inferences, namely the parental magma for the study amphibolites is tholeiite, possibly quartz tholeiite, and the partial melting being the order of 5–25%, on depth (km) vs. per cent melting diagram (in figure 7.12 of Condie 1989), it appears that the parental magma should be ‘quartz tholeiite’ with a depth of ~10–25 km for production of such a magma. Such relatively shallow depth for the generation of parental magma indicates steeper geothermal gradients. It is interesting to note that such steep geothermal gradient in the area is also supported by the Abukuma-type facies of metamorphism, inferred for the co-existing meta-sedimentary rocks in the area under study (Ramesh Babu 1993; Ramesh Babu and Dhana Raju 2016).

7.4 Bearing of amphibolites on the pegmatitic RM mineralisation

The S-type granite (Ramesh Babu and Dhana Raju 2016) and meta-sedimentary rocks, with the

exception of quartzite, host only type I and II pegmatites, whereas the important tin- and RM-bearing pegmatites of types III, IV and V, along with types I and II, are hosted by amphibolites (Ramesh Babu 1990, 1993). As the pegmatite melt, along with its rare-element and volatile components (F, Cl and B, along with H₂O) tends to migrate from the parental granite, it is expected that the parent granite is devoid of any mineralised pegmatites, as observed in the case of the Paliam granite in the study area (Ramesh Babu 1990, 1993; Ramesh Babu and Dhana Raju 2016). The meta-sedimentary rocks are relatively more pervasive (with foliation, bedding, etc.) and less competent, as compared to the massive and more competent amphibolites in the area. The amphibolites offer cavities of favourable forms and their non-pervasive nature creates conditions for regular and prolonged consolidation of the pegmatite melt solution along with rare-element-rich volatile components (Vlasov 1956, cited from Solodov 1964) to form well-zoned pegmatites, with the development of replacement units of greisenisation and albitisation, which are rich in mineralisation of RMs and tin (cf. Lamba and Agarkar 1988). In contrast, the meta-sedimentary rocks, except quartzite, although have favourable loci, due to their pervasive nature, much of the rare-element-rich volatile components of the pegmatite melt solution escape the system into the surrounding rock thereby hindering the formation of well-zoned and highly mineralised pegmatites. This feature is supported by very high contents of Rb (1242 ppm) and Nb (70 ppm) in the andalusite schist, collected from near a pegmatite of type II. Apart from the massive and more competent nature of the amphibolites, their highly contrasting chemical nature (basic), as compared to the ultra-acidic nature of intrusive pegmatitic melt, might have also helped in arresting the latter leading to mineralised pegmatites that are in contact with the amphibolites, as is the case in the area under study.

8. Conclusions

Amphibolites and meta-sedimentary rocks, belonging to the Archaean Bengpal Group having a regional metamorphic event around 2530 ± 89 Ma, were intruded by mineralised and hitherto partly exploited RM (Nb–Ta, Be and Li)- and Sn-bearings granite pegmatites in the BMPB in the SE part of the Bastar craton in the states of Chhattisgarh and Odisha. Based upon the field setting and

petrography, these amphibolites are classified as (i) tremolite-, (ii) hornblende–actinolite- and (iii) hornblende-bearing amphibolites, the petrochemistry of which corresponds, respectively, to high-Mg, intermediate-Mg and low-Mg amphibolites. The field, petrography and major–minor-trace elements petrochemistry, including REEs, and petrochemical patterns cumulatively point out that these amphibolites are ortho and sub-alkaline in nature, with *tholeiitic*, and possibly *quartz tholeiitic* magmatic affinity, and formed due to more of fractional crystallisation and less of 5–25% partial melting of an enriched primordial mantle magma (enriched mid-oceanic ridge basalt – E-MORB), emplaced at a deduced shallow depth of 10–25 km, with the main controlling phases being olivine, plagioclase, clinopyroxene and apatite; they show similarity to the Precambrian tholeiites of Minnesota, USA.

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