Geology and Geochemistry of metabasalts of Shimoga Schist Belt, Dharwar Craton: Implications for the Late Archean Basin Development

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Abstract

The Late Archaean Shimoga schist belt in the Western Dharwar Craton, with its huge dimensions and varied lithological associations of different age groups, is an ideal terrane to study Archean crustal evolution. The rock types in this belt are divided into Bababudhan Group and Chitradurga Group. The Bababudhan Group is dominated by mafic volcanic rocks followed by shallow marine sedimentary rocks while the Chitradurga Group is dominated by greywackes, pillowed basalts and deep marine sedimentary rocks with occasional felsic volcanics. The Nb/Th and Nb/La ratios of the studied metabasalts of the Bababudhan Group indicate crustal contamination. They were extruded onto the vast Peninsular Gneisses through the rifting of the basement gneiss. The Nb/Yb ratios of high magnesium basalts and tholeiitic basalts of Chitradurga Group suggest the enrichment of their source magma. Based on the flat primitive mantle normalized multi element plot with negative Nb anomalies and Th/Ta-La/Yb ratios, the high magnesium basalts and tholeiitic basalts are considered to have erupted in an oceanic-plateau setting with minor crustal contamination. The high magnesium basalts and tholeiitic basalts formed two different pulses of same magma type, in which first pulse of magma gave rise to high magnesium basalts which were derived from deep mantle sources and underwent minor crustal contamination enroute to the surface. While the second pulse of magma which gave rise to tholeiitic basalts formed at similar depths to that of high magnesium basalts and escaped crustal contamination. The associated lithological units found with the studied metavolcanic rock types of Bababudan and Chitradurga Group of Dharwar Supergroup of rocks in Shimoga schist belt of Western Dharwar Craton confirms the mixed-mode basin development with a transition from shallow marine to deep marine settings.

Keywords: Shimoga Belt, Dharwar Craton, Geochemistry, Geology, Crustal Evolution

Introduction

The Dharwar Craton is one of the largest Archean cratons in the Indian subcontinent, and hosts numerous greenstone (schist) belts (Chadwick et al., 2000; Ramakrishnan and Vaidyanadhan, 2010; Ramachandra, 2016). Because of the extensive development of schistose characteristics (Radhakrishna and Vaidyanathan, 1997), the greenstone belts of the Dharwar Craton are referred to as schist belts in this paper. The Shimoga schist belt, the largest belt in the Dharwar Craton, forms the focus of this study. This belt preserves the whole stratigraphy of the Dharwar Craton and is therefore an ideal terrain in which to study the tectonic evolution of the Dharwar Craton. Several crustal evolution models for the different schist belts in the Dharwar Craton have been proposed (Swami Nath et al., 1976; Swami Nath and Ramakrishnan, 1981; Naqvi and Rogers, 1987; Chadwick et al., 1996). Most of these models are based on geochemistry and petrology rather than on structure, metamorphism and tectonics. However, in this paper we propose a model of crustal evolution of one of the largest basins in the Dharwar Craton using an integrated approach and so following a detailed review of the geology and tectonics of the Shimoga schist belt, the geochemistry and petrogenesis of metabasalts will be discussed. Finally, a revised evolutionary model for the Shimoga schist belt will be presented.

Regional Geology

The Dharwar Craton (DC, Fig.1) had a complex tectonic and structural history, up to ~2.5 Ga when it became essentially stable (Chadwick et al., 1988; Jayananda et al., 2015, 2013a; Naqvi and Rogers, 1987; Radhakrishna, 1983; Radhakrishna and Naqvi, 1986; Swami Nath and Ramakrishnan, 1981). In the 1990s two contrasting structural models were proposed for the Dharwar Craton: in the first, the Closepet Granite, a massive linear pluton trending approximately north-south, divides the craton into Western Dharwar Craton (WDC, also known as Karnataka Nucleus) and Eastern Dharwar Craton (EDC) (Naqvi and Rogers, 1987; Swami Nath et al., 1976; Swami Nath and Ramakrishnan, 1981). In contrast the second model proposed by Chadwick et al., (1996) suggested a major mylonitic ductile shear zone (~400km long), also called as Chitradurga Shear Zone (CSZ) (on the eastern margin of the Chitradurga schist belt), separated the eastern (high- temperature - low-pressure metamorphic terrain, known as the Dharwar Batholith) and western (low-temperature - high-pressure metamorphic terrain, the Dharwar Foreland) blocks. This latter model has been more widely accepted as it is supported by geological and geophysical evidence (Chadwick et al., 2000; Jayananda et al., 2015, 2013a; Naqvi, 1973). The division of the craton into WDC or western block (Karnataka Nucleus) and EDC or eastern block is justified in terms of nature and abundance of greenstones, crustal thickness, grade of regional metamorphism and degree of melting (Chadwick et al., 2000; Chardon et al., 2008; Gupta et al., 2003; Jayananda et al., 2006; Swami

Nath et al., 1976). More recently these sub-divisions have been revised by Chardon et al. (2011) and Peucat et al. (2013) based on U–Pb zircon ages and Nd isotope data. These authors divided the DC into three provinces - western, central and eastern. The western province is dominated by older (3400–3200 Ma) crust, the central province by mixed old (3400–3200 Ma) and younger (2700–2520 Ma) crust, and the eastern province by mainly younger (2700–2520 Ma) crust with no significant crustal remnants older than 2700 Ma (Fig. 1a).

The WDC or western province (Dharwar Foreland) in the west of the Craton comprises four major schist belts (Western Ghats-Bababudhan-Shimoga-Chitradurga) and numerous minor schist belts (Sargur-Nuggihalli-Holenarsipur-JCPura-Kalyadi-Nagamangala-Ghattihosahalli-Kunigal-Sigegudda). The WDC is characterized by volcanic and sedimentary rocks of the late Archean Dharwar Supergroup deposited ca. 2900-2600 Ma (Taylor et al., 1984; Nutman et al., 1996; Kumar et al., 1996; Trendall et al., 1997a,b) on a basement of 3.36 – 3.2 Ga tonalitic-granitic gneiss and older supracrustal rocks, known as the Sargur Group (Table 1a; Viswanatha and Ramakrishnan, 1976; Chadwick et al., 1988; Janardhan et al., 1978; Jayananda et al., 2008, 2013b). The Sargur Group is dominated by a 3.35 Ga komatiite-basalt association (Jayananda et al., 2008) with occasional 3.29 Ga felsic volcanic rocks (Peucat et al., 1995) and interlayered 3.58-3.23 Ga sediments (quartzite-pelite-carbonate-banded iron formations) (Nutman et al., 1992; Ramakrishnan et al., 1994). The Late Archean Dharwar Supergroup is divided into a lower Bababudan and an upper Chitradurga Group. The Bababudan Group comprises oligomict conglomerate, quartzite, voluminous mafic flows (2.9-2.8 Ga; (Kumar et al., 1996)), phyllite, felsic volcanic tuffs (2.72 Ga; (Trendall et al., 1997a, 1997b)) and thick banded iron formations (BIFs). The Chitradurga Group has a polymict conglomerate at it base that is successively overlain by 2.75 Ga mafic volcanics (Kumar et al., 1996), dominant greywackes and argillites containing carbonate beds, 2.61 Ga felsic volcanics (Nutman et al., 1996) with BIFs at the top of the succession (Chadwick et al., 1981). The foreland is locally intruded by 2.61 Ga potassic plutons as a result of the reworking of its lower crust (Chadwick et al., 2007; Jayananda et al., 2006; Nutman et al., 1996; Taylor et al., 1984).

The EDC or eastern block (Dharwar Batholith) is dominated by an accretionary complex, characterized by NW-SE to N-S striking belts of diffusely banded, juvenile and crustally derived 2.56-2.50 Ga granites, granodiorites, monazites and diorites (Chadwick et al., 2007; Chardon et al., 2011; Jayananda et al., 2000; Krogstad et al., 1991; Peucat et al., 1993). They are interspersed with 2.7-2.55 Ga schist (auriferous) belts which are lithologically similar to the Dharwar Supergroup in the west (Balakrishnan et al., 1999; Chadwick et al., 1996; Nutman et al., 1996; Sarma et al., 2011). However, these belts, unlike their counterparts in the west, are not conformable with their surrounding granite-gneiss terrains and, with the exception of the Kolar Schist Belt, have sheared intrusive contacts with the Late Archean syn-tectonic plutons (Jayananda et al., 2013a).

The late Archean Dharwar Supergroup in WDC is folded and cleaved and metamorphosed mostly at PT conditions of greenschist to lower amphibolite facies, while the early Archean Sargur group of WDC has been metamorphosed to amphibolite to granulite facies during the intrusion of polyphase gneisses. The low-grade HT/LP metamorphism in the EDC were associated with folding and thrust-thickening of the schist belts, but higher grades along the belt margins are related to granite emplacement (Chadwick et al., 1996).

Geology of Shimoga Schist Belt

The Shimoga belt, the largest of the three belts in the Shimoga Basin, is separated from the other two belts, Bababudhan and Kudremukh in the south, by basement tonalite-trondhjemite gneiss (TTG) (Harinadha Babu et al., 1981). Large domal masses of basement gneiss surrounded by platform sediments and volcanics mark the western margin of the basin (Radhakrishna, 1983). The northern extension of the basin is covered by the Cenozoic Deccan Traps while the eastern margin is faulted. The southern region of the belt is dominated by shallow water sediments with subordinate intercalated volcanic and volcanoclastic rocks that grade into an extensive greywacke-argillite-chert-volcanic suite towards north in the Dharwar, North Kanara and Goa regions (Chadwick et al., 2007, 1988; Srinivasan and Naha, 1993; Ugarkar et al., 2017). The main rock formations of the Shimoga belt belong to Chitradurga Group, and to a lesser extent the Bababudhan Group, of the Dharwar Supergroup. Minor lenses of serpentine with chrysotile asbestos and chromite along with other ultramafic schists, amphibolites and BIF belonging to Sargur Group are also seen along the southern margin of the belt (Ramakrishnan and Vaidyanadhan, 2010).

The Chitradurga Group in Shimoga belt can be sub-divided into four formations - the Jhandimatti, Joldhal, Medur and Ranibennur Formations (Table 1b; Ramakrishnan and Harinadha Babu, 1981). A refined stratigraphy of the Shimoga schist belt was proposed by Chadwick et al. (1991) (Table 1b) based on extensive field and structural work. They divided the Dharwar Supergroup of Shimoga schist belt into the Bababudhan Group and the lower and upper Chitradurga Groups. The shallow marine metabasite-orthoquartzite association of Bababudhan Group is subdivided into Kudrekonda and Kalva Rangan Durga Formations. This is overlain by predominantly shallow marine sedimentary rocks, including polymict conglomerates and limestones with intercalations of basic to acid volcanic rocks, which belongs to the lower part of the Chitradurga Group and has been subdivided into Musinhal, Adrihalli, Aleshpur, Medur and Daginkatte Formations. The upper Chitradurga Group is comprised of the thin but persistent Basavapatna Formation of banded ferruginous cherts and is interbedded carbonaceous phyllites at its base. The Basavapatna Formation is overlain by greywackes of the Ranibennur Formation and local volcanic intercalations.

Structure and Metamorphism

The Dharwar Supergroup of rocks, which forms the Dharwar cover over the Peninsular Gneiss, in the Shimoga schist belt has been affected by two periods of deformation. Large regional fold structures follow the shape of the basement gneissic domes and comprise large upright synclines in the Dharwar Cover with intervening domal areas of basement (Chadwick et al., 1988). The Dharwar Cover beds dip away from the gneissic domes and younging of primary structures like current bedding and ripple marks in quartzites indicate the anticlinal nature of the folds. The major fold axial plane trends NNW with the regional schistosity being parallel to this trend (Harinadha Babu et al., 1981). This regional fold has been further refolded during the second phase of deformation (Radhakrishna, 1983). In contrast, the basement rocks in the Shimoga schist belt, which have experienced a major deformation phase prior to the deposition of Dharwar cover, have been deformed cataclastically along numerous fractures and retrograde shear zones. Cover-basement relationships indicate faulted contacts, but some have been interpreted as rotated and steepened unconformities (Chadwick et al., 1988).

Lower stratigraphic sections in the south of the Shimoga schist belt exhibit complicated fold styles, while the upper sections overlying carbonate-manganese-iron formation in the north have undergone little subsequent deformation except for the development of pronounced schistosity (Radhakrishna, 1983). The northern part of the schist belt is characterized by long linear folds extending for several kilometers with alternating anticlines and synclines. The beds have low dips and are occasionally horizontal.

Generally, the grade of metamorphism in the WDC increases from north (greenschist) to south where granulite facies metamorphism has affected the southern sections of the Craton at a late stage in its evolutionary history. Nevertheless, the schist belts in WDC often show an increase in metamorphic grade from the core (greenschist) to the margins (amphibolite) (Chandan-Kumar and Ugarkar, 2017; Jayananda et al., 2013b; Radhakrishna, 1983). The basal beds forming the Bababudhan Group in the south and southwest of the Shimoga schist belt, which are in contact with Peninsular Gneiss, show lower amphibolite facies metamorphism. Towards the central and northern part of the belt, dominated by Chitradurga Group, the rocks exhibit greenschist facies metamorphism even at the basement-cover contacts suggesting up-doming of basin during folding (Harinadha Babu et al., 1981; Ramakrishnan and Harinadha Babu, 1981; Viswanatha and Ramakrishnan, 1981).

Mafic Volcanism

Although the ratio of volcanics to sediments in the Shimoga schist belt is 1:3, significant proportions of mafic volcanic rocks, mainly metabasalts, belonging to Bababudan and lower and upper Chitradurga Groups are exposed in the Shimoga schist belt. The metabasalts in the southern part of the schist belt, belonging to Bababudhan Group, are exposed prominently around Pulvanahalli and Kudrekonda villages. Similarly, around Medur, Bailhongal, Hosur and Belwadi villages, prominent exposures of metabasalts of the lower and upper Chitradurga Groups are found within the central and northern part of the schist belt (Fig. 1b). The metabasalts around the Kudrekonda and Pulvanahalli villages are dark green and schistose with abundant secondary carbonates. Quartz, carbonate and chlorite fillings in the amygdales are not uncommon. In places, these metabasalts are interbedded with orthoquartzites, ferruginous phyllites and banded ferruginous cherts. The metabasalts in the centre and north of the schist belt are mainly pillowed, with subordinate massive forms found in the north. In the central region, the metabasalts are associated with pyritiferrous argillites, orthoquartzites and shales, while the those in the north are associated with an extensive greywacke-argillite suite with subordinate banded iron formations and occasional polymict conglomerates. The field relations of the volcano-sedimentary assemblages in the northern part of the belt indicate that the metabasalts are older than the metasedimentary assemblages (greywacke and banded iron formations) (Ugarkar et al., 2017, 2012).

Petrography of mafic volcanic rocks of Bababudan and Chitradurga Groups

Though original igneous textures like spherulitic, variolitic fabric, intergrowth and porphyritic are commonly seen intact, igneous mineral assemblages are changed into metamorphic mineral assemblages. Clino-pyroxenes, hornblende and plagioclase are common minerals forming phenocrysts within the groundmass of metabasalts of central and southern part of the schist belt. While most of the pyroxenes in the northern part of the belt are altered to chlorites, amphiboles and epidotes. The groundmass includes fine grained plagioclase, pyroxene, amphibole, carbonate, quartz and magnetite. Chlorite fills inter-granular spaces of minerals, while calcite occurs in varying proportions as a secondary mineral developed due to metamorphism. In the northern part, extensive development of asbestos needles/fibers from the amphiboles, especially actinolite-tremolite, across plagioclase lath suggests its secondary origin.

Geochemistry of mafic volcanic rocks of Bababudan and Chitradurga Groups

Metabasalts of Bababudhan Group (BM) have a narrow range of SiO_2 (47.8-48.4 wt.%), variable TiO_2 (0.5-1.1 wt.%) and are enriched in Al_2O_3 (12.3 to 15.9 wt.%) that are similar to the compositions of low-siliceous pillow lavas of Belingwe greenstone belt (Shimizu et al., 2005). They have moderate concentrations of magnesium, calcium, sodium and potassium oxides and are characterized by higher iron oxide (Table 2a). The metabasalts of the Shimoga schist belt (BM) differ from the Bababudan Group metabasalts of Bababudhan schist belt (BbM;

Bhaskar Rao and Drury, 1982) in their major oxide concentrations. Though they have similar MgO and Na_2O contents, BM metabasalts have higher concentrations of Al_2O_3, Fe_2O_3, K_2O and lower concentrations of SiO_2, CaO and TiO_2 than the BbM metabasalts and are characterized by higher total rare earth element (REE) contents (37 to 89 ppm). Chondrite normalized REE patterns (Fig.2a) display enriched LREE patterns with $(La/Sm)_N$=3.5-8.6, $(La/Yb)_N$ = 9.7-39.4 (Table. 2b). A primitive mantle normalised multi-element plot indicates relative enrichment of high-field strength elements (HFSE) over heavy rare earth elements (HREE) and significant negative Nb-Ta and Ti anomalies (Fig.2b).

Variable major oxide contents characterize Chitradurga Group metabasalts (CM) of Shimoga schist belt. The rocks are high magnesium basalts (MgO - 12.5-20.1 wt.%) and are correspondingly enriched in Cr (254-876 ppm) and Ni (108-242 ppm). These rocks from the central part are more magnesian and less siliceous (Table 2a) than the high mg-basalts (referred as basaltic komatiites by Ugarkar et al., 2014) of northern part of Shimoga schist belt (Ugarkar et al., 2014). The studied high magnesium basalts are characterized by lower TiO_2, Al_2O_3 and K_2O, and higher Fe_2O_3 concentrations. These high magnesium rocks also have higher total REE contents and have slightly enriched chondrite-normalized REE patterns that are 18-24 times chondrite. In contrast, the basalts from the northern part of the schist belt are characterized by lower total REE and have flat REE patterns (Ugarkar et al., 2014). Primitive mantle-normalized patterns (Fig.2c) of the high magnesium basalts are near flat from Th to Yb with pronounced negative Nb anomalies and slight negative Zr and Ti anomalies (Fig.2d).

Discussion

Petrogenesis of Bababudan Group

Since the BM metabasalts have undergone amphibolite facies metamorphism, secondary element remobilization is inevitable. Pronounced LREE enrichment observed in BM metabasalts may suggest LREE mobility during metamorphism. Chemical Index of Alteration (CIA) ranging between 51 and 62 (Table 2b) also indicates moderate alteration of the metabasalts. Significant crustal contamination, during the ascent of magma through continental lithosphere to the surface, is indicated by the Nb/Th values (1-4) of Bababudhan Group metabasalts (BM) (Sylvester et al., 1997). Nb/La ratio less than 1 is also consistent with crustal contamination (Xia, 2014). Such crustal contamination is unsurprising given that these basalts unconformably overlie basement gneiss (Peninsular Gneiss). The relatively flat HREE patterns [$(Tb/Yb)_N$ = 0.69-1.85] together with elevated HREE concentrations ~8 to 18 times chondritic values suggest a mantle source containing spinel.

Petrogenesis of Chitradurga Group

The high-magnesium basalts (this study) and tholeiitic basalts (Ugarkar et al., 2014) from the central and northern part of Shimoga schist belt respectively have undergone greenschist facies metamorphism and hence, the effects of secondary element remobilization must also be considered. CIA values ranging between 31 to 58 and the consistent patterns of selected elements on primitive mantle normalized element plots (Fig.2c-f) suggests minimal alteration in these high magnesium and tholeiitic basalts of Chitradurga Group. Consistently flat LREE patterns also suggest that there was no LREE mobility.

Marked negative Nb anomalies on primitive mantle-normalized multi element diagrams suggests magma generation at shallower mantle in arc environment or crustal contamination processes (Polat and Kerrich, 2000). Given the significant negative Nb anomalies (Fig.2d), the studied high magnesium basalts might probably reflect crustal contamination. Nb/Th ratios of high magnesium basalts in the present study range between 2 and 4 indicating crustal contamination. Most of the tholeiitic basalt samples from the northern part of the Shimoga schist belt have Nb/Th ratios ranging between 5 to 7 (Ugarkar et al., 2014) which also suggests minor crustal contamination. Supporting this is the low Nb/La ratio of most of the tholeiitic basalts and high magnesium basalts which indicate crustal contamination (Fig.3a, Table.2b).

Further, high MgO, Cr and Ni contents and $(Gd/Yb)_N > 1$ of high magnesium basalts suggest that the garnet remained in the residue during melting implying derivation of high magnesium basalt magmas from greater depths (Jayananda et al., 2008) than the BM metabasalts. This is also substantiated by negative Zr anomalies in primitive mantle-normalized multi element plots (Fig.2d). Minor crustal contamination of the source magma enroute to the surface cannot be ruled out as these high magnesium basalts are unconformably underlain by Bababudan Group lithological assemblages.

Nb/Th and Nb/La ratios (3-5 and 0.57-0.67 respectively) of the tholeiitic basalts perhaps indicate crustal contamination. However, Fig.3b suggests up to 70% subduction contribution to the source of the basalts. Nb/Yb ratios of these tholeiitic basalts range to higher values than that of global average N-MORB, which suggests the magma source was relatively enriched (Escuder Viruete et al., 2008). The parallel trend displayed by these basalts with the MORB-OIB array indicates addition of a subduction component followed by variable degrees of melting, such as dynamic melting (Fig.3b, vector C; Pearce et al., 1995).

Paleotectonic Setting and the Evolution of the Shimoga Basin

Archean greenstone belts can be classified as mafic-plain successions and platformal successions (Thurston and Chivers, 1990). Archean mafic-plain successions are characterized dominantly by pillow basalts with variable amounts of komatiite and small amounts of chemical sedimentary rocks (cherts and banded iron formations) with occasional felsic to intermediate volcanic rocks. They are tectonically bounded and interpreted to be allochthonous (Tomlinson and Condie, 2001). On the other hand, the platformal successions overlie tonalitic or felsic volcanic basement and are characterized by a basal unconformity, represented by tonalitic conglomerates and arkose/arenites overlying tonalite, followed by carbonates and banded iron formations (BIF), which are in turn overlain by komatiites and basalts with occasional felsic volcanic rocks (Tomlinson and Condie, 2001). Although the platformal greenstone association might be similar to modern continental flood basalts in terms of a volcanic sequence erupted through and deposited on continental basement, or rifted volcanic margins in terms of shallow water sedimentary rocks, it could be argued that this association may not have a direct modern analogue (Tomlinson and Condie, 2001). The reasons being that neither of these modern settings are characterized by komatiites and most of the Archean volcanic sequences are submarine.

The studied metabasalts of the Bababudhan Group (BM) in the southern part of the Shimoga schist belt are associated with shallow marine cross bedded orthoquartzites, ferruginous phyllites and banded ferruginous cherts which are unconformably underlain by basement gneisses (Peninsular Gneisses) (Chadwick et al., 1988). The basement gneiss and the metabasalts are in places separated by a thin layer of pebbly quartzites or arkosic basal sediments. The geochemical characteristics of the BM metabasalts indicate that they are significantly contaminated and are derived from magma sources at shallow mantle depths. The extrusion of basaltic magma onto the vast Peninsular Gneisses requires the rifting of the basement gneiss. As suggested by Chadwick et al., (2000), the intraplate rift volcanism took place during the oblique convergence of EDC with WDC which resulted in the development of the Shimoga Basin. Bhaskar Rao and Drury (1982) suggested a within plate setting for the metabasalts of Bababudhan Group of the Bababudhan schist belt (BbM). The geochemical characteristics of the BM metabasalts mostly resemble those of the BbM, except that they are more altered and contaminated. They have a similar stratigraphic succession and hence, are likely to have been emplaced due to passive upwelling of magma from the mantle onto the surface in an intraplate extensional setting during the early stage of basin development.

The high magnesium rocks of the Medur Formation of the lower Chitradurga Group in the central and northern parts of the Shimoga schist belt are characterized by pillow structures and are associated with shallow marine sedimentary rocks, including polymict conglomerates, greywackes and limestones with intercalations of basic to acid volcanic rocks (Chadwick et al., 1991; Ziauddin et al., 1978). This volcano-sedimentary assemblage overlies the Bababudhan Group rocks. The tholeiitic basalts of the Ranibennur Formation of the upper Chitradurga Group in the northern part of the Shimoga schist belt are associated with predominant greywackes and occasional banded ferruginous cherts and interbedded carbonaceous phyllites (Chadwick et al., 1991;

Ugarkar et al., 2017, 2012). These tholeiitic basalts are also characterized by pillow structures indicating their oceanic affinities (Ugarkar et al., 2014, 2012).

Tomlinson and Condie (2001) proposed a classification of basalts based on primitive mantle-normalized multi-element patterns. They proposed that the normal mid-ocean ridge basalts (N-MORBs) show depletion in incompatible elements, whereas oceanic-island basalts (OIBs) show enrichment. Oceanic-plateau basalts (OPBs) show flat patterns with slight depletion in the most incompatible elements, while arc-related basalts show significant Nb-Ta anomalies. McCulloch and Gamble (1991) suggested that the most striking distinction between arc-related and oceanic non-arc related basalts is the negative Nb-Ta anomaly which can be used to determine the tectonic setting of oceanic basalts in Archean greenstone belts (Condie, 1994). Tomlinson and Condie (2001) designed a binary plot of La/Yb versus Th/Ta to identify Ta-Nb anomalies. They based this diagram on the fact that the higher Th/Ta and La/Yb ratios reflect an enrichment in the mantle wedge of Th and LREEs, but not in Ta and Nb. Nevertheless, in most Archean greenstone belts crustal contamination is inevitable and hence, contamination of NMORB or plume derived magmas with upper continental crust raises Th/Ta and La/Yb ratios and the samples generally plot on mixing arrays between subduction zone basalts (SZB) and MORB. Fig.4 shows that the high magnesium basalts plot between the OPB and SZB fields with two samples, each from central and northern part of the schist belt, showing affinity towards OPB. Generally, these high magnesium basalts have Th/Ta and La/Yb ratios slightly higher than subduction zone basalts (SZB, Fig.4) However, their primitive mantle-normalized multi-element patterns are flat with little negative Nb anomalies. It is therefore, possible that these high magnesium basalts were erupted in an oceanic-plateau setting.

The uncontaminated pillowed tholeiitic basalts of the upper Chitradurga Group in the northern part of the Shimoga schist belt are characterized by flat patterns on primitive mantle-normalized multi-element plots (Ugarkar et al., 2014). They have La/Yb ≤ 3 and Th/Ta ≤ 2 that are similar to OPBs and occupy OPB field in Fig. 4. Therefore, these tholeiitic basalts are likely to have been erupted in an OPB setting similar to the underlying high magnesium basalts. It is proposed that the high magnesium basalts and tholeiitic basalts formed two different pulses of same magma type, to account for the differences in crustal contamination. We believe that the first pulse of magma which gave rise to high magnesium basalts originated from deep mantle sources and underwent crustal contamination en route to the surface. While the second pulse of magma which gave rise to tholeiitic basalts originated at the similar depths to the high magnesium basalts, as they have similar incompatible element characteristics.

As suggested by Radhakrishna (1983) and supported by Chadwick et al. (2000), the late Archean Dharwar Supergroup of rocks were deposited in rift basins developed during the oblique convergence of western Dharwar block and Eastern Dharwar block. The rifting of 3.36-3.2 Ga old sialic crust resulted in the creation of long linear basins, with passive mafic volcanism. The studied 2.9 to 2.7 Ga metabasalts (Drury et al., 1983) of the Bababudhan Group (BM) also support this model. These BM metabasalts are interspersed with minor shallow marine sedimentary deposits in the upper parts of the Bababudan Group. This was followed by fluvial and deep marine sedimentation represented by greywackes, polymict conglomerates, banded iron formations and stromatolitic limestones which were accompanied by further mafic volcanism in the deep oceans. This volcanism is perhaps represented by the studied high magnesium basalts and tholeiitic basalts which were erupted in an oceanic plateau setting. These later sequences have experienced variable uplift, due to granitic magmatism (Ugarkar et al., 2012) and substantial syn-depositional subsidence of the older Dharwar Cover and basement gneisses (Chadwick et al., 2000).

Conclusions

The Late Archaean Shimoga schist belt, with its huge dimensions and varied lithological associations of different age groups, is an ideal terrane to study Archean crustal evolution. The belt resembles a platformal sequence and is dominated by late Archaean Dharwar Supergroup of rocks resting unconformably over the early Archean Sargur Group of rocks and basement gneisses (Peninsular Gneisses). The late Archean Dharwar Supergroup of rocks in this belt are divided into Bababudhan Group and Chitradurga Group. The Bababudhan Group is dominated by mafic volcanic rocks followed by shallow marine sedimentary rocks while the Chitradurga Group is dominated by greywackes, pillowed basalts and deep marine sedimentary rocks with occasional felsic volcanics. The Nb/Th and Nb/La ratios of the studied metabasalts of the Bababudhan Group (BM) indicate that they are crustally contaminated and they were extruded onto the vast Peninsular Gneisses through the rifting of the basement gneiss. The Nb/Yb ratios of high magnesium basalts and tholeiitic basalts of Chitradurga Group suggest the enrichment of their source magma. Based on the flat primitive mantle normalized multi element plot with negative Nb anomalies and Th/Ta-La/Yb ratios, the high magnesium basalts and tholeiitic basalts likely erupted in an oceanic-plateau setting with minor crustal contamination. The high magnesium basalts and tholeiitic basalts formed two different pulses of same magma type, in which first pulse of magma gave rise to high magnesium basalts which were derived from deep mantle sources and underwent minor crustal contamination enroute to the surface. While the second pulse of magma which gave rise to tholeiitic basalts formed at similar depths to that of high magnesium basalts and escaped crustal contamination. The associated lithological units found with the studied metavolcanic rock types of Bababudan and Chitradurga Group of

Dharwar Supergroup of rocks in Shimoga schist belt of Western Dharwar Craton confirms the mixed-mode basin development with a transition from shallow marine to deep marine settings.

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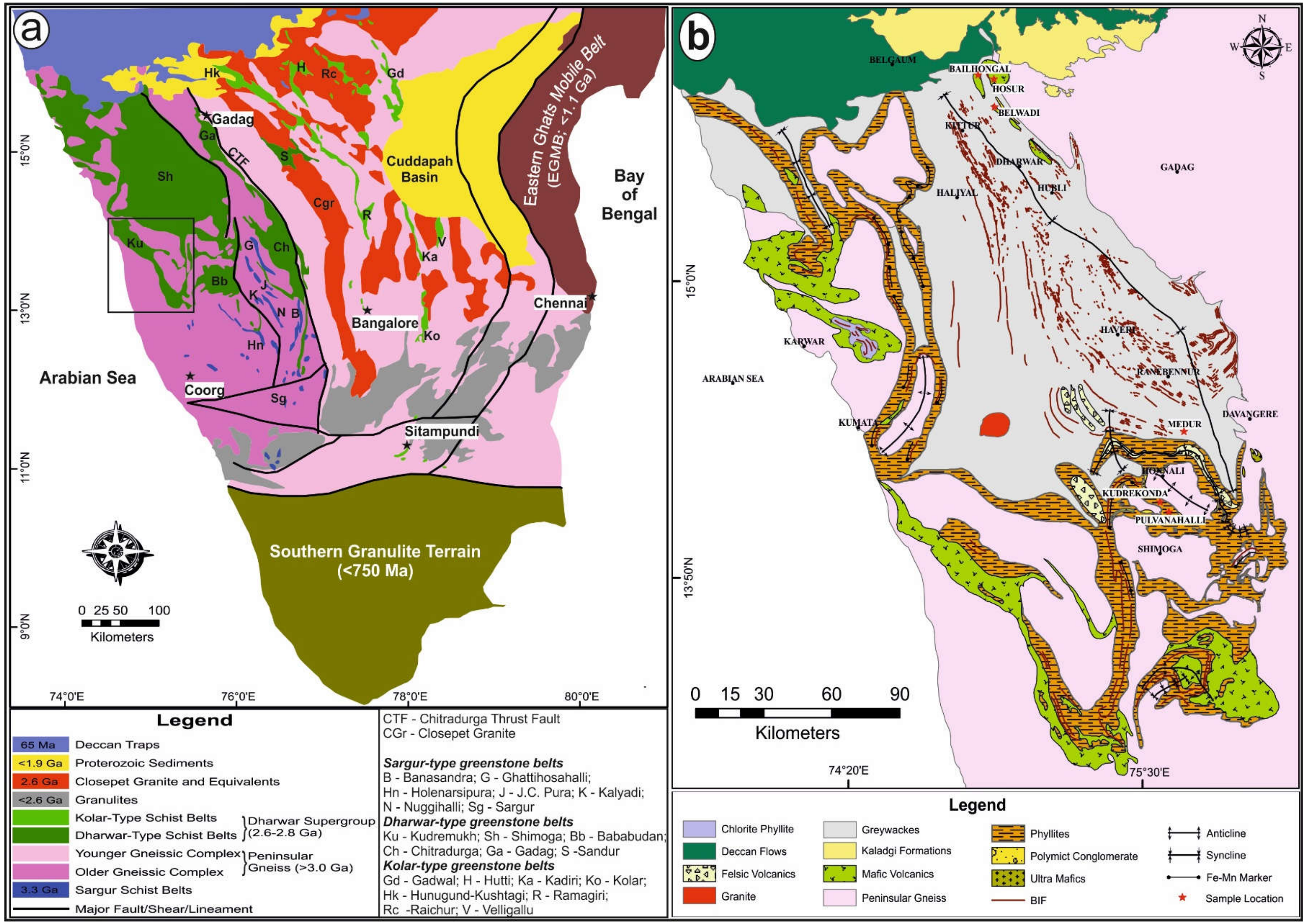
FIGURE CAPTIONS

Fig.1: (a) Geological map of the Dharwar Craton (adapted from project Vasundhara map of GSI, 1994); (b) Geological map of Dharwar-Shimoga greenstone belt (modified after Radhakrishna and Vaidyanadhan, 1994)

Fig.2: (a) REE plot of metabasalts of Bababudan Group (BM); (b) Multi-element plot of metabasalts of Bababudan Group (BM); (c) REE plot of metabasalts of Chitradurga Group (CM); (b) Multi-element plot of metabasalts of Chitradurga Group (CM)

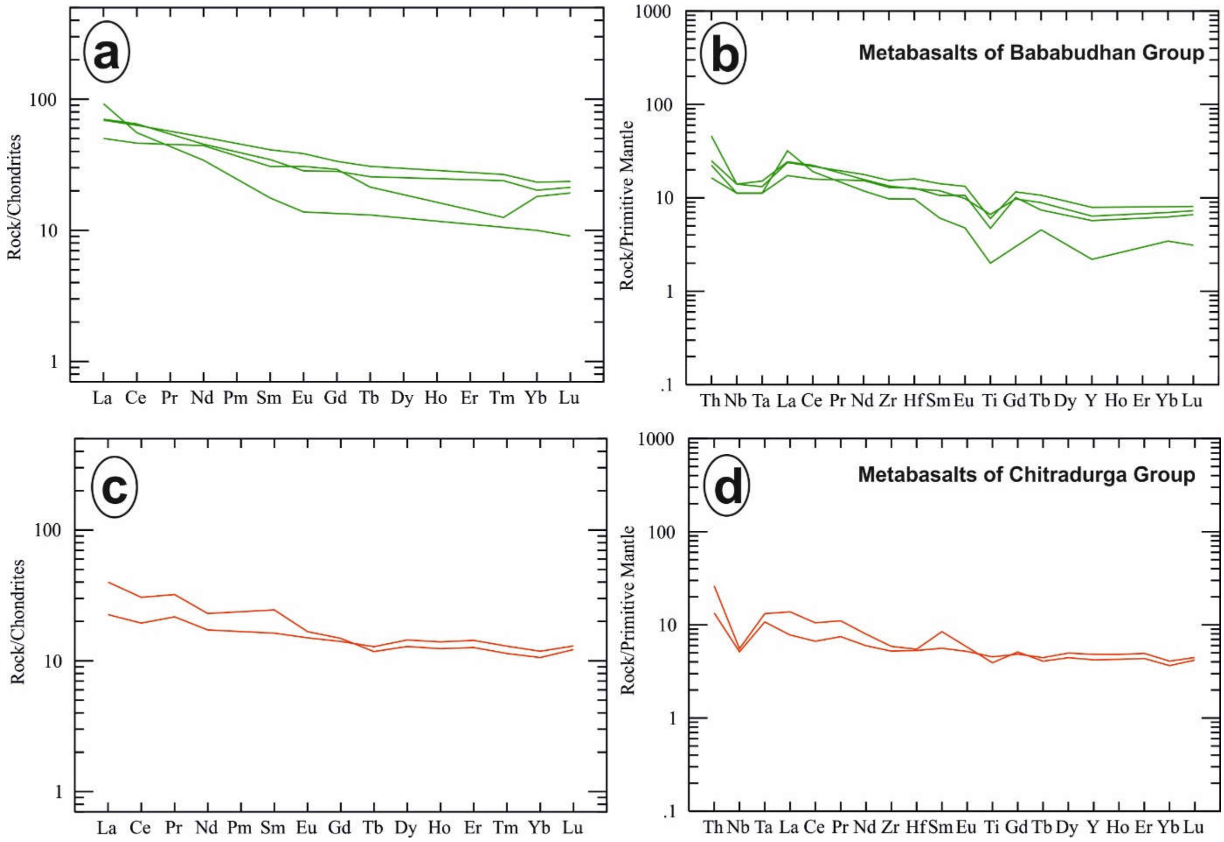
Fig.3: (a) Nb/La vs. Nb/Th binary plot; (b) Nb/Yb vs. Th/Yb binary plot (Pearce et al., 1995)

Fig.4: La/Yb vs. Th/Ta binary plot (Tomlinson and Condie, 2001)



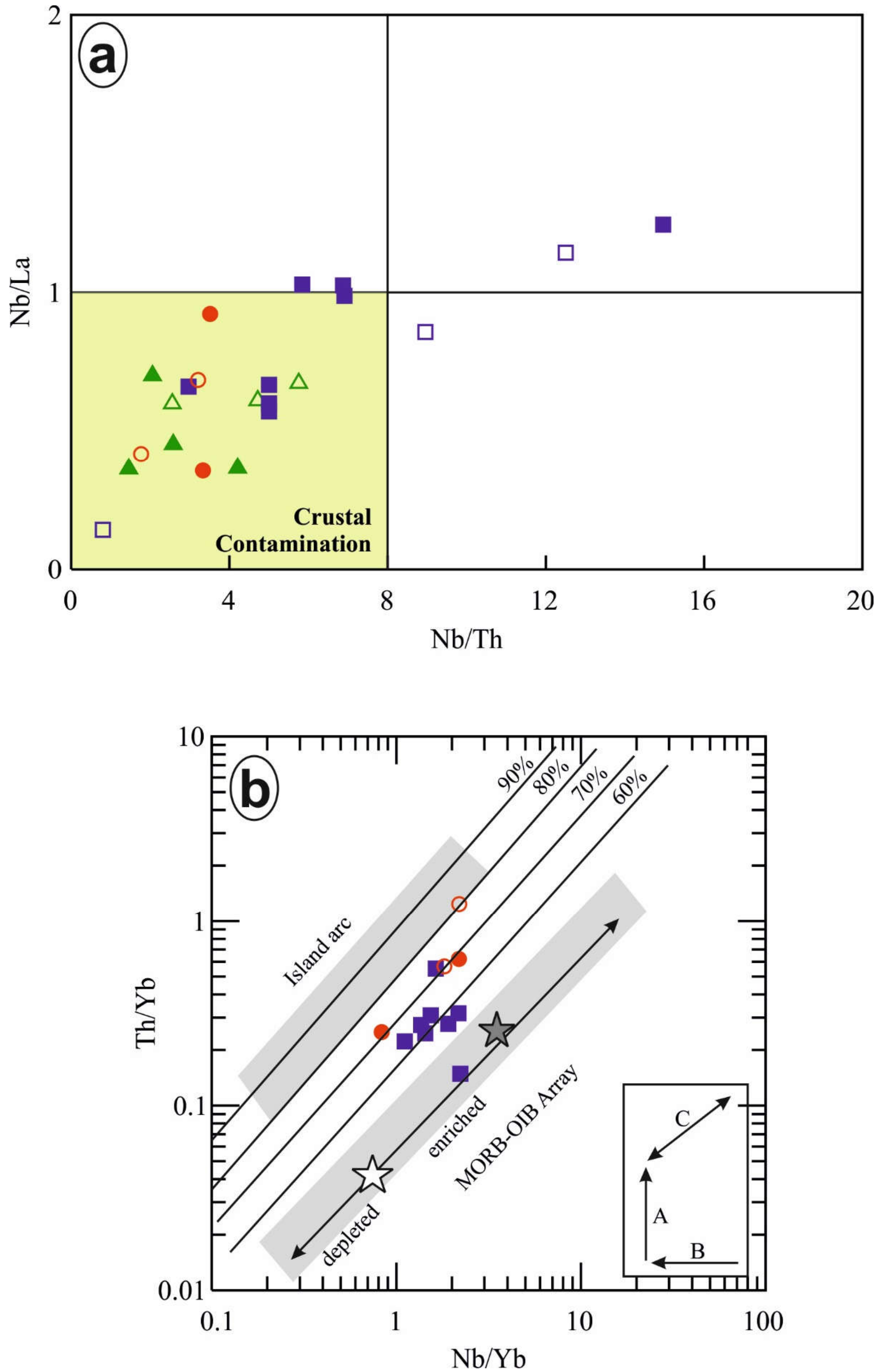
a
Hk
H
Rc
Gd
Gadag
Ga
CTF
S
Cuddapah Basin
Eastern Ghats Mobile Belt (EGMB; <1.1 Ga)
Bay of Bengal
Sh
Cgr
R
Ku
G
Ch
V
Ka
Bb
J
K
N
B
Bangalore
Chennai
Hn
Ko
Arabian Sea
Coorg
Sg
Sitampundi
Southern Granulite Terrain (<750 Ma)
0 25 50 100
Kilometers
15°0'N
13°0'N
11°0'N
9°0'N
74°0'E
76°0'E
78°0'E
80°0'E
Legend
65 Ma Deccan Traps
<1.9 Ga Proterozoic Sediments
2.6 Ga Closepet Granite and Equivalents
<2.6 Ga Granulites
Kolar-Type Schist Belts
Dharwar-Type Schist Belts
Dharwar Supergroup (2.6-2.8 Ga)
Younger Gneissic Complex
Older Gneissic Complex
Peninsular Gneiss (>3.0 Ga)
3.3 Ga Sargur Schist Belts
Major Fault/Shear/Lineament
CTF - Chitradurga Thrust Fault
CGr - Closepet Granite
Sargur-type greenstone belts
B - Banasandra; G - Ghattihosahalli;
Hn - Holenarsipura; J - J.C. Pura; K - Kalyadi;
N - Nuggihalli; Sg - Sargur
Dharwar-type greenstone belts
Ku - Kudremukh; Sh - Shimoga; Bb - Bababudan;
Ch - Chitradurga; Ga - Gadag; S -Sandur
Kolar-type greenstone belts
Gd - Gadwal; H - Hutti; Ka - Kadiri; Ko - Kolar;
Hk - Hunugund-Kushtagi; R - Ramagiri;
Rc -Raichur; V - Velligallu
b
N
W
E
S
BELGAUM
BAILHONGAL
HOSUR
BELWADI
KITTUR
DHARWAR
HUBLI
GADAG
HALIYAL
KARWAR
HAVERI
RANEBENNUR
ARABIAN SEA
KUMATA
MEDUR
DAVANGERE
HONNALI
KUDREKONDA
PULVANAHALLI
SHIMOGA
15°0'N
13°50'N
0 15 30 60 90
Kilometers
74°20'E
75°30'E
Legend
Chlorite Phyllite
Deccan Flows
Felsic Volcanics
Granite
Greywackes
Kaladgi Formations
Mafic Volcanics
Peninsular Gneiss
Phyllites
Polymict Conglomerate
Ultra Mafics
BIF
Anticline
Syncline
Fe-Mn Marker
Sample Location

Fig. 1



a
b
Metabasalts of Bababudhan Group
c
d
Metabasalts of Chitradurga Group
Rock/Chondrites
Rock/Primitive Mantle
1000
100
10
1
.1
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Th Nb Ta La Ce Pr Nd Zr Hf Sm Eu Ti Gd Tb Dy Y Ho Er Yb Lu

Fig.2



a
Crustal
Contamination
Nb/La
Nb/Th
b
Island arc
90%
80%
70%
60%
enriched
depleted
MORB-OIB Array
A
B
C
Th/Yb
Nb/Yb

Fig.3

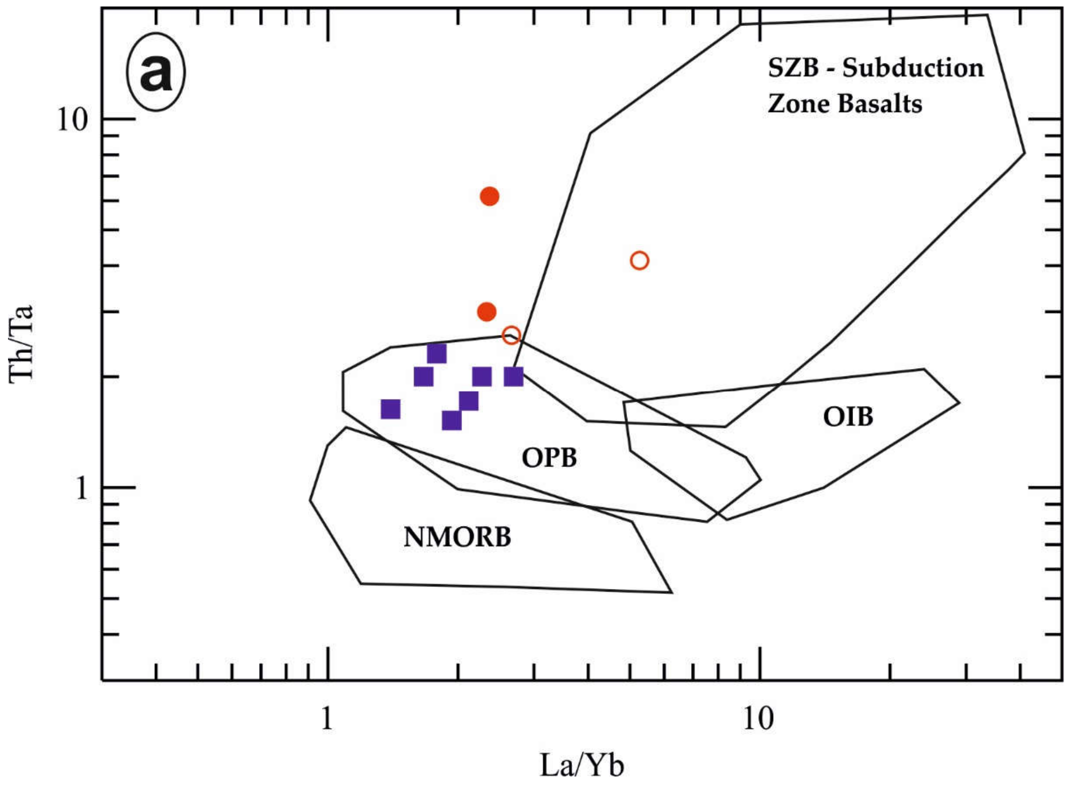

a
SZB - Subduction Zone Basalts
OIB
OPB
NMORB
10
1
Th/Ta
1
10
La/Yb

Fig.4

Table

Table 1a: Stratigraphic column of Western Dharwar Craton (after Chadwick et al., 2000)

Potassic Plutons (2.661 Ga)		
Late Archean Dharwar Super Group (2900-2600 Ma)	**Chitradurga Group**	Polymict conglomerate, mafic volcanics (2.75 Ga), dominant greywackes, argillites with occasional carbonates, felsic volcanics (2.61 Ga), banded iron formations
	---------- Disconformity ----------	
	Bababudan Group	Oligomict conglomerate, quartzite, voluminous mafic flows (2.9-2.8 Ga), phyllite, felsic tuffs (2.72 Ga), thick banded iron formations
---------- Deformed angular unconformity ----------		
Peninsular Gneiss with trondjhemite-granodiorite plutons (>3000 Ma)		
---------- Intrusive/tectonic contact ----------		
Early Archaean Sargur Group (3100-3300 Ma		Ultramafic-mafic layered complexes, tholeiitic amphibolites, komatiites, banded iron formations
		Quartzites, pelites, marbles and calc-silicate rocks
---------- Intrusive/tectonic contact ----------		
Gorur Gneiss (3300-3400 Ma)		

Table 1b: Stratigraphic column of Shimoga schist belt

	Ramakrishnan and Harinadha Babu (1981)		Chadwick et al. (1991)	
Late Archaean Dharwar Supergroup	Chitradurga Group	Ranibennur Formation	Ranibennur Formation	Upper Chitradurga Group
			Basavapatna Formation	
		Medur Formation	Daginkatte Formation	Lower Chitradurga Group
			Medur Formation	
		Joldhal Formation	Aleshpur Formation	
		Jhandimatti Formation	Adrihalli Formation	
			Mushinhal Formation	
	(Bababudan Group Absent)		Kalva Rangan Durga Formation	Bababudan Group
			Kudrekonda Formation	
Peninsular Gneiss – granodiorite and foliated multiphase orthogneisses				
Sargur Group				

Table 2: Geochemistry of metabasalts and high-magnesium basalts (HMB) of Shimoga schist belt

Bababudan Group					Chitradurga Group	
Metabasalts					HMB	
SAMPLE	P1	P2	P3	P4	T3	T5
SiO2	48.14	47.84	48.35	47.84	44.54	47.7
TiO2	0.77	0.76	0.54	1.07	0.85	0.98
Al2O3	15.36	15.85	13.23	12.28	11.99	12.4
Fe2O3	16.27	16.2	17.26	21.75	6.68	7.05
MnO	0.15	0.15	0.2	0.22	0.14	0.12
MgO	9.02	9.2	7.45	7.25	20.1	14.54
CaO	6.2	5.78	9.23	5.55	12.35	11.93
Na2O	2.26	2.32	2.75	2.12	1.72	2.06
K2O	1.54	1.56	0.7	1.62	0.13	0.73
P2O5	0.09	0.11	0.11	0.15	0.08	0.09
Cr	105	122	309	226	456.96	254.09
Ni	136	138	116	66	178.86	108.22
Co	63	64	49	63	53.47	48.78
Cu	336	557	144	395	93.75	58.6
Pb					6.89	1.08
Zn	86	83	84	107	616.97	242.82
Ba					256.92	83.25
Rb					6.97	14.74
Sr	55	57	122	125	803.91	133.67
Cs					0.48	0.65
Th	1.9	3.4	3.1	4.8	2.23	1.14
Nb	8	7	8	7	3.95	3.66
Ta	0.46	0.39	0.48	0.38	0.54	0.44
Zr	108.75	36.25	72.5	36.25	65.83	58.4
Hf	3	1	2	0.95	1.69	1.64
U					8.53	0.97
La	21.9	10	17.7	19.3	9.48	5.35
Ce	34	12	30	27	18.71	11.88
Pr					3.05	2.06
Nd	16	11	4.9	8	10.74	8.05
Sm	2.7	1.5	3.2	1.4	3.75	2.49
Eu	0.8	0.4	1.8	0.3	0.97	0.87
Gd					3.05	2.89
Tb	0.49	0.49	0.49	0.49	0.44	0.48
Dy					3.27	3.67
Ho					0.7	0.79
Er					2.09	2.37
Tm					0.29	0.33
Yb	1.7	1.2	3.2	0.7	1.8	2.01
Lu	0.23	0.049	0.36	0.05	0.31	0.33
Y	10	13	29	7	19.18	21.96
Ga					17.1	16.77
Ti	4620	4560	3240	6420	5100	5880
Sc	32.2	32.4	25.1	24.6	35	38.02
V	202	211	195	194	260.22	292.88