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Eastern Dharwar Craton, India: Continental lithosphere growth by accretion of diverse plume and arc terranes

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Abstract Greenstone belts of the eastern Dharwar Craton, India are reinterpreted as composite tectonostratigraphic terranes of accreted plume-derived and convergent margin-derived magmatic sequences based on new high-precision elemental data. The former are dominated by a komatiite plus Mg-tholeiitic basalt volcanic association, with deep water siliciclastic and banded iron formation (BIF) sedimentary rocks. Plumes melted at <90 km under thin rifted continental lithosphere to preserve intraoceanic and continental margin aspects. Associated alkaline basalts record subduction-recycling of Mesoproterozoic oceanic crust, incubated in the asthenosphere, and erupted coevally with Mg basalts from a heterogeneous mantle plume. Together, komatiites-Mg basalts-alkaline basalts plot along the Phanerozoic mantle array in Th/Yb versus Nb/Yb coordinate space, representing zoned plumes, establishing that these reservoirs were present in the Neoarchean mantle.

Convergent margin magmatic associations are dominated by tholeiitic to calc-alkaline basalts compositionally similar to recent intraoceanic arcs. As well, boninitic flows sourced in extremely depleted mantle are present, and the association of arc basalts with Mg-andesites-Nb enriched basalts-adakites documented from Cenozoic arcs characterized by subduction of young (<20 Ma), hot, oceanic lithosphere. Consequently, Cenozoic style “hot” subduction was operating in the Neoarchean. These diverse volcanic associations were assembled to give composite terranes in a subduction-accretion orogen at ~2.7 Ga, coevally with a global accretionary orogen at ~2.7 Ga, and associated orogenic gold mineralization.

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1. Introduction and scope

Conventionally, evolution of the continents has been framed in terms of crustal growth processes (Taylor and McLennan, 1985; Rudnick and Gao, 2003; Rollinson, 2008). This brief review synthesizes evolution of the eastern Dharwar Craton, but inasmuch as continents are aspects of lithospheric plates we consider evolution of crust and lithosphere. Several recent papers have systematically addressed the geochemistry of volcanic units in four greenstone terranes of the eastern Dharwar Craton: the Sandur Superterrane, and the Penakacherla, Hatti, and Gadhwal greenstone terranes. A brief overview of the Dharwar Craton sets the stage, followed by summaries of geological, metamorphic, structural, and age relationships of those four terranes.

From elemental geochemistry we summarise volcanic sequences interpreted as erupted from mantle plumes, and compositionally distinct volcanic sequences inferred to have erupted in convergent margin subduction zones. The former are characterized by the association of komatiites with tholeiitic basalts. The latter are dominated by tholeiitic to calc-alkaline basalts akin to recent intraoceanic arc basalts and paired volcaniclastic trench turbidites, but include new examples of boninites that were formerly thought to be restricted to Phanerozoic intraoceanic arcs. Included also in the convergent margin sequences are the association of adakites—Nb-enriched basalts (NEB)—high-Mg andesites (HMA), with tholeiitic to calc-alkaline arc basalts. That association was first documented from Cenozoic arcs featuring subduction of hot, young, oceanic lithosphere aged <20 Ma (Sajona et al., 1996).

Based on these compositional constraints we address a number of questions: (1) Were mantle plumes erupted in ocean basins or through continents; (2) Did mantle plumes erupt through continents thermally erode mantle lithosphere as well as crust; (3) Was the 2.7 Ga Archean plume-arc crust. plateaus, and the refractory, low density, residue of plume melting coupled with accreted imbricated plume-arc crust.

2. Geological setting

2.1. Dharwar Craton

Archean “greenstone belts” are now generally understood to be composite tectonostratigraphic terranes, or superterrane, accreted from a number of allochthonous to autochthonous terranes, and developed variously in intraoceanic or continental settings (Desrochers et al., 1993; Kimura et al., 1993; Manikyamba and Naqvi, 1996; Polat et al., 1998; Wyman et al., 1999; Manikyamba and Kerrich, 2006, 2011). The Archean Dharwar Craton of Peninsular India is composed of greenstone belts ranging in age from 3.4 to 2.7 Ga, with intrusive granitoids. This craton has been divided into western (WDC) and eastern (EDC) sectors by the Closepet granite dated at 2518 Ma (Fig. 1; Naqvi and Rogers, 1987; Jayananda et al., 2000; Moyen et al., 2003; Ramakrishnan and Vaidyanadhan, 2008). The western sector, dominated by the Dharwar and Chitradurga greenstone terranes, has larger dimension of greenstone terranes, with predominant metabasalts along with komatiite-tholeiite association, and minor bimodal volcanic rocks. The eastern sector has smaller greenstone terranes with prevalent bimodal volcanic rocks but some komatitites: from west to east these are the Ramagiri-Hungund Superterrane (RHST), Hatti-Kolar-Kadiri, Narayanpet-Gadhwal-Veligallu, and Nellur-Khammam greenstone terranes. The Sandur Superterrane is distinctive in lying within the belt of Closepet granites (Fig. 1A; Sreeramachandra Rao, 2001; Manikyamba and Khanna, 2007; Manikyamba and Kerrich, 2011). These supracrustal terranes are surrounded by younger granitoid batholiths aged ~2552–2534 Ma (Jayananda et al., 2000; Manikyamba and Kerrich, 2011 and references therein). Distinct volcano-sedimentary associations present in greenstone terranes of the WDC and EDC are consistent with distinct geodynamic settings, as endorsed by recent geochemical studies (Zachariah et al., 1996; Jayananda et al., 2000; Naqvi et al., 2002, 2006; Manikyamba et al., 2004a,b, 2005, 2008).

2.2. Sandur Superterrane

The Sandur Superterrane (SST) is unique amongst the composite greenstone-granite terranes of the Dharwar Craton in that its geological and geographic position is within the belt of Closepet granite complex (Fig. 1). There are lithotectonic differences between greenstone terranes of the EDC and WDC (Manikyamba and Khanna, 2007). However, the SST has excellent preservation of lithologies commonly present in both the EDC and WDC.

The Sandur Superterrane is a composite of different lithotectonic terranes. Each terrane has its own characteristic combination of lithologies, stratigraphic succession, and structural-metamorphic history. Volcanic sequences include ultramafic flows, massive and pillowd metabasalts, and intermediate to felsic rock suites such as andesites, rhyolites and adakites. Sedimentary rocks include quartzites, conglomerates, turbidites, shales, stromatolitic carbonates, cherts, banded iron formation (BIF) and banded manganese formation (BMF). These diverse volcanic and sedimentary lithologies are present in eight distinct terranes (Fig. 1A; Table 1). Four terranes were tectonically accreted along high angle complex structures (Sandur Discontinuity), whereas the other four terranes are demarked by low-angle thrust faults (Timmappanagundi, Joga and Vibhatigudda; Fig. 1A; Table 1; Manikyamba and Kerrich, 2006). Abrupt changes of
lithology, structure, and metamorphic grade have been recognized across the terrane boundaries which were interpreted as accretionary structures (Table 1; Mukhopadhyay and Matin, 1993; Chadwick et al., 1996; Naqvi et al., 2002; Manikyamba and Kerrich, 2006). Earlier work suggested ~8 times crustal shortening due to horizontal compression as a consequence of convergent margin tectonism in this greenstone superterrane (Manikyamba and Naqvi, 1996).

The Sandur Superterrane has three phases of deformation (Mukhopadhyay and Matin, 1993), and the metamorphic grade varies from greenschist to upper amphibolite facies depending on the terrane. U-Pb SHRIMP age of zircons from the Eastern Felsic Volcanic Terrane (EFVT) yielded an age of 2.7 Ga (Nutman et al., 1996), and the poorly defined Sm/Nd date for Sultanpura Volcanic Terrane (SVT) komatiites is 2.7 Ga (Naqvi et al., 2002). The composite supracrustal terranes have been intruded by a series of granitoids after their accretion, among which one granitoid from the EFVT has been dated at 2719 ± 40 Ma (Table 1; Nutman et al., 1996).

2.3. Penakacherla terrane

The Penakacherla terrane occupies the central domain of the Ramagiri-Hungund composite terrane or superterrane (RHST), a linear composite supracrustal belt of multiple accreted terranes having different tectonostratigraphic characteristics, extending ~280 km from Ramagiri in the south to Hungund in the north. Based on metamorphic grade, lithological association and trace element signatures, the rocks of Ramagiri belt have been divided into three blocks. Eastern and Central blocks have a tectonic contact between them and the western block is highly sheared (Zachariah et al., 1995, 1996). Greenstone belt lithologies, which include komatiites, mafic, and felsic volcanic flows, and BIF, are well exposed at the Ramagiri, Penakacherla and Hungund-Kushtagi areas (Fig. 1B; Table 1; Manikyamba et al., 2004a,b; Manikyamba and Kerrich, 2011).

The Penakacherla Volcanic Terrane (PT) of the RHST has abundant pillow basalts, with minor units of felsic volcanic rocks, BIF, cherts and carbonaceous shales, endorsing subaqueous eruption of the lavas. Basalt flows are prevalent: pillowd tholeiitic basalts, with compositions typical of intra-oceanic arc basalts, are best preserved at Venkatampalli (Fig. 1B; Manikyamba et al., 2004a; Manikyamba and Kerrich, 2011). Alkaline- and high-Mg basalts are spatially associated, and both are associated with arc-like tholeiitic basalts lower in the stratigraphic section (Manikyamba and Kerrich, 2011). BIF and felsic volcanic units (now quartz-chlorite-mica schists) are interlayered with tholeiitic basalts higher in the stratigraphic section, and all lithologies share common outcrop trends in the east of the Penakacherla terrane (Manikyamba et al., 2004a). Collectively, these field relationships are consistent with a subaqueous
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<td>Ramagiri (Central)</td>
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<td>Buddine</td>
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<td>2586 ± 50</td>
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<td>Gadwal</td>
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<td>2576 ± 12</td>
<td>Andesites, pyroxenite, mafic dykes, granite</td>
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<td>Ulindakonda</td>
<td>Volcanic agglomerate</td>
<td>2576 ± 12</td>
<td>Mafic and felsic tuff, andesite, dacite, rhyolite, BIF</td>
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<td>Ramam and Murty, 1997; Matin, 2001</td>
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Banded Iron Formation (BIF), Banded Manganese Formation (BMF), Granular Iron Formation (GIF), Peloidal Iron Formation (PIF), Carbonaceous Shales (C-Shales), Ferrugenous Chert (Fe-Cherts), Banded Ferruginous Quartzite (BFQ).

environment, and broadly contemporaneous volcanism and chemical sedimentation.

All lithologies are tightly folded and metamorphosed to upper greenschist to lower amphibolite facies. Most basalt flows retain pillow structures (Manikyamba et al., 2004a). Basalts from the Ramagiri greenstone terrane have been dated at 2746 ± 64 Ma by Pb-Pb methods (Zachariah et al., 1996). This age is consistent with SHRIMP U-Pb zircon ages of 2658 ± 14 Ma for rhylolites (Nutman et al., 1996), and Sm/Nd ages of 2706 ± 184 Ma for basalt and komatitites of the adjacent Sandur greenstone belt to the west of the PT (Narvi et al., 2002). Granites intruding the Sandur belt are dated at 2719 ± 40 Ma and 2570 ± 62 Ma by the SHRIMP U-Pb technique (Table 1; Nutman et al., 1996).

2.4. Hutti greenstone terrane

The Hutti greenstone terrane is mainly composed of metavolcanic and subordinate metasedimentary rocks (Fig. 1C). Mafic volcanic rocks are prevalent, which are variously pillowed, massive or schistose; BIF, limestone, quartz arenites, and pelitic horizons, are interlayered with basalt flows (Manikyamba et al., 2009). Felsic volcanic units include adakites (Manikyamba et al., 2009). Polymictic conglomerate, having granodioritic clasts, is interbedded with greywackes in the NE of the belt. Srikantia (1995) adopted the term Hutti Group for the greenstone belt lithological associations of the Hutti-Maski belt, and divided this group into four formations on the basis of younging direction (Table 1). The lower Hussainpur Formation is predominantly amphibolites which texturally range from fine grained, to streaky or banded. The 530 Hill Formation is pillowed and vesicular metabasalts, whereas the Ballapur Formation has mafic volcanic rocks associated with Palkanmardi conglomerate and quartzites. Amphibolites have lenses of pyroxenite, garnetiferous amphibolite, diorite and tuffs. Basalt is prevalent in the Budde Formation, with pillowed, vesicular, amygdaloidal, variolitic, and massive volcanic textures.

Amphibolites of the Hussainpur Formation have been intruded by the protetonic Kavital granite which yielded a U-Pb age of 2543 ± 8 Ma (Rogers et al., 2007), whereas the post-tectonic Yelagatti granitoid, intruded into the Budde Formation, gave a Pb-Pb age of 2250 Ma. Felsic volcanic rocks of the Buddine Formation have been dated by U-Pb method at 2586 ± 50 Ma (Rogers et al., 2007), and granodioritic clasts present in the conglomerate yielded a SHRIMP zircon ages of 2576 ± 12 Ma (Vasudev et al., 2000). Recent studies have documented that the U-Pb zircon age of the felsic volcanic rocks of Hutti belt are 2587 ± 7 Ma and the age of gold mineralization is 2547 ± 10 Ma (Sarma et al., 2008; Ram Mohan and Sarma, 2010). The available geochronological data indicate that this belt was formed ~2.6 Ga.

Metamorphic grade is amphibolite facies (Table 1). The belt has been subjected to three phases of deformation. First generation isoclinal folds (F1) generated regional schistosity (S1), and have been refolded by second generation (F2) folds. Third generation folds (F3) are broad warps and kinks (Roy, 1979; Vasudev and Chadwick, 2008). This belt has numerous faults and shear zones. The irregularly shaped, structurally deformed, Hutti belt has intrusive or tectonic contact with gneissic basement.

2.5. Gadwal greenstone terrane

The Gadwal greenstone belt (GGB) is situated at the centre of the Narayanpet–Veligallu composite belt, or accretionary terrane, extending from Narayangpet (north) to Veligallu (south), in the easternmost part of the eastern Dharwar Craton (EDC). Metabasalts are the dominant lithology with well preserved pillow structures that show younging towards the east and NE; at Garlapadu and Gunipalli there are associated boninites. Felsic volcanic flows, including dacites, rhyodacites, rhyolite and adakites, and calcisilicate units, are present in the south (Fig. 1D; Manikyamba et al., 2005). Metabasalts are metamorphosed to lower amphibolite facies resulting in the development of amphibolites. Banded iron formations are also present in this belt. Further, a shear zone passes through the amphibolites in which gold mineralization has been reported (Ananda Murthy and Bhattacharjee, 1997). In the south, near Ulindakonda, volcanic agglomerates consisting of fragments of TTG, tonalities, basalts are set in a matrix of intermediate rocks. To the south of Ulindakonda, near Veldurti, this belt is unconformably overlain by the Mesoproterozoic Cuddapah Basin; the basal Cuddapah QPC (Quartz pebble conglomerate) was deposited on this belt and adjoining gneisses and granitoids (Ramam and Murty, 1997). Three generations of folding are recognized in this belt. Major D2 structure is schistosity parallel to F1 axial plane in banded iron formation. This schistosity is folded into D2 folds and the crenulation cleavage is parallel to D2 folds. D3 are cross wraps with subvertical axial planes on schistosity (Matin, 2001).

Radiometric ages are not available on the metavolcanics of this belt, but whole rock Sr-isotopic ages on three adakite samples are 2825 ± 45 Ma, and metavolcanics of the adjacent Kolar (~2.7 Ga) and Ramagiri belts (~2.7 Ga) are consistent with this belt having formed during the Neoarchaean (Table 1; Balakrishnan et al., 1990; Zachariah et al., 1995).

3. Mantle plume-related volcanic sequences

3.1. Komatiites and basalts

Komatiites, komatiitic basalts, and tholeiitic basalts having near-flat HREE patterns, are well preserved in the Sandur Superterrane (Fig. 1A). Komatiites are the Al-undepleted variety, signifying melting in a mantle plume above the garnet-peridotite facies at <90 km (Xie et al., 1993; Arndt, 2008). This association has been explained as komatitites being erupted from the hot core of a mantle plume, whereas tholeiitic basalts represent melts of cooler ambient asthenospheric mantle entrained into the annulus of the plume (Campbell et al., 1989). Tholeiitic basalts are compositionally akin to those of the komatite-basalt association of the Superior Province (Kerrich et al., 1999a,b), and Kambalda Terrane of the Yilgarn Craton (Said and Kerrich, 2010; Said et al., 2010), which collectively are similar to basalts that dominate Phanerozoic intracratonic plateaus such as Ontong Java, Kerguelen, and Naru (Floyd, 1989; Kerr, 2003).

Melts of asthenospheric mantle erupted in ocean basins have Nb/Th ratios close to, or greater than, the primitive mantle value of 8, whereas the continental crust, and all are magmatism, feature the conjunction of enriched LREE with Nb/Th < 8 (Sun and McDonough, 1989; Rudnick and Gao, 2003). Accordingly, for plume-related magmas this ratio, or Nb/La, can be used to test for plume-related magmas this ratio, or Nb/La, can be used to test for plume-related magmas this ratio, or Nb/La, can be used to test for plume-related magmas this ratio, or Nb/La,
characteristic of crustal AFC. The most straightforward interpretation of these data is that the Sandur plume erupted at a rifted continental margin (Manikyamba et al., 2008).

3.2. High-Mg basalt-alkaline basalt association

High-Mg basalts are stratigraphically associated with alkaline basalts in the Penakacherla greenstone terrane (Fig. 1B). High-Mg basalts are abundant in Archean terranes, likely reflecting melting of hotter ambient mantle than in the Phanerozoic (Redman and Keays, 1985; Herzberg et al., 2010), whereas alkaline basalts are rare in Archean greenstone terranes, with some documented in the 2.7 Ga Wawa belt (Polat et al., 1999; Polat, 2009).

The majority of high-Mg basalts from the Penakacherla terrane, eastern Dharwar Craton are characterized by Nb/Th > 8, but two record the conjunction of LREE enrichment with Nb/Th < 8. As for the Sandur terrane komatiite-basalt association, the most reasonable explanation is eruption of a mantle plume at a rifted continental margin. Alkaline basalts are all crustally uncontaminated. Compositionally they resemble Phanerozoic alkaline ocean island basalts (OIB): these have three endmember uncontaminated compositions. These 2.7 Ga alkaline basalts have fractionated HREE, like Phanerozoic OIB, and plot on the Phanerozoic OIB array in SiO2 versus Nb/Yb (Fig. 2A). The Iceland plume, as at Hawaii, erupted abundant tholeiitic basalts with volumetrically minor alkaline basalts. In the Penakacherla terrane, high-Mg basalts resemble Iceland tholeiitic basalts but extend to more primitive compositions, and alkaline basalts are similar to Iceland counterparts albeit with more fractionated HREE signifying a deeper melt regime (Fig. 2B).

3.3. Interaction of plumes with lithospheric mantle

Many studies have focussed on the absence, or extent, of crustal assimilation-fractional crystallisation (AFC: De Paolo, 1981) of Archean volcanic sequences, but few have addressed interaction of liquids ascending from the asthenosphere with continental lithospheric mantle (CLM). Lasserre and DePaolo (1997) documented distinct vectors for crustal contamination of asthenospheric liquids versus interaction with CLM. For example, in the oceanic sector of the Cameroon volcanic line (CVL), asthenospheric liquids record two distinct compositional trends: contamination by interaction with continental lithospheric mantle and separately by continental lithosphere, likely a fragment of crust rifted into the Atlantic (Rankenburg et al., 2005).

Two high-Mg basalts from Penakacherla (Fig. 1B) show clearcut contamination by continental crust. In contrast, komatiitic basalts, and basaltic from the Sandur terrane record trends closer to plume-CLM interaction than crustal AFC. Consequently, fragments of continental lithosphere that predated these Neoarchean terranes, and which the Neoarchean plumes erupted at the rifted margins of, had both crustal and mantle lithosphere aspects (Fig. 3; cf. Said and Kerrich, 2010).

3.4. Mantle sources and the mantle array

On the Th/Yb versus Nb/Yb diagram, Sandur komatiites and basalts, and PT high-Mg basalts, plot on the mid ocean ridge basin (MORB) to ocean island basalt (OIB) “mantle array”, between normal MORB (N-MORB) and enriched MORB (E-MORB). Alkaline basalts plot with Recent OIB. Consequently, depleted and enriched reservoirs had been established in the Neoarchean mantle. The Nb/Yb axis is a measure of mantle depletion or enrichment. High-Mg basalts at Penakacherla (PT HMB), including magnesian basalts from a second locality in this terrane (PT MB), were erupted from the most depleted mantle, whereas Sandur komatiites were derived from less depleted mantle and associated basalts from distinct mantle too, consistent with a zoned plume (Fig. 4A). Given samples spanning the primitive mantle Nb/Th ratio of 8, the PT MB could also represent a mantle plume erupting into a backarc (see Section 4.2).

The significance of the alkaline basalts is that Mesoarchean oceanic crust, possibly with sediments, was subducted into the convecting mantle, incubated for ~500 Ma, and incorporated into the mantle source of a 2.7 Ga plume. Consequently, some form of plate tectonics was operating from the Mesoarchean (Fig. 4A).

4. Convergent margin volcanic associations

4.1. Oceanic transitional to continental margin arcs

Modern and Recent arcs are characterized by the conjunction of enriched and fractionated LREE with primitive mantle normalised anomalies at Nb-Ta, and Ti relative to neighbouring REE (Pearce, 2008, and references therein). Shales from the Sandur terrane (Fig. 1A) are compositionally first cycle basaltic volcanioclastic turbidites shed from a convergent margin arc. That arc records the transition from a calc-alkaline oceanic arc at low Nb/Yb to shoshonitic magma series of a continental margin arc at high Nb/Yb. A possible analogue is the Aleutian arc which is oceanic in the west transitional to continental margin in the east (Fig. 4B; Manikyamba and Kerrich, 2006). These volcanioclastic turbidites preserve a more complete record of diverse volcanism in the Sandur terrane than is preserved in the volcanic sequence (cf. Fralick et al., 2009).

4.2. A paired arc and backarc

In the Hutti greenstone terrane (Fig. 1C) two compositional classes of pillow basalt are present both with the characteristics of convergent margin magmas. The depleted class has lower abundances of compatible elements and is relatively Fe-rich, whereas the enriched class is relatively Fe-poor with enriched, fractionated LREE.

In modern paired arc-backarc systems of the Southwest Pacific, backarc basalts, being distal from the trench, involve deeper melting under less hydrous conditions, generating Fe-rich basalts. The residue of the mantle wedge from melting in the backarc is drawn by induced convection under the arc where melting under more hydrous conditions produces relatively Fe-poor basalts but with fractionated LREE. On the Th/Yb versus Nb/Yb diagram, modern forearc, arc, and backarc basalts plot as overlapping
ellipses where forearc have the most enriched character and backarc the least (Fig. 4B; Metcalf and Shervais, 2008; Pearce, 2008).

Consequently, the Hutti depleted and enriched basalt classes likely represent a paired backarc and arc. Some of the depleted basalts feature LREE depletion with positive Nb anomalies (\(\text{Nb/La} > 1.03\)) characteristic of Recent MORB, overlapping the mantle array, and thus may be the best candidates for Archean backarc oceanic crust. Mantle sources of the enriched basalts have similar depletion in terms of Nb/Yb as Sandur komatiites (Fig. 4B). Polat and coworkers have documented ranges of Th/Yb and Nb/Yb as large as compiled in this review for ultramafic to mafic arc-related volcanic suites of Eoarchean to Mesoarchean age in SW Greenland. Consequently, depleted and enriched mantle reservoirs developed early in Earth history (Polat et al., 2011 and references therein).

![Figure 2](image)

**Figure 2** A: Plot of Nb/Y versus SiO₂(%) for Phanerozoic ocean island basalts illustrating the continuum from tholeiitic basalts at high degrees of partial melting at low pressures to alkaline basalts at low degrees of partial melting at high pressures (Greenough et al., 2005). Alkaline basalts at Penakacherla plot with this Phanerozoic array, whereas high-Mg basalts plot to lower SiO₂ at a given ratio of Nb/Y compared to Iceland Tholeitic Basalts. B: Multielement plot normalised to primitive mantle values (Sun and McDonough, 1989). Iceland tholeitic and alkaline basalts from Kokfelt et al. (2006). High-Mg basalts and alkaline basalts from the Penakacherla greenstone terrane from Manikyamba and Kerrich (2011).
4.3. Boninites

In some Recent and Phanerozoic intraoceanic arcs a distinctive type of magnesian volcanic flow has been documented, termed boninites. These flows are characterized by the conjunction of U-shaped REE patterns, negative anomalies at Nb, and elevated Al₂O₃/TiO₂ ratios typically 30–60 (Cameron et al., 1983; Stern et al., 1991; Pearce et al., 1992; Taylor et al., 1994). Boninites are interpreted as second stage melts: in stage 1, extraction(s) of basalt liquid leaves an extremely depleted, refractory residue featuring high Mg#, Cr, Co, and Ni contents, with negatively sloping REE and hence elevated Al₂O₃/TiO₂ ratios. During stage 2, in a convergent margin, melts are generated by hydrous fluxing of the residue which introduces LREE but not Nb, and negatively sloping HREE with elevated Al₂O₃/TiO₂ ratios is inherited from the refractory residue.

Boninites were formerly considered to be restricted to Phanerozoic arcs. However, flows with boninitic composition have been documented from the 2.7 Ga Abitibi terrane, Superior Province (Kerrich et al., 1998), and by Manikyamba et al. (2005) from the Gadwal terrane, eastern Dharwar Craton (Fig. 1D). In keeping with a highly refractory mantle source the Gadwal boninites have the lowest Nb/Yb ratios of all Dharwar plume and arc volcanic lithologies (Fig. 4B). Accordingly, convergent margin processes akin to some Phanerozoic arcs were operating in the Neoarchean (see Polat and Kerrich, 2006 for a review).

4.4. The tholeiitic to calc-alkaline basalt-Mg-andesite-Nb enriched basalt-adakite association

Adakites are Al- and Na-enriched intermediate to felsic calc-alkaline rocks having high (La/Yb)N ratios that were first described from Cenozoic arcs characterized by subduction of young (<20 Ma), hot, oceanic lithosphere in intraoceanic convergent margins. Adakites are generally interpreted as slab
Table 2  Summary of the literature and concepts on the greenstone terranes of the eastern Dharwar Craton (EDC).

<table>
<thead>
<tr>
<th>Terrane</th>
<th>Authors/source</th>
<th>Concept</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandur</td>
<td>Manikyamba et al., 1993</td>
<td>Volcano-sedimentary rocks formed in ocean spreading centre and subduction zone process</td>
<td>Geochemistry of BIFs, mafic and felsic volcanic rocks</td>
</tr>
<tr>
<td></td>
<td>Manikyamba and Naqvi, 1997</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hanuma Prasad et al., 1997</td>
<td>Magmatic rocks of Copper Mountain Region are evolved in an active plate margin environment</td>
<td>Geochemistry of bimodal volcanic rocks.</td>
</tr>
<tr>
<td></td>
<td>Naqvi et al., 2002</td>
<td>Mantle plume magmatism.</td>
<td>Geochemistry and Nd isotopic studies on komatiites</td>
</tr>
<tr>
<td></td>
<td>Manikyamba and Khanna, 2005</td>
<td>Slab melting in subduction zone environment</td>
<td>Geochemistry of adakites</td>
</tr>
<tr>
<td></td>
<td>Manikyamba and Kerrich, 2006</td>
<td>Intraoceanic arc or backarc distal to an active continental margin</td>
<td>Geochemistry of black shales</td>
</tr>
<tr>
<td></td>
<td>Manikyamba et al., 2008</td>
<td>Zoned mantle plume source, erupted through or at the margin of continental lithosphere associated with island arc magmatism</td>
<td>Geochemistry of komatiites, komatiic basalts and adakites</td>
</tr>
<tr>
<td>Ramagiri</td>
<td>Zachariah et al., 1995, 1996</td>
<td>Island arc tectonic setting</td>
<td>Trace element and Nd isotopic studies of tholeiitic basalts</td>
</tr>
<tr>
<td>Penakacherla</td>
<td>Manikyamba et al., 2004a</td>
<td>Partial melting of plume influenced mantle wedge in an intraoceanic island arc tectonic setting</td>
<td>Geochemistry of tholeiitic basalts</td>
</tr>
<tr>
<td>Penakacherla</td>
<td>Manikyamba and Kerrich, 2011</td>
<td>Eruption of mantle plume at a rifted continental margin</td>
<td>Geochemistry of alkaline and high-Mg basalts</td>
</tr>
<tr>
<td>Hutti</td>
<td>Ananta Iyer et al., 1980</td>
<td>Volcanism characteristic of Midoceanic ridges and backarc marginal basins.</td>
<td>Major, trace and REE data of the basalts</td>
</tr>
<tr>
<td></td>
<td>Satyanarayana and Reddy, 1996</td>
<td>Primitive continental or island arc setting for the volcanism</td>
<td>Selected major and trace element data on the mafic and felsic flows</td>
</tr>
<tr>
<td></td>
<td>Vasudev et al., 2000</td>
<td>Rapid basin evolution through island arc accretion</td>
<td>SHRIMP U-Pb zircon ages of granodiorite clast in conglomerate</td>
</tr>
<tr>
<td></td>
<td>Chadwick et al., 2000</td>
<td>Intra-arc setting for the greenstone terranes of EDC and their oblique convergence to the foreland continental margin of WDC</td>
<td>Magmatic fabrics in plutonic rocks and structural fabrics in shear zones of EDC</td>
</tr>
<tr>
<td></td>
<td>Rogers et al., 2007</td>
<td>Cratonic collision and subsequent craton wide magmatism</td>
<td>U-Pb dating of metamorphic events in granitoids</td>
</tr>
<tr>
<td></td>
<td>Manikyamba et al., 2009</td>
<td>Intraoceanic arc-backarc sequence obducted onto older basement</td>
<td>Geochemistry of basaltas, magnesian andesites and adakites</td>
</tr>
<tr>
<td>Kolar</td>
<td>Rajamani et al., 1985</td>
<td>Low percentage melting of the mantle; partial melting of enriched mantle sources</td>
<td>Geochemistry of komatiites and amphibolites</td>
</tr>
<tr>
<td></td>
<td>Balakrishnan et al., 1990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kolar</td>
<td>Rajamani, 1990</td>
<td>Rift related volcanism associated with mantle plume activity</td>
<td>Petrogenetic modelling of volcanic rocks</td>
</tr>
<tr>
<td>Kolar</td>
<td>Manikyamba et al., 2005</td>
<td>Melting of metasomatized peridotitic mantle wedge</td>
<td>Geochemistry of boninites</td>
</tr>
<tr>
<td>Gadwal</td>
<td>Manikyamba et al., 2005</td>
<td>Island arc tectonic setting</td>
<td>Geochemistry of metavolcanic rocks</td>
</tr>
<tr>
<td></td>
<td>Khanna, 2007</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manikyamba and Khanna, 2007</td>
<td>Slab dehydration wedge melting</td>
<td>Geochemistry of tholeiitic basalts and Nb-enriched basalts</td>
</tr>
<tr>
<td></td>
<td>Manikyamba et al., 2007</td>
<td>Slab melting wedge hybridization; complex arc magmatism through possible ridge subduction</td>
<td>Geochemistry of rhyolites and adakites</td>
</tr>
</tbody>
</table>

Meta is implicit for all lithologies.
melts that hybridized with the mantle wedge in transit from the slab to the oceanic arc, acquiring enhanced Mg, Cr, and Ni. They contrast with “normal” basalt-andesite-dacite-rhyolite (BADR) associations of continental margin arcs which involve slab dehydration wedge melting (Drummond et al., 1996; Martin et al., 2005; for a review see Richards and Kerrich, 2007; Lazaro and Garcia-Casco, 2008). According to Foley et al. (2002), melting of low-Mg garnet amphibolite on the subducting slab generates the dacitic compositions of adakites, residual garnet generates high (La/Yb)N ratios, and melting of amphibole, which concentrates Zr and Hf, causes positive Zr-Hf/MREE anomalies reflected in Zr/Sm ratios greater than the primitive mantle value of 25 (Drummond et al., 1996; Sun and McDonough, 1989). Martin et al. (2005) divided adakitic rocks from intraoceanic arcs into low-silica adakites (LSA) and high-silica adakites (HSA). The former are synonymous with magnesian andesites, or high-Mg andesites, and the latter with adakites. On a plot of MgO versus SiO2, LSA and HSA together define a negatively sloping array with overlapping fields (Martin et al., 2005).

Magnesian andesites are generally considered to be slab melts that have undergone greater degrees of hybridization with the mantle wedge than adakites, whereas Nb-enriched basalts are melts of the residue after magnesian andesites are extracted (Kelemen, 1995; Sajona et al., 1996).

As for boninites, adakites and associated Mg-andesites and Nb-enriched basalts were considered to be restricted to the Phanerozoic. However, this association has now been documented from numerous Neoarchean greenstone terranes of several cratons (Polat and Kerrich, 2006). In the eastern Dharwar Craton adakites have been reported from the Sandur and Kushtagi terranes, and from the Gadwal terrane where they coexist with “normal” arc rhyolites. Adakites and Mg-andesites are present in the Hutti and Gadwal greenstone terranes. On Fig. 4B there is a trend from oceanic arc basalts through Mg-andesites to adakites reflecting complex hybridization of arc basalt and adakitic liquids in a convergent margin. By analogy with examples of this association in Cenozoic arcs, the Neoarchean associations record subduction of young, hot, oceanic lithosphere.

A summary of historical models for development of greenstone terranes of the eastern Dharwar Craton is given in Table 2.

5. Lithosphere growth by assembly of plume and arc sequences in a subduction-accretion complex

Orogenic belts have been divided into accretionary and continent-continent types (Tables 3A and 3B; Şengör and Natal’ in, 1996). At ~2.7 Ga there appears to have been accretionary orogens on most

### Table 3A
Synthesis of accretionary and continent-continent orogenic belts.

<table>
<thead>
<tr>
<th>Orogen</th>
<th>Location</th>
<th>Age</th>
<th>Orogen</th>
<th>Location</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isua greenstone belt</td>
<td>W. Greenland</td>
<td>3.8 Ga</td>
<td>Terminal Trans Hudson</td>
<td>S. Dakota, Saskatchewan</td>
<td>1.7 Ga</td>
</tr>
<tr>
<td>Dharwar</td>
<td>India</td>
<td>2.7 Ga</td>
<td>Barramundi</td>
<td>N. Australia</td>
<td>1.9 Ga</td>
</tr>
<tr>
<td>Kenoran</td>
<td>Superior Province</td>
<td>2.7 Ga</td>
<td>Grenville</td>
<td>E. Canada Fennoscandia</td>
<td>~1.2 Ga</td>
</tr>
<tr>
<td>Yilgarn</td>
<td>W. Australia</td>
<td>2.7 Ga</td>
<td>Appalachian-Caledonian</td>
<td>N. America-Scandinavia</td>
<td>&lt;500 Ma</td>
</tr>
<tr>
<td>Altaiads</td>
<td>C. Asia</td>
<td>700–500 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tasman</td>
<td>E. Australia</td>
<td>&lt;500 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nipponides</td>
<td>E. Asia</td>
<td>&lt;240 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cordillera</td>
<td>N. America</td>
<td>&lt;200 Ma</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

As for boninites, adakites and associated Mg-andesites and Nb-enriched basalts were considered to be restricted to the Phanerozoic. However, this association has now been documented from numerous Neoarchean greenstone terranes of several cratons (Polat and Kerrich, 2006). In the eastern Dharwar Craton adakites have been reported from the Sandur and Kushtagi terranes, and from the Gadwal terrane where they coexist with “normal” arc rhyolites. Adakites and Mg-andesites are present in the Hutti and Gadwal greenstone terranes. On Fig. 4B there is a trend from oceanic arc basalts through Mg-andesites to adakites reflecting complex hybridization of arc basalt and adakitic liquids in a convergent margin. By analogy with examples of this association in Cenozoic arcs, the Neoarchean associations record subduction of young, hot, oceanic lithosphere.

### Table 3B
Comparison of the Accretionary-Altaid-Cordilleran and Alpine-Himalayan type orogens.

<table>
<thead>
<tr>
<th>Altaid-Cordilleran orogeny</th>
<th>Alpine-Himalayan orogeny</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accretion of allochthonous juvenile oceanic island arcs, forearcs, and continental blocks</td>
<td>Continent-continent collision, presence of giant ophiolite nappes between two continents</td>
</tr>
<tr>
<td>Closure of external ocean</td>
<td>Closure of internal ocean, such as Tethys</td>
</tr>
<tr>
<td>Multiple sutures, ophiolites (e.g., esimatic arc basement, forearc), numerous ophiolitic fragments (ophirags) in the accretionary prism</td>
<td>Long, narrow single suture zone with more or less complete ophiolite nappe emplaced onto passive continental margins (e.g., Oman, Kizildag)</td>
</tr>
<tr>
<td>Subduction–accretion complex</td>
<td>Deformed passive margin sedimentary rocks</td>
</tr>
<tr>
<td>Multiple deformation of subduction–accretion complex, large degree of structural shuffling by thrusting and strike-slip faulting</td>
<td>Reworking of pre-existing crust</td>
</tr>
<tr>
<td>Magmatic arc migrates through subduction–accretion complex</td>
<td>Subdued magmatism</td>
</tr>
<tr>
<td>Heat advected by magmas</td>
<td>Internal radiogenic heat production</td>
</tr>
<tr>
<td>Subduction–erosion of lithospheric mantle</td>
<td>Delamination of thickened lithospheric mantle</td>
</tr>
<tr>
<td>Highly prospective for orogenic gold</td>
<td>Low prospectivity for orogenic gold</td>
</tr>
<tr>
<td>Prospective for porphyry Cu-Mo, magmatic Sn-W</td>
<td>Prospective for MVT</td>
</tr>
</tbody>
</table>
Figure 5  Cartoon illustrating a possible scheme for the development of Archean CLM by plume-arc interaction, based on data for the Abitibi-Wawa arc. A: Slab pull of subducting oceanic lithosphere under arc induces ocean-ward arc migration, resulting in formation of intraoceanic arc volcanic suites. Slab melting generates TTG. Komatiites and basalts erupt from a mantle plume to generate an intraoceanic plateau, leaving a buoyant refractory residue at >100–400 km depth. B: Migrating arc captures, and is jammed by, thick plateau crust, which imbricates. Subduction steps back across thickened plume-arc composite lithosphere. Buoyant plume residue rises to couple with imbricated plume-arc crust, and imbricates with arc mantle lithosphere and slab remnants. Slab break off (same decoration as oceanic lithosphere in panel A) a remnant from previous subduction zone, to left of buoyant rising plume residue, is a shallow primary component. C: Archean CLM coupled to composite crust, induces layering in lower crust and sets young ages \( \approx 2650–2640 \) Ma in mid-crust. Remnant subducting slab of panel B a primary shallow component incorporated into depleted harzburgite of CLM. Lithospheric mantle metasomatized by low degree melts from OIB’s and thermal boundary layer, and post-Archean steeper subduction featuring slab dehydration that generates shallow secondary metasomatized components of CLM (Modified after Kerrich et al., 2000). Box A in panel B illustrates approximate position of flat subduction inset B’ of panel C, with subduction-related shoshonitic lamprophyres and diamonds. On panel B, inset A’ illustrates temperature contours in °C and depths in km where flat subduction-related shoshonites and diamonds form (inset modified from Wyman et al., 2006). Box B in panel B keyed to box B’ of panel C. Modified from Wyman and Kerrich (2009).
cratons, including the Superior and Dharwar, associated with orogenic gold deposits (Kerrich and Wyman, 1990; Kerrich et al., 1999a,b, 2005, 2010; Goldfarb et al., 2001). These accretionary orogens amalgamated the diverse plume- and arc-derived volcanic sequences of the greenstone terranes; contemporaneous lithospheric mantle associated with plume and crust, as sampled by plumes, did not apparently survive the accretionary process. Eastern Dharwar greenstone terranes lie allochthonously on older Peninsular Gneisses aged 3.0–2.7 and 2.55–2.53 Ga (Peucat et al., 1993; Moyen et al., 2003; Naqvi, 2008). These terranes were obducted onto the gneisses likely at the termination of the 2.7 Ga accretionary orogen.

Continental lithospheric mantle (CLM) is thick and stable under all Archean cratons, including the Dharwar Craton. This CLM is responsible for preservation of Archean crust (Srinagesh et al., 1989; Artemieva, 2009, and references therein). According to Wyman and coworkers, accretionary orogens in the Neoarchean were critical both for growth of continental crust and its counterpart the CLM. This model, founded in the coexistence of plume-related and arc-related volcanic sequences in Neoarchean greenstone terranes, considers that migrating arcs capture thick plume crust, which then becomes imbricated with arc crust. A contemporaneous example is capture of the Ontong Java plateau by the Solomon arc (McInnes et al., 1999). In the Archean, as plume and arc crust imbricate, the low density, refractory, residue of melting in a mantle plume from which the plume-derived ocean plateau crust formed, rises from approximately >90 km and buoyantly couples to the crust. Arndt et al. (2002) had termed the arc-dominated crust and plume residue CLM “strange partners”. In fact, field relations of arc volcanic and plume-related komatiite-basalt sequences in Neoarchean greenstone terranes endorse their separate origins, but related accretion and coupling. This thick CLM buoyantly coupled to the crust after accretionary tectonics and magmatism ceased (Fig. 5; Kerrich et al., 1999a,b; Wyman et al., 2002; Wyman and Kerrich, 2009).

6. Future directions

A number of unresolved issues remain with respect to evolution of the Dharwar Craton. Greenstones terranes of the eastern Dharwar Craton are smaller than counterparts in the west but the reasons are as yet not understood. As well, it is not yet well constrained as to whether the WDC and EDC developed contemporaneously. In addition, the Kolar, Hutti, and Ramagiri terranes of the EDC are richly endowed with orogenic gold deposits whereas terranes of the WDC are sparsely mineralised (Viswanathan, 2008; Viswanathan and Radhakrishna, 2008; Deb and Bheemalingeswara, 2010; Ram Mohan and Sarma, 2010; Sarma et al., 2011). Stromatolites and manganese deposits are present in the greenstone belts proximal to the Closupet granite: are this connected to rise of $p(O_2)$ in the oceans and continental margins first in the WDC and then gradually in the EDC? (Manikyamba and Khanna, 2007).

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