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Proterozoic felsic and mafic magmatism in India: Implications for crustal evolution through crust-mantle interactions

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The Proterozoic felsic and mafic magmatism in India in varied tectonic settings is reviewed and discussed based on available geological, geochemical, and geochronological constraints. Neoarchean-Paleoproterozoic magmatism, as discrete volcano-plutonic complexes and Large Igneous Provinces (LIPs) in the Bastar, Singhbhum and Dharwar cratons and associated mobile belts are also included. Paleoproterozoic magmatism also contributed to the geodynamics of Himalaya. Meso- to Neoproterozoic magmatism comprises kimberlites and lamproites in the Bastar and Dharwar cratons. Neoproterozoic magmatic rocks chiefly constitute the Aravalli-Delhi mobile belts. Mantle-derived magmas, mainly as mafic to hybrid enclaves and syn-plutonic dykes, have contributed significantly in the evolution of calc-alkaline, metaluminous (I-type) to peraluminous (S-type) granites formed in subduction to post-collision tectonic zones. Anorogenic (A-type) granites are commonly reported in post-collision to rift environments. As a whole Proterozoic mafic-felsic magmatism contributed greatly in the crustal architecture and evolution of Indian subcontinent that are correlatable with the construction and break-up of Columbia and Rodinia supercontinents.

Introduction

The Proterozoic Eon (2500 – 541 Ma), the greatest part of the Precambrian Supereon, represents a time span just before the build-up of oxygen and explosion of multifaceted life on the Earth (e.g. Roverato et al., 2019). This period, tectonically, was perhaps the most active in the Earth's history during which the largest amount of the crust comprising granites (s.l.), subordinate volcanics and metamorphic rocks, and mineral ores were produced (Condie, 2000, Rino et al., 2004).

Indian continental landmass is formed by amalgamation of north Indian and south Indian continental blocks following a collision along ca. 1500 km east-west trending Central India Tectonic Zone (CITZ) (e.g., Naqvi and Rogers, 1987; Stein et al. 2004), that stabilized during Proterozoic (e.g. Bhowmik et al., 2012). Broadly S-shaped Proterozoic mobile belt encompasses Aravalli belt passing through CITZ and finally culminates in the Eastern Ghat Mobile Belt (EGMB) (Fig. 1). The Shillong-Meghalaya Gneissic Complex (SMGC) is the northeastern extension of the Precambrian Indian peninsula (Evans, 1964). The magmatic and metamorphic events recorded along CITZ are synchronous to that occurred in the SMGC, which strongly point to the extension of the CITZ through the eastern India tectonic zone (EITZ) into the SMGC (e.g. Kumar et al., 2017a). The CITZ and EITZ bear a protracted geological history of development between ca. 2.5 and ca. 1.0 Ga (Roy et al., 2001; Chatterjee et al., 2011).

The CITZ separates Aravalli and Bundelkhand cratons in the north from Singhbhum, Bastar and Dharwar cratons in the south of the Indian peninsula (Fig. 1). These cratons and adjoining mobile belts of India are dominantly formed by Proterozoic granites, granite gneisses, volcano-plutonic complexes, mafic dykes and dyke swarms, volcano-sedimentary and metamorphosed lithounits. In recent years, rigorous use of zircon U-Pb chronology, Lu-Hf isotopes, whole rock (WR) Rb-Sr and Sm-Nd isotopes, and elemental geochemistry of felsic to mafic magmatic rocks have revealed that most Proterozoic magmatic provinces of India are recycled products of ancient continental crust, with variable juvenile mantle input. Mantle plumes below Proterozoic supercontinent may have led to rifting and emplacement of A-type magmatism, mafic dykes, dyke swarms and large igneous provinces (LIPs) in many cratons and mobile belts of India (e.g. Santosh, 2012). However, neither the plume nor the plate tectonics could adequately explain field, petrological and geochemical intricacies in LIPs (Sensarma et al., 2018). In this contribution the status of Proterozoic magmatism of India been reviewed and critically evaluated in order to bring out genetic and geodynamic scenario integrating the geological, geochemical and geochronological database. Neoarchean-Paleoproterozoic transition (ca.2.55 Ga) magmatism is also taken into consideration.

The large published database is handled using GCDkit (Janoušek et al., 2006). The available information on lithology, geochemistry, isotopes, chronology, and possible tectono-magmatic environments

Figure 1. Generalized tectonic map of the Indian. AFB: Aravalli Fold Belt; DFB: Delhi Fold Belt; EGB, Eastern Ghat Mobile Belt; SMB: Satpura Mobile Belt; NSL, Narmada Son lineament; CIS, Central Indian Suture; PCSZ, Palghat-Cauvery Shear Zone; EDD: Eastern Dharwar Domain; WDD: Western Dharwar Domain; MR: Mahandi Rift; R: Rajmahal Traps; SIB: South Indian Block; NIB: North Indian Block (Meert and Pandit, 2015).

for Proterozoic magmatic rocks of Indian cratons and adjoining mobile belts are summarized in Table 1.

Proterozoic magmatic episodes and their characteristic features

Aravalli craton and adjoining Delhi fold belt

Paleoproterozoic Aravalli and Mesoproterozoic Delhi fold belt lie unconformably over the Archean Banded Gneissic Complex (BGC >2.5 Ga) (see in Ramakrishnan and Vaidyanathan, 2008). The BGC has been intruded by a number of *ca.* 2.5 Ga plutons. Delhi fold belt has been divided into north Delhi fold belt (NDFB) and south Delhi fold belt (SDFB) based on timing of magmatism in NDFB (1.44–1.66 Ga) and SDFB (730–960 Ma) (Sinha-Roy et al., 1998).

The Berach granites (2.53 Ga, 2.44 Ga) intrude the BGC, and bear metaluminous (I-type), calc-alkaline and sanukitoid characters (Crawford, 1970; Choudhary et al., 1984; Mondal and Raza, 2013).

High-Al Tonalite-Trondhjemite-Granodiorite (TTG) (3.31 ± 0.07 Ga; Gopalan et al., 1990) constitute the part of BGC (Ahmad and Mondal, 2014) and basement mafic rocks occur as enclaves within the BGC (Ahmad and Tarney, 1994).

Neoproterozoic-Paleoproterozoic felsic rocks of Aravalli craton belong largely to calc-alkaline granite and granodiorite (Fig. 4a, b). The rare earth elements (REE) patterns are moderately fractionated ($La_N/Yb_N = 18.72-30.87$; avg. 22.91) with negative to no Eu-anomalies ($Eu_N/Eu^* = 0.43-1.06$; avg. 0.76), which are transitional between TTG and arc granites. A zircon from Jhamarkotra gneiss yielded minimum age of 3281 ± 3 Ma, whereas a zircon overgrowth (30 μ m) provided an age of 2536 ± 20 Ma (Wiedenbeck and Goswami, 1994) that point to the timing of partial melting of 3200 Ma gneissic protolith. Similarly, Ahar river (2560 Ma), Gingla (2400–2500 Ma), Berach (2440 Ma) granites, and a granite gneiss (2530 Ma) at Jhamarkotra (Wiedenbeck et al., 1996) were produced by recycling of older protoliths in subduction to collision settings.

Mantle contribution in the origin of Paleoproterozoic granites

The Nathwada mafic rocks (2.0–1.8 Ga) of komatiite, komatiitic basalt and tholeiite nature were derived from heterogeneous enriched sub-continental lithospheric mantle (SCLM) sources ($\epsilon Nd^{(t)} = -2.4$ to -24.6) (Ahmad and Rajamani, 1991; Ahmad et al., 2009). The contribution of mantle in the genesis of 2.5 and 1.70 Ga calc-alkaline to alkaline magmatism in the Aravalli craton is supported by amphibolite (2.83 ± 0.05 Ga

with positive $\epsilon Nd^{(t)}$) enclosed within gneisses (Gopalan et al., 1990).

The Jasrapur granites (1.82 Ga) of calc-alkaline affinity from Khetri copper belt bear isotopic signatures ($\epsilon Nd^{(t)} = -4.8$ to -7.89 ; initial Sr-isotopic ratios ($SrI = 0.705 - 0.725$) of crustal and mantle-derived magmas formed in an Andean type arc setting (Kaur et al., 2009). A-type granite (1.70–1.72 Ga) in the Khetri is strongly albitised with isotopic evidences ($\epsilon Nd^{(t)} = -1.33$ to -7.24 ; $SrI < 0.737$) for its crust-mantle interactive origin (Kaur et al., 2011, 2012). Kaur et al. (2017) integrating data from thirteen plutons (1.73–1.70 Ga) advocated that A-type magmas with sub-chondrite zircon ϵHf values were formed by high degree melting of 1.85 Ga old calc-alkaline granites, whereas slightly super-chondrite zircon ϵHf were generated by mixing of crust- and depleted mantle-derived magmas.

Paleoproterozoic felsic rocks of Aravalli craton correspond to A- and I-type calc-alkaline (Fig. 4a) granite and granodiorite (Fig. 4b). The REE fractionation ($La_N/Yb_N = 8.63-39.19$; avg. 15.94) with negative to positive Eu anomalies ($Eu_N/Eu^* = 0.28-2.28$; 0.63) (Fig. 4c) indicates fractional differentiation and crustal assimilation.

Table 1: Mineralogical, chemical, isotopic and chronological data of Proterozoic felsic and mafic magmatic rocks of Indian cratons and adjoining mobile belts.

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Aravalli craton and adjoining Delhi fold belt							
Berach	Granitoids	Qtz+Pl+Kfs±Hbl±Bt±Chl±Ep±Spm±Zrn±Ap	Calc-alkaline and Sanukitic	Ca. 2.53 Ga (Whole rock Rb-Sr)	-	Intruded in banded gneiss complex	Crawford, 1970; Sivaraman and Odom, 1982; Choudhary et al., 1984; Gopalan et al., 1990; Wiedenbeck et al., 1996; Butik et al., 2006; Mondal and Raza, 2013
Jasrapur (Khetri)	Granitoids	Pl+Kfs+Qz+Bt±Hbl±Ep±Ttn±Ap±Zrn±Aln±Mag	Calc-alkaline	Ca. 1.82 Ga (zircon Pb–Pb evaporation)	$\epsilon\text{Nd}(t) = -4.8$ to -7.89 ; $\text{Sri} = 0.705356$ to 0.725712	Andean type arc magmatism	Kaur et al., 2009
Khetri complex	Granitoids	Qtz+Kfs+Pl±Bt±Chl±Ep±Zrn±Ap	A-type affinity	Ca. 1.72 to 1.70 (zircon U–Pb evaporation)	$\epsilon\text{Nd}(t) = -1.33$ to -7.24 ; $\text{Sri} = 0.639922$ to 0.737452	extension-related granitoids and presence of extreme albification	Kaur et al., 2011; Kaur et al., 2012
Peshua (Sirohi)	Plagiogranite	Pl+Qz+Hbl±Ttn±Aln±Ep±Ap±Zr	Calc-alkaline	Ca. 1015 Ma (SHRIMP U–Pb zircon)	-	Continental are related	Dharma Rao et al., 2013
Devala (Sirohi)	Granite gneiss	Qtz+Kfs+Pl±Bt±Chl±Zrn±Ap±Ilm±Mag	High K Calc-alkaline	Ca. 966 Ma (SHRIMP U–Pb zircon)	-	Continental are related	
Sai (Sirohi)	Porphyritic granite	Qtz+Kfs+Pl±Bt±Chl±Zrn±Ap±Ilm±Mag	High K Calc-alkaline	Ca. 808 Ma (SHRIMP U–Pb zircon)	-	Continental are related	
Chang (Eripura Gr)	Granitoids	Qtz+Kfs+Pl±Bt±Ms±Ttn±Mag±Ilm±Ap±Zrn±Mnz	S as well as I-type affinity	Ca. 967 Ma (TIMS U–Pb zircon)	$\epsilon\text{Nd}(t) = -2.734$ to -4.144 ; $\text{Sri} = 0.695638$ to 0.712470	-	Pandit et al., 2003
Moras	Granitoids	Qtz+Kfs+Pl±Bt	I-type affinity	Ca. 976 Ma (LA–ICP–MS U–Pb zircon)	$\epsilon\text{Nd}(t) = -1.42$ to 0.42 ; $\text{Sri} = 0.7068$ to 0.7019 ; $\epsilon\text{Hf}(t) = 2.34$ to 9.35 ; $\delta^{18}\text{O} = 6.48$ to 7.58‰	Derived by partial melting of juvenile mafic crust	Zhao et al., 2018
Plai	Granitoids	Qtz+Kfs+Pl±Bt	A-type affinity	Ca. 811 Ma (LA–ICP–MS U–Pb zircon)	$\epsilon\text{Nd}(t) = 0.84$ to 0.46 ; $\text{Sri} = -1.0395$ to -1.1575 ; $\epsilon\text{Hf}(t) = -1.80$ to 8.62 ; $\delta^{18}\text{O} = 6.15$ to 7.80‰	Derived by partial melting of dehydrated mafic crust	
Mirpur	Granitoids	Qtz+Kfs+Pl±Bt	A-type affinity	Ca. 780 Ma (LA–ICP–MS U–Pb zircon)	$\epsilon\text{Nd}(t) = -2.10$ to -2.28 ; $\text{Sri} = 0.5712$ to 0.6921 ; $\epsilon\text{Hf}(t) = -1.9$ to 2.41 ; $\delta^{18}\text{O} = 5.71$ to 6.79‰	Derived by partial melting of dehydrated mafic crust	
Siwaya (Eripura Gr)	Granite gneiss	Qtz+Kfs±Ms±Grt±Ap±Zrn±Mnz	-	Ca. 836 Ma (Zircon U–Pb evaporation)	-	-	Deb et al., 2001
Mt. Abu	Granitoids	Qtz+Kfs+Pl±Bt±Hbl±Spm±Mag±Ap±Zrn±Mnz	Metavolcanic calc-alkaline	Ca. 765 Ma (TIMS U–Pb zircon)	-	Presence of coeval mafic dykes and enclaves	Ashwal et al., 2013
Sindreh Gr (MIS)	siliceous tuff	-	-	Ca. 765 Ma (SHRIMP U–Pb zircon)	-	-	Rao et al., 2012
Sindreh Gr (MIS)	rhyolite tuff	-	-	Ca. 768 (SHRIMP U–Pb zircon)	-	-	
Sindreh Gr (MIS)	rhyolite tuff	-	-	Ca. 666 to 644 Ma (SHRIMP U–Pb zircon)	-	-	
Sirohi (MIS)	Porphyritic rhyolite	Qtz+Pl+Kfs±Hbl	-	Ca. 763 to 758 Ma (LA–ICP–MS U–Pb zircon)	$\delta^{18}\text{O} = -5.12$ to 8.23‰ ; $\epsilon\text{Hf}(t) =$ mainly positive	LIP related	Wang et al., 2017
Jodhpur (MIS)	Porphyritic rhyolite	Qtz+Pl+Kfs±Hbl	-	Ca. 776 to 769 Ma (LA–ICP–MS U–Pb zircon)	$\delta^{18}\text{O} = -4.12$ to -1.1‰ ; $\epsilon\text{Hf}(t) =$ mainly positive	LIP related	
Punaghar (MIS)	Dacite	Qtz+Pl+Kfs±Mag±Hbl	-	Ca. 760 Ma (LA–ICP–MS U–Pb zircon)	$\delta^{18}\text{O} = 6.2$ to 6.81‰ ; $\epsilon\text{Hf}(t) =$ mainly positive	LIP related and presence of early proterozoic xenocrystic zircon cores	

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Nathdwara mafic	komatiite and komatiitic basalt	-	Tholeiitic	Ca. 2.0 to 1.8 Ga (Sm-Nd whole rock)	$\epsilon Nd(0) = -2.4$ to -24.6	Produce by melting of heterogeneous enriched SCLM	Ahmad and Rajamani, 1991; Ahmad et al., 2009
Sankara and Redana (MIS)	Mafic dykes	-	-	Ca. 750 Ma (LA-ICP-MS U-Pb zircon)	-	Represent late stage magmatic activity related to MIS	Meert et al., 2013
Bundelkhand craton							
Gwalior	Mafic sills	Pl+Cpx±Opx±Qtz±Kfs±Opq	Sub-alkali tholeiitic	Ca. 2104 Ma (Sm-Nd whole-rock)	$\epsilon Nd(0) = -6.41$ to 3.92	LIP and intracontinental rifting related	Samom et al., 2017
Mauranipur	Mafic dyke	-	-	Ca. 1979 Ma (LA-ICP-MS U-Pb baddeleyite/Zircon)	-	-	Pradhan et al., 2012
Mahoba	Mafic dyke	-	-	Ca. 1113 Ma (LA-ICP-MS U-Pb baddeleyite/Zircon)	-	-	Pradhan et al., 2012
Majhgawan pipe	Kimberlite	Olv+Phl+Spl+Prv±Ap	potassic-ultrapotassic alkaline	Ca. 1073.5 Ma (Ar-Ar phlogopite)	$\epsilon Nd(t)=0.0$; Sri= 0.7030 to 0.7064	rift related	Paul, 1979; Chalapathi Rao, 2005; Gregory et al., 2012
Karera	Granodiorite	-	High-K calc-alkaline with sanukitic	Ca. 2563 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Near Raksa	Granodiorite	-	High-K calc-alkaline with sanukitic	Ca. 2559 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Khajuraho	Monzogranite	Qtz+Kfs+Bt±Zrn±Ap±Epx±Spn	High-K calc-alkaline with sanukitic	Ca. 2544 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Orecha	Granodiorite	Pl+Qtz+Kfs+Hbl+Bt±Chl±Spn±Ap±Mag	High-K calc-alkaline with sanukitic character	Ca. 2560 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Near Raksa	Granodiorite	-	High-K calc-alkaline	Ca. 2557 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Garnau	Monzogranite	-	High-K calc-alkaline	Ca. 2569 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Garnau	Migmatite	-	High-K calc-alkaline	Ca. 2571 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Babina	Monzogranite	Qtz+Pl+Bt±Zrn±Ap	High-K calc-alkaline	Ca. 2546 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Talbehat	Monzogranite	Qtz+Kfs+Pl+Bt±Chl±Mag±Zrn	High-K calc-alkaline	Ca. 2544 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Mauranipur	Monzogranite	Qtz+Kfs+Pl+Bt±Chl±Opq	High-K calc-alkaline	Ca. 2578 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Near Khajuraho	Monzogranite	Qtz+Kfs+Pl+Bt±Chl±Opq	High-K calc-alkaline	Ca. 2565 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Bijoli	Monzogranite	Qtz+Kfs+Pl+Bt±Chl±Opq	High-K calc-alkaline	Ca. 2562 Ma (LA-ICP-MS U-Pb zircon)	-	Slab break-off or delamination related	Joshi et al., 2016
Karera	Gneiss	Qtz+Pl+Kfs+Bt±Ap±Zrn	Calc-alkaline	Ca. 2563 Ma (Ion microprobe U-Pb zircon)	-	Volcanic arc related	Mondal and Zaimuddin, 1997; Mondal et al., 2002
Jahaura	Hornblend granitoids	Qtz+Pl+Hbl+Bt±Ap±Zrn	Calc-alkaline	Ca. 2516 Ma (Ion microprobe U-Pb zircon)	-	Volcanic arc related	Mondal and Zaimuddin, 1997; Mondal et al., 2002
Mahoba	Hornblend granitoids	Qtz+Pl+Hbl+Bt±Ap±Zrn	Calc-alkaline	Ca. 2454 to 2551 Ma (Ion microprobe U-Pb zircon)	-	Volcanic arc related	Mondal and Zaimuddin, 1997; Mondal et al., 2002

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Lalitpur	Biotite granitoids	Qtz+Pl+Kfs+Bt±Ap±Zrn	Calc-alkaline	Ca. 2521 Ma (Ion microprobe U-Pb zircon)	-	Volcanic arc related	Mondal and Zaimuddin, 1997; Mondal et al., 2002
Bansi	Rhyolite	-	Calc-alkaline	Ca. 2517 Ma (Ion microprobe U-Pb zircon)	-	Volcanic arc related	Mondal and Zaimuddin, 1997; Mondal et al., 2002
Dinara	Granodiorite gneiss	Pl+Qtz+Kfs+Hbl+Bt±Ttn±Ep±Ap±Zrn±Aln	Calc-alkaline	Ca. 2561 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.8$	Subduction related	Kaur et al., 2016
Bilbai	Granodiorite gneiss	Pl+Qtz+Kfs+Hbl+Bt±Ttn±Ep±Ap±Zrn±Aln	Calc-alkaline	Ca. 2566 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -8.3$	Subduction related	Kaur et al., 2016
Baghora	Granodiorite gneiss	Pl+Qtz+Kfs+Hbl+Bt±Ttn±Ep±Ap±Zrn±Aln	Calc-alkaline	Ca. 2358 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -7.8$	Subduction related	Kaur et al., 2016
Bedaura	Granodiorite gneiss	Pl+Qtz+Kfs+Hbl+Bt±Ttn±Ep±Ap±Zrn±Aln	Calc-alkaline	Ca. 2551 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -7.2$	Subduction related	Kaur et al., 2016
Kolhara	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2583 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.5$	Subduction related	Kaur et al., 2016
Jhansi	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2529 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -7.6$	Subduction related	Kaur et al., 2016
Jhansi	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2566 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.7$	Subduction related	Kaur et al., 2016
Lalitpur	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2564 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -11.4$ to -8.3	Subduction related	Kaur et al., 2016
Kuraicha	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2545 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -11.3$ to -8.0	Subduction related	Kaur et al., 2016
Dinara	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2563 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -6.6$	Subduction related	Kaur et al., 2016
Patha Bhadhan	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2543 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = +0.3$	Subduction related	Kaur et al., 2016
Vijaypur	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2537 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -10.4$ to -4.3	Subduction related	Kaur et al., 2016
Baghora	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2525 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -8.5$	Subduction related	Kaur et al., 2016
Mauranipur	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2548 Ma (MC-SF-ICP-MS U-Pb zircon)	-	Subduction related	Kaur et al., 2016
Charkhari-Kabani	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2549 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -8.1$	Subduction related	Kaur et al., 2016
Cggatarpur-Tikahgarh	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2516 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -8.8$	Subduction related	Kaur et al., 2016
Chhayan	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2491 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.9$	Subduction related	Kaur et al., 2016
Panchaura	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2539 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -8.1$ to -2.5	Subduction related	Kaur et al., 2016
Utwaha	Granite	Qtz+Pl+Kfs+Bt±Ttn±Ep±Aln±Ap±Zrn±Mag	Calc-alkaline	Ca. 2554 Ma (MC-SF-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -7.1$	Subduction related	Kaur et al., 2016
Bastar craton and associated large igneous province							
Gidam	Dolerite dyke	Cpx+Pl+Qtz+Ap±Hbl±Bt±Chl±Baddeleyite	-	Ca. 1.82 to 1.84 Ga (baddeleyite U-Pb IDTIMS)	-	LIP related	French et al., 2008
Dantewara	Dolerite dyke	Cpx+Pl+Qtz+Ap±Hbl±Bt±Chl±Baddeleyite	-	Ca. 1.86 to 1.89 Ga (baddeleyite U-Pb IDTIMS)	-	LIP related	French et al., 2008

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Bijli (Nandgaon Gr)	Porphyritic Rhyolite	Kfs+Qtz+Pl±Bt±Zrn	Calc-alkaline	Ca. 2.47 to 2.46 (zircon LA-ICP-MS)	$\epsilon\text{Hf}(t) = -10$ to -4.2	Arc related	Manikyamba et al., 2016
Dongargarh (Nandgaon Gr)	Porphyritic Granite	Kfs+Qtz+Pl±Bt±Zrn±Ap	A-type affinity	Ca. 2.5 (zircon LA-ICP-MS)	$\epsilon\text{Hf}(t) = -8.8$ to -5.0	Arc related	Manikyamba et al., 2016
Bijli (Nandgaon Gr)	Rhyolite	Kfs+Qtz+Pl±Bt±Zrn	A-type affinity	-	$\delta^{18}\text{O} = 4.4$ to 7.80‰	LIP related and presence of mafic enclave	Sensarma et al., 2004
Malanjhand	Granitoids	Pl±Hbl±Bt±Kfs+Qtz±Ap±Ilm±Mag	Calc-alkaline	Ca. 2490 Ma (Zircon SHRIMP)	$\epsilon\text{Hf}(t) = -2.8$ to 3.03 ; $\epsilon\text{Nd}(t) = -6.8$ to 0.0 ; $\text{Srr} = 0.699$ to 0.7103 ;	Arc related and presence of mafic enclaves	Panigrahi et al., 2004; Kumar and Rino, 2006; Asthana et al., 2016; Arya et al., in press
Singbhum craton and adjoining mobile belts							
Kaptipada	Dolerite dyke	Pl+Cpx±Opx±Bt±Qtz	-	Ca. 2.26 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Srivastava et al., 2018
Phalaborwa	carbonatite	-	-	Ca. 2.06 Ga (TE-TIMS Pb-Pb baddeleyite)	-	LIP related	Shankar et al., 2014
Newer dolerite	Dolerite dyke	-	-	Ca. 1.77 Ga (TE-TIMS Pb-Pb baddeleyite)	-	LIP related	Shankar et al., 2014
Dalma volcanic belt	mafic-ultramafic intrusives	Pl+Pyx	Tholeiitic	Ca. 1.6 Ga (Rb-Sr whole-rock)	$\epsilon\text{Nd}(t) = -8$ to 12 ; $\text{Srr} = 0.70549$ to 0.70555	Mantle plume related	Roy et al., 2002
Arkasani Granophyre	Granite	Pl+Kfs+Qtz+Bt±Ms±Ttn±Epx±Zrn±Ap±Ttn±Mag	Metaluminous	Ca. 1.861 Ga (SHRIMP U-Pb Zircon)	-	Subduction related	Bhattacharya et al., 2015
Dalma volcanic belt	Rhyolite	-	A-type character	Ca. 1.631 Ga (SHRIMP U-Pb Zircon)	-	non-orogenic rift related	Bhattacharya et al., 2015
Barabazar granite	Granite	Qtz+Kfs+Pl+Bt±Chl±Epx±Zrn±Spm±Aln	A-type	Ca. 1.77 Ga (TIMS Pb-Pb whole-rock)	-	non-orogenic rift related	Dwivedi et al., 2011
Mahakoshal-Satpura Mobile Belt							
Bichhya (SMB, CITZ)	Kfs-megacryst bearing charnokite	Kfs+Pl+Qtz+Opx±Cpx±Ap±Zrn±Mag	-	Ca. 938 Ma (SHRIMP U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.8$ to -2.9	Formed by melting of proterozoic crust during decompression	Bhomoik et al., 2012
Northern and southern domain of SMB (CITZ)	Migmatites, gneiss, schist	Grt-Crd, Grt-Amp, Grt-St-Ky respectively	-	Ca. 955 to 1062 Ma (EPMA Monazite)	-	formed during final amalgamation of northern and southern Indian block	Bhomoik et al., 2012
Tirodi (SMB, CITZ)	Biotite gneiss	Qtz+Kfs+Pl+Bt+Grt	-	Ca. 1603 Ma (core); 1572 Ma (rim) (SHRIMP U-Pb zircon)	$\epsilon\text{Hf}(t) = -3.3$ to $+3.7$	Formed during accretional orogeny and later metamorphic imprint	Bhomoik et al., 2011
Dongargaon and Pipariya (SMB, CITZ)	Felsic gneiss	Qtz+Kfs+Pl+Bt±Ttn±Mag±Opx	-	Ca. 1563 Ma (SHRIMP U-Pb zircon); Ca. 1572 Ma (EPMA magmatic monazite); Ca. 1415 Ma (EPMA metamorphic monazite)	$\epsilon\text{Hf}(t) = -2.19$ to -1.25	Formed during accretional orogeny and later metamorphic	Bhomoik et al., 2011
Jhigadandi, Mahakoshal belt	Granitoids	Qtz+Kfs+Pl+Bt±Hbl±Cpx±Ttn±Ap±Zrn	Metaluminous calc-alkaline	Ca. 1753 Ma (SHRIMP U-Pb zircon)	-	Accretionary orogeny related	Bora et al., 2013
Jhigadandi, Mahakoshal belt	Microgranular enclaves	Qtz+Kfs+Pl+Bt±Hbl±Cpx±Ttn±Ap±Zrn	Metaluminous calc-alkaline	Ca. 1758 Ma (SHRIMP U-Pb zircon)	-	Accretionary orogeny related	Bora et al., 2013
Shillong-Meghalaya plateau							
Northern rim of Mikir Hills (Meghalaya)	Granites, foliated granites and granite dykes	-	-	Ca. 1111 to 1084 Ma (Ion microprobe U-Pb zircon)	-	-	Yin et al., 2010
Northern and central margin of Myllem pluton (Meghalaya)	Granites	-	-	Ca. 1100 to 1000 Ma (Ion microprobe U-Pb zircon)	-	-	Yin et al., 2010

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Rongjeng (Garo hills, Meghalaya)	Granite gneiss	Qtz+Kfs+Pl+Bt±Zrn±Ap	Calc-alkaline	Ca. 1778 Ma (SHRIMP U-Pb zircon)	-	Recycling of Neoproterozoic crust	Kumar et al., 2017a
Longavalli (Mikir hills, Meghalaya)	Granite gneiss	Kfs+Pl+Bt+Qtz±Zrn±Ap	Alkali-calcic	Ca. 1430 Ma (SHRIMP U-Pb zircon)	-	Recycling of early Proterozoic crust	Kumar et al., 2017a
Dharwar craton and associated mobile belts							
Bangalore-Karimnagar dyke swarm	Mafic dyke	-	-	Ca. 2.37 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Yeragumballi	Mafic dyke	Cpx+Pl±Hbl±Qpx±Opx±Ap	Tholeiitic	Ca. 2366.7 Ma (U-Pb baddeleyite)	-	LIP related	Halls et al. 2007
Harohalli dyke swarms	Mafic dyke	Pl+Cpx±Opx	Sub-alkali tholeiitic	Ca. 2365.5 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Penukonda dyke swarm	Mafic dyke	Pl+Opx	Sub-alkali tholeiitic	Ca. 2365.9 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Chemetkotapalle dyke swarm	Mafic dyke	Pl+Cpx+Opx	Sub-alkali tholeiitic	Ca. 2368.6 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Ippaguda-Dhiburahalli dyke swarm	Mafic dyke	-	-	Ca. 2.25 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Kandlamadugu dyke swarm	Mafic dyke	-	-	Ca. 2.22 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Somala dyke swarm	Mafic dyke	Pl+Opx+Cpx+Olv	Sub-alkali tholeiitic	Ca. 2209.3 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Kandlamadugu dyke swarm	Mafic dyke	Pl+Cpx±Opx	Sub-alkali tholeiitic	Ca. 2220.5 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Anantapur-Kumigal swarm	Mafic dyke	-	-	Ca. 2.21 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Bandepalem dyke swarm	Mafic dyke	Pl+Cpx±Opx	Sub-alkali tholeiitic	Ca. 2176.5 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Dandeli dyke swarm	Mafic dyke	Pl+Hbl+Cpx±Qtz±Opx	Sub-alkali tholeiitic	Ca. 2180.8 Ma (IDTIMS U-Pb baddeleyite)	-	LIP and intracontinental rifting related	French and Heaman, 2010
Mahabubnagar-Dandeli swarm	Mafic dyke	-	-	Ca. 2.18 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Devarabanda swarm	Mafic dyke	-	-	Ca. 2.08 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Cuddapah dyke swarm	Mafic-ultra mafic	Pl+Opx±Opx	-	Ca. 2.081 Ga (TE-TIMS Pb-Pb baddeleyite)	-	LIP related	Kumar et al., 2015
Tadpatril sills (Cuddapa Fm)	Mafic dyke	Olv+Opx+Cpx+Pl±Phl	Sub-alkali tholeiitic	Ca. 1.9 Ga (Ar-Ar Phlogopite)	$\epsilon\text{Nd}(t) = -9.86$ to 1.06 ; $\text{Sri} = 0.70562$ to 0.73907	Extension related	Anand et al., 2003
Hampi dyke swarm	Mafic dyke	-	-	Ca. 1.88 to 1.89 Ga (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Pebbair dyke Swarm	Kimberlite	-	-	Ca. 1788 Ma (IDTIMS U-Pb baddeleyite)	-	LIP related	Söderlund et al., 2018
Wajrakurur	Kimberlite	Olv+Spr+Phl+Cal+Spl+Prv±Ap	-	Ca. 1083 to 1134 Ma (SIMS U-Pb pervoskite)	$\epsilon\text{Nd}(t) = 2.08$ to 2.51 ; $\text{Sri} = 0.70240$ to 0.70255	LIP and intracontinental rifting related	Chalapathi Rao et al., 2013
Narayanpet	Kimberlite	Olv+Spr+Phl+Cal+Spl+Prv±Ap	-	Ca. 1126 to 1141 Ma (SIMS U-Pb pervoskite)	$\epsilon\text{Nd}(t) = 0.68$ to 1.99 ; $\text{Sri} = 0.70302$ to 0.70339	LIP and intracontinental rifting related	Chalapathi Rao et al., 2013
Raichur	Kimberlite	Olv+Spr+Phl+Cal+Spl+Prv±Ap	-	Ca. 1089 Ma (SIMS U-Pb pervoskite)	$\epsilon\text{Nd}(t) = 1.72$; $\text{Sri} = 0.70306$	LIP and intracontinental rifting related	Chalapathi Rao et al., 2013

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Siddanpalli	Kimberlite	-	-	Ca. 1090 Ma (Rb-Sr whole rock)	Sr _i = 0.70340	LIP and intracontinental rifting related	Kumar et al., 2007
Bangalore granites (Closepet granite)	Granite	Qtz+Pl+Kfs+Hbl+Bt±Cpx	calc-alkaline with sanukitic nature	Ca. 2541 Ma (SHRIMP U-Pb zircon evaporation)	εNd(t)= -7 to 0; Sr _i = 0.6929 to 0.7011	subduction related	Jayananda et al., 2000
Hoskote-Kolar granites (Closepet granite)	Granite	Qtz+Pl+Kfs+Hbl+Bt±Cpx	calc-alkaline with sanukitic nature	Ca. 2540 Ma (SHRIMP U-Pb zircon evaporation)	εNd(t)=0 to 1; Sr _i = 0.6443 to 0.7012	subduction related	Jayananda et al., 2000
Kamasandra (Closepet granite)	Granite	Qtz+Pl+Kfs+Hbl+Bt±Cpx	calc-alkaline with sanukitic nature	Ca. 2534 to 2552 Ma (SHRIMP U-Pb zircon evaporation)	εNd(t)= -1 to 0; Sr _i = 0.7003 to 0.7023	subduction related	Jayananda et al., 2000
Eastern Ghat Mobile Belt							
Chimakurti, Errakonda and Uppalapadu (southern EGMb)	ferrosyenite, nepheline syenite	Cpx+Pl+Ol; Fa+Opx+Aug+Qtz+Grt+Ilm±Amp	A-type affinity	Ca. 1352 Ma (U-Pb zircon)	εNd(t)= -6.3 to +0.1; Sr _i = 0.70372 to 0.74814	Intracratonic rifting related	Vijaya Kumar et al., 2007
Jojuru (Kondapalle, EGMb)	Nepheline syenite	-	A-type affinity	Ca. 1263 Ma (SHRIMP U-Pb zircon)	εNd(t)= -4.2; Sr _i = 0.710162	Intracratonic rifting related	Upadhyay and Raith, 2006
Sunki (Central, EGMb)	High Mg-Al granulites	Grt+Opx+Qtz+Ilm+melt; Opx+Spl+Sil	-	Ca. 1043 to 922 Ma (SHRIMP U-Pb Monazite)	-	Ultra high temperature metamorphism	Korhonen et al., 2011
Krishna province (Domain 1A, Southern EGMb)	Charnokite and migmatites	-	-	Ca. 1630 to 1600 Ma (SHRIMP U-Pb zircon)	-	Granulite reworking and charnokite emplacement	Bose et al., 2011
Krishna province (Domain 1A, Southern EGMb)	Granulites	-	-	Ca. 1760 Ma (SHRIMP U-Pb zircon)	-	Ophiolite emplacement	Bose et al., 2011
Domain 2 (Central EGMb)	Granulites	-	-	Ca. 990 to 950 Ma (SHRIMP LA-ICP-MS U-Pb zircon)	-	Granulite metamorphism	Bose et al., 2011
Domain 2 (Central EGMb)	Granulites	-	-	Ca. 1300 to 990 Ma (SHRIMP U-Pb zircon)	-	Ultra high temperature metamorphism	Bose et al., 2011
Balugaon (Chilka lake domain, EGMb)	Anorthosite massif (Noritic)	Pl+Opx+Bt+Cpx+Ilm+Kf+Qtz±Zrn±Ttn±Mnz	-	Ca. 983 Ma (ID-TIMS U-Pb zircon)	-	Intruded in metamorphosed Chilka lake domain	Chatterjee et al., 2008
Balugaon (Chilka lake domain, EGMb)	Anorthosite massif (Noritic)	Pl+Opx+Bt+Cpx+Ilm+Kf+Qtz±Zrn±Ttn±Mnz	-	Ca. 714 (Core) and 655 Ma (Rim) (EPMA U-Th-Pb monazite)	-	High grade metamorphism	Chatterjee et al., 2008
Pangidi and Kandapalle (Southern EGMb)	Anorthosite (Layered intrusion)	Pl+Hbl+Opx+Cpx	-	Ca. 1634 and 1693 Ma (LA-ICP-MS U-Pb zircon)	-	Subduction related magma underplating	Dharama Rao et al., 2012
Himalaya							
Anritpur (Kumaun Lesser Himalaya)	Granite	Kfs+Pl+Qtz+Bt	-	Ca. 1880 Ma (Whole rock Rb-Sr)	-	-	Varadarajan, 1978
Rangarh (Kumaun Lesser Himalaya)	Granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1765 Ma (Whole rock Rb-Sr)	Sr _i = 0.7235	-	Trivedi et al., 1984
Askot (Kumaun Lesser Himalaya)	Granite gneiss and porphyritic granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1857 Ma (LA-ICPMS U-Pb zircon)	εHf(t)= -5.5 to -1.2	Arc related	Mandal et al., 2016
Budhakedar (Chail Gr, NW Lesser Himalaya)	Gabbro	Cpx+Pl+Opq	-	Ca. 1907 Ma (Whole rock Rb-Sr)	Sr _i = 0.7022	Rift related	Ahmad et al., 1999
Debguru (Kumaun Lesser Himalaya)	Granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1856 Ma (LA-ICPMS U-Pb zircon)	-	-	Celerier et al., 2009

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Askot (Kumaun Lesser Himalaya)	Granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1983 Ma (Whole rock Rb-Sr)	-	-	Bhanot et al., 1980
Askot (Kumaun Lesser Himalaya)	Augen gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1810 Ma (Whole rock Rb-Sr)	Sr=0.7092	-	Trivedi et al., 1984
Tawaghat (Chiplakot, Kumaun Lesser Himalaya)	Granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1906 Ma (Whole rock Rb-Sr)	-	-	Singh et al., 1985
Along Mandakini river (Base of Berinag Thrust, Kumaun Lesser Himalaya)	Granite gneiss	Kfs+Pl+Qtz+Bt±Hbl	-	Ca. 1865 Ma (LA-ICPMS U-Pb zircon)	-	-	Celerier et al., 2009
Lari-Kullu-Rampur window (NW Lesser Himalaya)	Metabasalts	Hbl+Bt+Pl+Qtz+Spm+Ilm	Tholeiitic	Ca. 1.80 Ga (zircon Pb-Pb evaporation)	$\epsilon\text{Nd}(t) = -0.7$ to 5.04	Formed by melting of enriched SCLM	Miller et al., 2000
Lari-Kullu-Rampur window (NW Himalaya)	Metathylite and Granite gneiss	-	Mostly peraluminous	Ca. 1.84 Ga (zircon Pb-Pb evaporation)	$\epsilon\text{Nd}(t) = -8.8$ to -5.8 ; $\text{Sr} = 0.711$ to 0.721	Formed by melting of Archean crust	Miller et al., 2000
Ulleri (Nepal Lesser Himalaya)	Orthogneiss	-	-	Ca. 1831 Ma (U-Pb zircon)	-	-	DeCelles et al., 2000
Lesser Himalayan sequence of Nepal Himalaya	Granitic orthogneiss and metavolcanics	-	-	Ca. 1780 to 1880 Ma (LA-ICPMS U-Pb zircon)	-	Arc related	Kohn et al., 2010
Daling orthogneiss (Lesser Himalaya of Bhutan)	Orthogneiss	-	-	Ca. 1884 Ma (LA-MC-ICP-MS U-Pb zircon)	-	-	Long et al., 2011
Shang (Besham, NW Himalaya, Pakistan)	Orthogneiss	-	-	Ca. 1864 Ma (U-Pb zircon)	-	-	DiPietro and Isachsen, 2001
Rangit window (Lesser Himalaya of Darjeeling-Sikkim)	Pegmatite	Qtz+Kfs+Pl+Ms	-	Ca. 1850 Ma (Ar-Ar muscovite)	-	-	Acharyya et al., 2017
Lingste (MCT zone, Sikkim Himalaya)	Orthogneiss	-	-	Ca. 1840 Ma (Avg.) (LA-MC-ICP-MS U-Pb zircon)	-	-	Mottram et al., 2014
Masang Kang (Greater Himalayan sequence of NW Bhutan)	mafic granulite and amphibolite	Grt+Pl+Opx±Amp (metabasalt), Olv+Opx±Amp±Spl (meta-ultramafic)	Tholeiitic and alkali in nature	Ca. 1742 Ma (SIMS U-Pb zircon)	$\epsilon\text{Nd}(t) = -3.3$ to -8.4	Formed by melting of enriched SCLM	Chakungal et al., 2010
Bandal (MCT zone Himachal Himalaya)	Orthogneiss	Qtz+Kfs+Pl+Bt+Ms±Grt±Zrn±Ap±Tur±Opq	Peraluminous	Ca. 1860 Ma (SHRIMP U-Pb zircon)	-	formed by partial melting of metasediments	Sharma and Rashid, 2000; Singh et al., 2009
Jutogh Gr (MCT zone, Sutlej valley)	Leucogranite	-	-	Ca. 1810 Ma (LA-ICP-MS U-Pb zircon/uranite)	-	Formed by crustal melting	Chambers et al., 2008
Wangtu (MCT zone, Sutlej valley)	Orthogneiss	-	-	Ca. 1.8 Ga Ma (ID-TIMS U-Pb zircon)	$\epsilon\text{Hf}(t) = -4$ to -1	-	Richards et al., 2005
Kada and Lhagoi kangari (Tibet Greater Himalayan sequence)	Monzonitic granite gneisses	-	Peraluminous	Ca. 1811 Ma (SHRIMP U-Pb zircon)	-	-	Lio et al., 2008
Bondila (Arunachal Lesser Himalaya)	Granite gneiss	Qtz+Kfs+Pl+Bt+Ms±Zrn±Ap±Tur±Opq	Peraluminous	Ca. 1752 Ma (LA-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -7.99$ to -1.67	formed by partial melting of metasediments	Pathak and Kumar, 2019

Table 1: Contd....

Pluton / Region	Rock type	Mineral assemblage	Geochemical nature	Age	Isotopic signature	Remark	References
Salari (Arunachal Lesser Himalaya)	Granite	Qtz+Kfs+Pl+Hbl+Bt±Zrn±Ap±Tur±Opq	High- to medium-K calc-alkaline with adakitic affinity	Ca. 1749 Ma (LA-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -3.95$ to -1.13	Arc related	Pathak, 2012
Chingalai (NW Himalaya, Pakistan)	Orthogneiss	Kfs+Pl	-	Ca. 816 Ma (LA-ICP-MS U-Pb zircon)	-	-	Ahmad et al., 2013
Cona (Greater Himalayan sequence, eastern Himalaya)	Orthogneiss	Pl+Qtz+Bt±Kfs±Ms±Grt±Ap±Opq	Medium to high-K peraluminous	Ca. 817 to 838 Ma (LA-ICP-MS U-Pb zircon)	$\epsilon\text{Hf}(t) = -5.62$ to $+2.46$	Andean-type orogeny	Ding and Zhang, 2016
Greater Himalayan sequence of Bhutan Himalaya	Orthogneiss	-	-	Ca. 825 Ma (TIMS U-Pb zircon)	-	-	Richards et al., 2006
Chor (Greater Himalayan sequence, Himachal, India)	Granitoids	Pl+Kfs+Qtz+Bt+Ms±Ap±Zrn±Tn±Opq	Medium to high-K peraluminous	Ca. 823 Ma (SHRIMP U-Pb zircon)	-	formed by melting of older crust	Singh et al., 2002
Black mountain complex (NW Himalaya, Pakistan)	Orthogneiss	Qtz+Kfs+Pl+Bt±Grt	-	Ca. 823 Ma (U-Pb zircon)	-	-	DiPietro and Isachsen, 2001
Greater Himalayan sequence of Sikkim Himalaya	Orthogneiss	-	-	Ca. 829 Ma (LA-MC-ICP-MS U-Pb zircon)	-	-	Mottram et al., 2014

Mineral's symbols are after Kretz (1983).

Zircon Lu-Hf isotopes point to little role of radiogenic mantle in their evolution (Fig. 4d). Paleoproterozoic mafic rocks show negative $\epsilon\text{Nd}(t)$ values (Fig. 4e) more akin to crustal assimilation.

Neoproterozoic magmatism of Aravalli Belt

The plagiogranite (1015 ± 4.4 Ma) of oceanic character in the Peshua, high-K granite (966.5 ± 3.5 Ma) in the Devala, and high-Na, high field strength element (HFSE) and the light rare earth element (LREE) enriched granite of Sai (808 ± 3.1 Ma) from Sirohi, western Delhi Fold Belt formed in volcanic arc and active continental margins. A protracted subduction province in NW India seems to have resulted in Neoproterozoic magmatism of diverse composition (Dharma Rao et al., 2013). The proposed model poses challenge to an alternate model which links the magmatism to extensional tectonics associated with Rodinia supercontinent breakup. Granite gneisses (967.8 ± 1.2 Ma, $\epsilon\text{Nd}(t) = -2.734$ to -4.144 ; $\text{SrI} = \leq 0.712$) of Chang pluton of Delhi Supergroup were derived from Archean amphibolite of the BGC (Pandit et al., 2003) whereas the associated metagabbro bears ocean-floor and island-arc characters formed in convergent margin. Muscovite-garnet granite gneiss (ca. 836 Ma, Deb et al., 2001) from the Siwaya region is derived from crustal sources.

Mt. Abu granites (765 ± 5 Ma) cross cut by mafic dykes (Ashwal et al., 2013) contain coeval microgranular enclaves (elsewhere porphyritic biotite granite, dated ca. 750 Ma, Fig. 3b), which are oxidized to reduced, metaluminous A-type (Singh and Kumar, 2009). Mt. Abu granites appear similar to Neoproterozoic granitoids in LIP Malani Igneous Suite (MIS), but they are ca. 100 Ma younger and chemically distinct from Erinpara granites. These granites probably represent fragments of Andean-type magmatic arc of Rodinia supercontinent (Ashwal et al., 2013), as opposed to its *mantle-plume* origin (e.g. Kochhar, 2000).

Siliceous (765.1 ± 7.2 Ma) tuffs including the rhyolite (768.2 ± 6.9 Ma) intercalated with chert of Sindreh Group bear volcanic arc character (Dharma Rao et al., 2012). The younger zircons in the rhyolite (666 to 644 Ma) suggest continuation of arc magmatism till late Cryogenian, correlatable to the MIS. Voluminous MIS (~780-750 Ma) with zircon oxygen (depleted $\delta^{18}\text{O} = 4.12$ to -1.11‰ and enriched $\delta^{18}\text{O} = 8.23$ – 5.12‰) and Hf ($\epsilon\text{Hf}(t) = +13.0$ to $+3.6$) isotopes indicates a high-T bulk cannibalization of upper level juvenile mafic crust for the production of low- $\delta^{18}\text{O}$ felsic magma. However, zircon xenocrysts having high $\delta^{18}\text{O}$ and low $\epsilon\text{Hf}(t)$ values for magmas older than 800 Ma reflect a dramatic transition in tectono-thermal regime during 800–780 Ma in the NW India (Wang et al., 2017).

Moras I-type granites (ca. 976 Ma, $\epsilon\text{Nd}(t) = +0.41$ to $+1.40$, $\epsilon\text{Hf}(t) = +2.34$ to $+9.35$, $\delta^{18}\text{O} = 6.48\text{‰}$ to 7.58‰) were produced by melting of juvenile crust whereas A-type Pali (ca. 811 Ma) and Mirpur (ca. 780 Ma) granites ($\epsilon\text{Nd}(t) = -2.28$ to $+0.84$, $\epsilon\text{Hf}(t) = -2.31$ to $+8.62$, $\delta^{18}\text{O} = 5.77\text{‰}$ to 7.01‰) formed from dehydrated mafic crust in rift setting. These granites are correlatable with those of South China, which share the configuration of Rodinia supercontinent (Zhao et al., 2018). Mafic dykes (ca. 750 Ma) represent late stage magmatic activity of MIS (Meert et al., 2003).

Neoproterozoic felsic rocks are calc-alkaline, A-type granite (Fig. 4a, b) formed in rift-environment (e.g. Petro et al., 1979). The REE patterns ($\text{La}_N/\text{Yb}_N = 1.21$ – 34.88 ; avg. 7.17) with strong negative to no Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.04$ – 1.22 ; 0.35) indicate plagioclase fractionation from a primary felsic melt (Fig. 4c). Zircon Lu-Hf

Figure 2. (a) Supracrustal xenolith in Bundelkhand granite showing sedimentary fabric. (b) Elongated microgranular enclaves follow the direction of magmatic flowage of host Bundelkhand granites. (c) Migmatite formed within the central Bundelkhand tectonic zone. (d) Partial assimilation of granites by intruding volcanics.

isotopes suggest role of juvenile and crustal sources during intracratonic magmatism (Fig. 4d).

Bundelkhand craton

The Bundelkhand Craton records the multiple pulses of

Archean (3.5-2.7 Ga for TTG gneisses) to Palaeoproterozoic (2.5-2.3 Ga) calc-alkaline granitic magmatism (e.g. Sarkar et al., 1996; Mondal et al., 2002; Kumar et al., 2011; Joshi et al., 2017; and Kaur et al., 2016). Mondal et al., (2002) were first to provide zircon $^{207}\text{Pb}/^{206}\text{Pb}$ ages of hornblende granites (2516 ± 4 Ma; $2551\text{--}2454$ Ma), biotite-granites (2515 ± 5 Ma; 2521 ± 7 Ma), leucogranite (2492 ± 10

Figure 3. (a) Subrounded microgranular enclave in Malanjkhanda granite. Note the felsic-mafic xenocrysts in enclave. (b) Hybrid microgranular enclave in Dongargarh granite. Ocellar quartz and mafic-felsic xenocrysts in enclave. (c) Crenulated margins showing pillow-like contact of mafic magma against Closepet granite.

Ma), granite gneisses (2563 ± 6 Ma, 2500 Ma zircon growth), and associated rhyolite (2517 ± 7 Ma). TTG-migmatite (2685 ± 9.8 Ma) was formed by melting of Archean (*ca.* 3291 Ma) protocrust (Kumar et al., 2011). Calc-alkaline comagmatic hornblende diorite (2549 ± 9.8 Ma) and granodiorite (2545 ± 4.9 Ma) were formed synchronous with rhyolite (2553 ± 13 Ma). An inherited zircon core (*ca.* 2759 Ma) in hornblende diorite suggests Neoproterozoic component in the genesis of hornblende diorite-granodiorite cogenetic series.

The felsic volcanism near Mauranipur greenstone (2557 ± 33 Ma) contains inherited 2864 ± 46 Ma zircon, which is believed to indicate subduction along continental margin during Neoproterozoic (Slabunov and Singh, 2018). Synchronous rhyolites at Mauranipur and Bansi may have similar origin. Zircon concordia age of *ca.* 2551 Ma from microgranular enclave (ME) (Fig 2b) is similar to granodiorite (2545 ± 4.9 Ma) that underlines coexistence of mafic and felsic magmas. Quartz monzodiorite porphyry (2535 ± 4.2 Ma) intrudes

Figure 4. Elemental and isotopic geochemical features of Proterozoic magmatic rocks of Aravalli craton (a) A($\text{Na}_2\text{O}+\text{K}_2\text{O}$)-F(FeO)-M(MgO) diagram (boundary separating the tholeiitic and alkaline series are taken after Irvine and Baragar (1971)). (b) Total alkali silica (TAS) diagram showing rock types (after Cox et al., 1979). The boundary line is after Irvine and Baragar (1971). (c) Chondrite normalized REE patterns (after Anders and Grevesse, 1989). (d) $\epsilon\text{Hf}(t)$ vs Age (Ma) plot. (e) $\epsilon\text{Nd}(t)$ vs Age (Ma) plot. Data source: Ahmad and Rajamani, 1991; Deb et al., 2001; Pandit et al., 2003; Ahmad et al., 2009; Kaur et al., 2009; Kaur et al., 2011; Kaur et al., 2012; Dharma Rao et al., 2012; Mondal and Raza, 2013; Dharma Rao et al., 2013; Ashwal et al., 2013; Wang et al., 2017; Zhao et al., 2018.

granodiorite. Syenogranite (2525 ± 6.8 Ma), monzogranite (2523 ± 8.3 Ma) and leucogranites (2492 ± 10 Ma; Mondal et al., 2002) probably mark the timing of stabilization of Bundelkhand craton.

Chronological data imply existence of five major events in Bundelkhand craton, which began with the formation of TTG protolith at ca. 3.59 Ga, and it was partially melted at ca. 2.68 Ga to produce migmatite (Fig. 2c), followed by 2.55-2.52 Ga volcano-plutonic magmatism. It is speculated that the evolved felsic melt from the deep chamber erupted and formed rhyolites, genetically linking volcano-plutonic complex. These were later intruded by minor felsic pulses (Fig. 2d). However, there is serious lack of petrological study on rhyolites in the craton.

The Bundelkhand craton has been considered formed by amalgamation and accretion of northern and southern Bundelkhand blocks along E-W trending Bundelkhand central tectonic zone (BCTZ), which brought together diverse litho-assemblages (e.g. Slabunov et al., 2017). Some workers favour BCTZ as a shear zone within same country, supported by some others who have found granites of similar nature and age on either side of BCTZ. These contradictions need to be resolved.

Nature and source of magmatism

Felsic rocks of Bundelkhand craton belong to calc-alkaline (Fig. 5a) granite and granodiorite (Fig. 5b). They exhibit fractionated nature of REE ($\text{La}_N/\text{Yb}_N = 1.71-114.18$; avg. 23.21) with variable

negative Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.09-0.93$; avg. 0.49) (Fig. 5c). Zircon $\epsilon\text{Hf}(t)$ values (Fig. 5d) imply dominant role of crust-derived melts with small mantle input in their formation. The sanukitoid, calc-alkaline and K-rich nature of voluminous 2.57-2.50 Ga old granites were emplaced as coeval magmatic suites (e.g. Kaur et al., 2016; Joshi et al., 2017).

Mafic dykes, quartz reef and mechanism of reddening of granites

Paleoproterozoic (ca. 2.0, 1.80 Ga) and Neoproterozoic (1.0 Ga) dolerite dykes trending NNW-SSE and NW-SE mark mafic magmatism in Bundelkhand craton (Pradhan et al., 2012; Radhakrishna et al., 2013). Palaeoproterozoic (ca. 1.9–1.8 Ga) quartz reefs trending NE-SW represent endogenic activity (Pati et al., 2007) related to granite. The large scale reddening of granitoid rocks is the result of post-magmatic fluid flushing (Kumar et al., 2010). However, Sensarma et al., (2018) demonstrated reddening of ~2.5 Ga granites due to high temperature Fe-Mg-Na-K rich fluids (~950°C) derived at crust-mantle depths from mantle-derived magma that plausibly linked to mafic dyke swarm activity.

Paleoproterozoic mafic rocks are tholeiitic (Fig. 5a, b) and show inclined REE patterns ($\text{La}_N/\text{Yb}_N = 4.9-27.79$; avg. 5.87) with negative or no Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.70-1.01$; avg. 0.92) (Fig. 5c). These are derived from enriched mantle, and subsequently evolved through fractionation and crustal assimilation. The $\epsilon\text{Nd}(t)$ values indicate

Figure 5: Plots of Proterozoic rocks of Bundelkhand craton. (a) A-F-M plot. (b) TAS plot (c) REE patterns (d) $\epsilon\text{Hf}(t)$ vs Age (Ma) plot. (e) $\epsilon\text{Nd}(t)$ vs Age (Ma) plot. Fields are the same as shown in figure 4. Data source: Mondal and Zainuddin, 1997; Mondal et al., 2002; Pradhan et al., 2012; Joshi et al., 2016; Kaur et al., 2016; Samom et al., 2017. The abbreviations and references used for various plots are the same as given in Figure 4.

assimilation and possible role of depleted mantle in their origin (Fig. 5e). Neoproterozoic kimberlites exhibit typical alkaline (Fig. 5b) and highly inclined REE patterns ($\text{La}_N/\text{Yb}_N=56.3\text{--}126.32$; avg. 97.23) without significant Eu anomalies ($\text{Eu}_N/\text{Eu}^*=0.85\text{--}1.13$; avg. 0.97) (Fig. 5c). Chondritic $\epsilon\text{Nd}(t)$ values indicate primitive mantle like source (Fig. 5e).

Bastar craton and associated large igneous province

The Bastar craton, erstwhile Bastar-Bhandara or Central India craton, (Fig. 1), similar to Aravalli and Bundelkhand cratons, is composed of basement granite gneisses (Amgaon Group), TTG, amphibolite, metamorphosed supracrustals, BIF, and mafic-ultramafic rocks (3.5–3.0 Ga) (Sharma, 2009). The granites surrounding the gneissic enclaves provide zircon crystallization age of 2480 ± 3 Ma (Sarkar et al., 1993).

Bimodal volcanic sequences (Nandgaon Group) in the Dongargarh-Kotri belt are thought to be intruded by Paleoproterozoic Malanjhand and Dongargarh granites. The Nandgaon Group is unconformably overlain by volcano-sedimentary lithounits (Khairagarh Group) within Dongargarh Supergroup (Sarkar, 1958). On the basis of new generation field mapping (1:25000), and results of petrological and geochemical studies, the Nandgaon-Khairagarh Groups are considered a continuous succession, the Dongargarh Group (Sensarma and Mukhopadhyay, 2014 and references therein; see also Sensarma and Palme, 2013). Although a limited geochronological data of Bastar craton are available (Table 1), the position of Dongargarh Group needs to be clarified further.

Indravati-Chattisgarh basin contains felsic tuffs (1000 Ma, $\epsilon\text{Hf}(t)=-4$ to -6 , Bickford et al. 2014) deposited with sediments, which were derived from juvenile and crustal sources during the collision of East Antarctica with India.

A unique Dongargarh-Kotri bimodal LIP

The Dongargarh Group is recognized as a bimodal LIP (ca. 2.5 Ga) (Sensarma, 2007), not much known in the literature. The succession begins with Bijli rhyolites, overlain by Pitepani, Sitagota, and Mangikhuta volcanics (mafic to intermediate volcanics), successively interspersed by mafic volcanogenic wacke (Chandsuraj Formation) and arenites (Karutola Formation) respectively (Chakraborty and Sensarma, 2008; Sensarma, 2011). Although some features of LIP favour plume origin, its longer eruption history (30–73 Ma) does not. Moreover, sub-equal proportions of silicic and mafic volcanic rocks indicate crustal and mantle input in extensional setting, and do not match with contemporary mantle- or crust-melting models for LIP genesis (Sensarma, 2007).

Recently Khanna et al., (2019) reviewed chronological status of Dongargarh rocks and suggested contemporaneous evolution of Dongargarh volcanics around 2.5 Ga. Zircon crystallization ages of Malanjhand (2478 ± 9 Ma; 2477 ± 10 Ma; Panigrahi et al., 2004), Dongargarh (2506 ± 50 Ma) granites and Bijli rhyolites (2463 ± 14 Ma; 2479 ± 13 Ma) (Manikyamba et al., 2017), and single zircon ages of 2506 ± 4 Ma and 2525 ± 15 Ma from youngest and oldest rhyolites respectively in the Kotri belt (Ghosh, 2004) suggest synchronous rhyolites and granites within error limits, and hence they may have cogenetic volcano-plutonic link. Neoarchean Sonakhan greenstone

belt comprises pillowed and massive tholeiitic basalts emplaced within an intra-oceanic setting, and dykes with island arc tholeiite and boninite affinities, which signify the episodic melt extraction, dehydration of the subducting slab, and hydrous fluxing in supra-subduction zone (Prasanth et al., 2018). Three sets of Proterozoic mafic dyke swarms (2.7 Ga, 2.4–2.5 Ga, 1.88–1.89 Ga, Table 1) in the craton are emplaced in an intracratonic rift setting. U–Pb ages of 1891.1 ± 0.9 Ma and 1883.0 ± 1.4 Ma for SE-trending mafic dykes in the southern Bastar craton, and 1885.4 ± 3.1 Ma for a mafic sill from Cuddapah basin may together constitute a late Paleoproterozoic LIP of $\geq 90,000$ sq km (French et al., 2008).

Source characterisation and possible tectonic model

Asthana et al., (1996) favoured an arc system whereas Sensarma and Mukhopadhyay (2014 and reference therein) preferred a rift setting for the evolution of Dongargarh succession of rocks. Calc-alkaline rhyolites (zircon $\epsilon\text{Hf}^{(t)} = -10$ to -4.2) originated from ancient crustal sources in an arc setting (Manikyamba et al., 2016) as opposed to the rhyolite ($\delta^{18}\text{O} = 4.4$ to 7.80 ‰) formed in extensional setting (Sensarma et al., 2004). Interestingly both the rhyolites belong to Nandgaon Group and bear same mineral assemblage (Table 1). Asthana et al., (2016) further argued that copper deposits at Malanjkhanda are hosted in adakitic granite (modern subduction), which are coeval with calc-alkaline rhyolites and high-Mg andesite, followed by rift-related tholeiites and A2-type granites of nearby Dongargarh-Kotri regions. According to Khanna et al., (2019) Pitapani ($\epsilon\text{Nd}^{(t)} = -0.36$ to $+0.41$) and Mangikhuta ($\epsilon\text{Nd}^{(t)} = -0.62$ to -0.49) volcanics interacted with continental crust whereas Kotima ($\epsilon\text{Nd}^{(t)} = +0.01$ to $+0.92$) and Sitagota

($\epsilon\text{Nd}^{(t)} = +1.75$ to $+2.24$) basalts escaped crustal assimilation. Initial $\epsilon\text{Hf}^{(t)}$ values ($+0.31$ to $+6.26$) of these volcanics indicate subduction of an oceanic spreading ridge beneath the continent in a back-arc or marginal sea basin with contemporaneous sedimentation, forming Andean-type arc around 2.5 Ga in Bastar craton.

Morphology and chemistry of zircons from Malanjkhanda pluton imply zircon crystallization in calc-alkaline, metaluminous hybridizing calc-alkaline magma (Arya et al., 2019). Neoproterozoic-Paleoproterozoic felsic rocks of Bastar craton are calc-alkaline (Fig. 6a) granite and granodiorite (Fig. 6b). Dongargarh rocks show fractionated REE patterns ($\text{La}_N/\text{Yb}_N = 0.88$ – 15.26 ; avg. 11.20) with negative Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.19$ – 0.49 ; avg. 0.31) (Fig. 6c) and $\epsilon\text{Hf}^{(t)}$ values (Fig. 6d), which together point to its typical crustal origin. Zircon $\epsilon\text{Hf}^{(t)}$ (Fig. 6d) and whole-rock $\epsilon\text{Nd}^{(t)}$ (Fig. 6e) indicate crustal-mantle sources in the genesis of Malanjkhanda granites. Dongargarh mafics (tholeiites) (Fig. 6a, b) exhibit REE fractionation ($\text{La}_N/\text{Yb}_N = 2.16$ – 16.47 ; avg. 5.86) without significant Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.72$ – 1.01 ; avg. 0.85) (Fig. 6c), and bear $\epsilon\text{Nd}^{(t)}$ values (Fig. 6d), together pointing their origin from enriched mantle, and subsequent crustal assimilation.

Paleoproterozoic mafic dykes are tholeiitic (Fig. 6a, b). REE patterns ($\text{La}_N/\text{Yb}_N = 1.73$ – 2.59 ; avg. 2.02) with or without negative Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.88$ – 1.08 ; avg. 0.95) (Fig. 6c) probably originated from enriched mantle, plagioclase fractionation and crustal contamination during ascent. Mesoproterozoic dykes are alkaline to tholeiitic (Fig. 6a, b). REE patterns ($\text{La}_N/\text{Yb}_N = 2.81$ – 13.23 ; avg. 5.99) and Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.73$ – 1.02 ; avg. 0.93) (Fig. 6c) advocate their origin through low degree of melting of slightly enriched mantle. Neoproterozoic felsic tuffs show highly fractionated REE patterns with negative Eu anomalies (Fig. 6c) due to plagioclase fractionation.

Figure 6. Proterozoic rocks of Bastar craton (a) AFM plot. (b) TAS plot (c) REE patterns (d) $\epsilon\text{Hf}^{(t)}$ vs Age (Ma) plot. (e) $\epsilon\text{Nd}^{(t)}$ vs Age (Ma) plot. Data source: Neogi et al., 1996; Sensarma et al., 2002; Sensarma et al., 2004; Panigrahi et al., 2004; Srivastava and Singh, 2004; Kumar and Rino, 2006; Srivastava and Gautam, 2015; Asthana et al., 2016; Khanna et al., 2018; Arya et al., 2018. The abbreviations and references used for various plots are the same as given in Figure 4.

Sub-chondritic zircon ϵHf^0 values (Fig. 6c, d) however imply crust-mantle interactive origin.

Malanjkhanda and Dongargarh granites contain rounded, subrounded to ellipsoidal mafic to hybrid ME (Figs. 3a, b), which were formed by synchronous mixing-fractionation of coeval felsic and mafic magmas (Kumar et al., 2004a, b), and have undergone chemical re-equilibration (Kumar and Rino, 2006). The brecciated ME in Pithora pluton represent disrupted syn-plutonic dykes (Elangovan et al., 2017).

Singhbhum craton and adjoining mobile belts

Singhbhum craton comprises TTG, K-rich granites and gneisses that are bounded by greenstone belts known as Iron Ore Group. It is separated from the Singhbhum mobile belt (SMB) and surrounded by the Mahanadi rift in SW, the Narmada–Son rift, Gangetic alluvium and Mahakoshal–Satpura mobile belt on the NW, the Indo-Gangetic Bengal basin on the SE and the Rajmahal traps on the E–NE (Naqvi and Rogers, 1987) (Fig. 1).

Although Singhbhum craton lacks much record of Neoproterozoic–Early Paleoproterozoic (*ca.* 2.55–2.45 Ga) magmatism, early earth Hadean and Paleoproterozoic crustal components are preserved. Zircons from Paleoproterozoic (*ca.* 3.4 Ga) tonalite-gneiss contains 4.24–4.03 Ga old xenocrystic zircons ($\epsilon\text{Hf}^0 = -2.5$ to -5.2), reported for the first time in India (Chaudhury et al., 2018). A-type granites from Barabar and Munger–Rajgir regions are derived from crustal source with mantle input in post-collision setting (Yadav et al., 2016). Popularly known Soda granite (*ca.* 2.2 Ga, Sarkar et al., 1986) intrudes the Chaibasa Formation syntectonically that fixes upper age limit of Singhbhum Group (Sharma, 2009).

Malangtoli volcanics (*ca.* 2.25 Ga) comprise arc basalt, boninite, high-Mg andesite and Nb-enriched basalt series preserve the signature of subduction initiation to arc maturation (Singh et al., 2017). Chhotanagpur granite gneiss complex (CGGC) experienced lithospheric thinning and formed the Proterozoic basins filled with sediments accompanied with Dalma–Dhanjori–Chaibasa–Dhalbhum volcanism, later intruded by dolerite dykes (Bhattacharya, 1992; Chatterjee et al., 2013). Dhanjori basalt (2072 ± 106 Ma, Roy et al., 2002) indicates an existence of Paleoproterozoic volcanic province. At the same time or later there occur dolerite dykes in Kaptipada region (*ca.* 2.26 Ga, Srivastava et al., 2018), carbonatite (*ca.* 2.06 Ga) in Phalaborwa, and newer dolerite (*ca.* 1.77 Ga, Shankar et al., 2014). Arkasani granophyre (1861 ± 6 Ma) represents syn- to post-kinematic magmatism along Singhbhum shear zone (SSZ). Barabazar granite (1771 Ma, $\text{SrI} = 0.7302$) in south Purulia shear zone is rift-related formed by melting of lower/middle crust (Dwivedi et al., 2011). The high-K, arc-related calc-alkaline granites (1752 ± 9 Ma, 1737 ± 15 , 1714 ± 3 , 1706 ± 32 , 1691 ± 8 , 1686 ± 14 , 1664 ± 3 Ma) intrude the central litho-domain of Bathani volcano-sedimentary sequence of CGGC (Saikia et al., 2017).

Zircons (1631 ± 6 Ma, Bhattacharya et al. 2015) from the base of Dalma trap are similar to proximal mantle plume derived gabbro-pyroxenite (1619 ± 38 Ma, $\text{SrI} = 0.705$; $\epsilon\text{Nd}^0 = +8$ to $+12$, Roy et al., 2002). Tuffaceous horizon of Dalma trap is followed upward a thick sequence of high-iron, low-potassium pillowed tholeiites of ocean-floor affinity (Gupta et al., 1980). The other reported magmatic ages are 1677 ± 11 Ma (Sarkar et al., 1986), 1638 ± 38 Ma (Sengupta et al., 1994), 1628.5 ± 4.3 Ma (Reddy et al., 2009), 1600 Ma (Nelson et al., 2007), 1580 Ma (Krishna Rao et al., 1979), which together constrain

prevalence of middle to late Paleoproterozoic vast bimodal (mafic-felsic) magmatism accompanied with sedimentation in the Singhbhum craton and adjoining mobile belts. Nepheline syenite (922 ± 10 Ma, Reddy et al., 2008) represents youngest event in the north SMB (Goswami and Basu, 2013).

Mahakoshal-Satpura mobile belt

Mahakoshal-Satpura belt, north of CITZ, is an intraplate graben basin filled with volcano-sedimentary successions (Srivastava et al., 2000). Dudhi gneisses were earlier thought to be ≥ 2.3 Ga old basement (Mazumder, 1988). However, zircon chronology (1749 ± 6 Ma) suggests recycling of Neoproterozoic crust in the formation of Dudhi gneisses (Bora et al., 2014). Recent data account for syn-collisional two-mica, S-type nature for Nerueadamar (1882 ± 32 Ma) and Tumiya (1776 ± 6 Ma) granites, followed by post-collision calc-alkaline I-type Jhirkadandi (1753 ± 9 Ma), Katoli (1726 ± 7 Ma) and Harnakachar (1713 ± 5 Ma) granites, coeval with minor amount of mantle-derived enclave magma (Bora et al., 2013). The volcanics (1746 ± 9 Ma) are synchronous with granites. S-type magmatism (1880–1770 Ma) probably resulted from amalgamation of Bundelkhand and Bastar cratons leading to crustal thickening. Subsequently the belt experienced lithospheric delamination and thermal relaxation marked by vast post-collision magmatism (1750–1710 Ma) related to Columbia supercontinent assembly and growth (Bora and Kumar, 2015).

Basalt to andesite dykes of high-iron tholeiitic affinity intrude the volcano-sedimentary sequences of Mahakoshal belt, which experienced N-MORB magmatism around 2.5 Ga and within-plate magmatism around 1.5–1.8 Ga forming tholeiites, alkaline and carbonatite rocks (Srivastava, 2012). Rhyolite (1642 ± 7 Ma, $\epsilon\text{Hf} < \text{CHUR}$) from Vindhyan Supergroup, proximal to Mahakoshal belt, was formed by continental collision and basin subsidence induced melting (Bickford et al., 2017). Whether the 1640 Ma magmatism marking the minimum age of development of a rift basin in the central India is an open question.

Shillong-Meghalaya plateau

Shillong-Meghalaya Gneissic Complex (SMGC) is dominantly composed of Proterozoic basement gneisses, granites, migmatites and granulites, which are intruded by a number of Cambrian granite plutons. Rongjeng gneiss (1778 ± 37 Ma) represents the basement formed by recycling of Neoproterozoic crust (zircon core of 2566.4 ± 26.9 Ma) (Kumar et al., 2017a). Umling (1560–2637 Ma), Riango (1415 Ma), Rhesu (1535–1862 Ma) gneisses and Nongstoin charnockite (1077–1284 Ma) strongly point to a protracted crustal evolutionary processes for the SMGC similar to the EGMB (Bidyananda and Deomurari, 2007) and Mahakoshal-belt (Bora and Kumar, 2015). Yin et al. (2010) reported major magmatism at ~1600, 1100 and 500 Ma whereas Kumar et al., (2017a) recognized granite episodes at ~1800, 1600, 1400, and 500. These gneisses and granites are metaluminous to peraluminous, syn-orogenic to post-collisional similar to those found in Mahakoshal belt. The SMGC records crustal growth of the Columbia and Gondwana supercontinents related to Pan-African-Indian-Prydz-Brasiliano orogens.

Dharwar craton and associated mobile belts

Conventionally, Dharwar craton is thought to have formed by

assembly of western and eastern crustal blocks having contrasting petrological features (Swami Nath et al., 1976) with a pronounced decrease in the crustal thickness from western to eastern block (Gupta et al., 2003). Chitradurga greenstone belt is considered as the fundamental boundary between these two crustal blocks (Swami Nath and Ramakrishnan, 1981). Dharwar craton is divided into three age provinces (western, central and eastern) with independent thermal records and accretionary histories (Peucat et al., 2013; Jayananda et al., 2018). Five major periods of felsic crustal growth at ca. 3450–3300 Ma, 3230–3150 Ma, 3000–2960 Ma, 2700–2600 Ma, and 2560–2520 Ma sub-contemporaneous with greenstone volcanism have been suggested building the Dharwar craton (Jayananda et al., 2018).

Paleoproterozoic magmatism is more abundant in the central block and to a lesser extent in eastern block, which are represented by subduction-related calc-alkaline granites of sanukitoid affinity including the 500 km N-S trending Closepet batholith. These are derived from juvenile sources and are exposed in Bangalore (ca. 2541 Ma; $\epsilon\text{Nd}^{\text{t}} = -7$ to 0; $\text{SrI} \leq 0.701$), Hoskote-Kolar (ca. 2540 Ma; $\epsilon\text{Nd}^{\text{t}} = 0$ to 1; $\text{SrI} \leq 0.701$), and Kamasandra (ca. 2552–2534 Ma; $\epsilon\text{Nd}^{\text{t}} = -1$ to 0; $\text{SrI} \leq 0.702$) regions (Chardon et al., 2011; Jayananda et al., 2000). Numerous enclaves having sharp and crenulated contacts occur within Closepet granites (Fig. 3c), which indicate undercooling and pillowing of coeval mantle-derived magma against relatively cooler felsic magma. Closepet granites are formed by interaction of LREE enriched mantle-derived magma with juvenile-source derived calc-alkaline magma in subduction setting (Jayananda et al., 1995), and are surrounded by anatectic granites (ca. 2520 Ma) as hot intrusion-induced melting products.

Neoproterozoic-Paleoproterozoic felsic rocks of Dharwar craton are

calc-alkaline granodiorite and granite (Fig. 7a, b). Strong REE fractionation ($\text{La}_N/\text{Yb}_N = 10.09\text{--}82.55$; avg. 32.54) with variable Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.21\text{--}1.25$; avg. 0.66) (Fig. 7c) indicate fractional differentiation, and zircon $\epsilon\text{Hf}^{\text{t}}$ and $\epsilon\text{Nd}^{\text{t}}$ values (Fig. 7d and e) point to crustal contribution exhibited by inclined REE patterns ($\text{La}_N/\text{Yb}_N = 2.18\text{--}7.16$; avg. 3.10) without mantle participation. Paleoproterozoic tholeiitic basalt and a few alkaline-peralkaline trachytes (Fig. 7a, b) without significant Eu anomalies ($\text{Eu}_N/\text{Eu}^* = 0.9\text{--}1.11$; avg. 0.98) (Fig. 7c), and chondritic to sub-chondritic $\epsilon\text{Nd}^{\text{t}}$ (Fig. 7e) reveal slightly enriched source, and subsequent enroute assimilation.

Mesoproterozoic lamproites are alkaline (Fig. 7b), and exhibit REE patterns ($\text{La}_N/\text{Yb}_N = 34.11\text{--}188.42$; avg. 103.43) without Eu anomaly ($\text{Eu}_N/\text{Eu}^* = 0.86\text{--}1.05$; avg. 0.99) (Fig. 7c), which are distinct from other mafics. They show elevated sub-chondritic $\epsilon\text{Nd}^{\text{t}}$ (Fig. 7e) due to enriched mantle source and strong crustal contamination.

Southern Granulite Terrain

Adjoining the Dharwar craton, to its south, lies the Southern Granulite Terrain (SGT). The multiple metamorphic and magmatic events recorded in SGT are related to at least three supercontinent formations and break up in the Proterozoic, viz., Columbia, Rodinia and Gondwana. This terrain, therefore, could be composed of more than one terranes that accreted together during different times. The northern block (NB) to the north of the Palghat Cauvery Shear Zone (PCSZ) has been shown to be contiguous with the Dharwar craton during Paleoproterozoic as confirmed with the paleomagnetic

Figure 7. Proterozoic rocks of Dharwar craton (a) AFM plot (b) TAS plot (c) REE patterns (d) $\epsilon\text{Hf}^{\text{t}}$ vs Age (Ma) plot. (e) $\epsilon\text{Nd}^{\text{t}}$ vs Age (Ma) plot. Fields are the same as shown in figure 4. Data source: Jayananda et al., 2000; Anand et al., 2003; Halls et al. 2007; Kumar et al., 2007; French and Heaman, 2010; Kumar et al., 2012; Chalapathi Rao et al., 2013; Kumar et al., 2015; Pandey et al., 2017; Talukdar et al., 2018. The abbreviations and references used for various plots are the same as given in Figure 4.

evidences from the mafic dykes of ~2.3 Ga age (Dash et al. 2013; Pivarunas et al., 2019). The NB is mainly composed of hornblende-biotite gneisses and charnockite massifs of Neoproterozoic age. To the south of PCSZ is the Madurai Block (MB). PCSZ has long been thought to be a Neoproterozoic suture, closing the Mozambique Ocean between the Dharwar craton and the MB during the pan-African orogeny. However, extensive geochronological studies (Ghosh et al. 2004; Plavasa et al. 2012; Brandt et al. 2014; Chandra Sekaran et al. 2015 and the references therein) suggest continuity of Neoproterozoic and Paleoproterozoic lithounits across the PCSZ till the KKPTSZ (Karur-Kambam-Painauv-Trissur Shear Zone). Brandt et al. (2014) emphasized the petrological, geochemical and geochronological differences between the western and eastern parts of the MB to propose a new tectonomorphic model for the SGT. According to this model, the western Madurai domain (WMD) was part of the Neoproterozoic-Paleoproterozoic Dharwar craton along with the Moyar-Bhavani-shear zone, a northwestern continuation of the PCSZ. The late Neoproterozoic mafic granulites and Charnockites that form large massifs in WMD are similar to those present in the NB. The eastern Madurai domain (EMD), on the other hand is characterized by the hornblende-biotite gneisses with low-lying charnockite patches within it. Younger granite intrusions, some of which are identified as A-type granites (Chandra Sekaran et al. 2015, and references therein), are exposed in all parts of the Madurai block and intruded during mid- to late-Neoproterozoic. A type granites were also correlated with the extension related syenite-alkali granite-carbonatite rocks of ~800 Ma age. Origin of charnockites in the SGT and the Dharwar craton has been a matter of debate since Pichamuthu discovered 'incipient charnockite' in a quarry in Kabbal village in Karnataka. Subsequently, similar charnockites were widely reported from Trivendrum block which lies south of the Achankovil shear zone and is characterized by paragneisses and S-type granites, and also from the other parts of the SGT (Ravindra Kumar et al. 1985, Chandra Sekaran et al. 2015, Touret et al., 2019 and the references therein). The charnockite patches within the granitic gneisses, are believed to be related to the dehydration caused by CO₂ influx whereas the charnockite massifs could be magmatic intrusions. Chandra Sekaran et al. (2015) reported two generations of charnockites from the northeastern part of the MB, the older associated with the biotite gneiss, and the younger one with the garnet-bearing metaluminous granite. The Sr-Nd isotopes revealed the older one to be of Neoproterozoic age, while the younger granite-charnockite originated from a common source in mid-Neoproterozoic. These charnockite-granite associations, therefore, appear to be ubiquitous spanning the entire Proterozoic in the SGT and calls for an evolutionary model that accounts for the repeated formation of these rock-associations.

Eastern Ghat Mobile Belt

Proterozoic magmatism in EGMB is mainly confined to Mesoproterozoic to Neoproterozoic periods (Table 1). Vijay Kumar et al., (2011) reported high-T, moderate-P melting of a Ba-Sr rich hornblende-bearing tonalite (2521±5 Ma zircon cores 2485±5 Ma rims), which produced a co-spatial Rb-Zr-Pb-Th-U- REE rich biotite leucogranite (2518±5 Ma, 2483±3 Ma) in a post-collisional setting immediately after accretion of the tonalite crust in the Guramkoda-Vendou regions of Nellore Schist Belt (NSB).

Anorthosite massif (ca. 1634-1693 Ma, Dharma Rao et al., 2012) in the Pangidi and Kandapalle was generated due to magma

underplating. Granulites (ca. 1760 Ma) and charnockite migmatite (1630 to 1600 Ma, Bose et al., 2011) record Paleoproterozoic thermal events in the Krishna province, whereas ferro-syenite and nepheline syenite (ca. 1352 Ma, $\epsilon\text{Nd}^{(t)} = -6.3$ to $+0.1$; $\text{SrI} = 0.703$ to 0.748 , Vijay Kumar et al., 2007; 1263 Ma, $\epsilon\text{Nd}^{(t)} = -4.2$; $\text{SrI} = 0.710$, Upadhyay and Raith, 2006) from Chimakurti-Errakonda-Uppalapadu and Jojuru-Kondapalle, south EGMB formed in an intracratonic rift setting. Central part of the EGMB is dominated by granulites (990-950 Ma, 1300-990 Ma, Bose et al., 2011) associated with ophiolites formed under ultra-high T condition. Anorthite massif (ca. 983 Ma, Chatterjee et al., 2008) in the Chilka Lake marks Neoproterozoic magmatism.

A-type two-mica Kanigiri granite (ca 1284 Ma, Sain et al., 2017) in the NSB contains enclaves, which display high- to moderate-T crystal plastic deformation fabric, suggesting an overprinting of subsolidus deformation over a relict magmatic fabric. An intrusive relationship with the 1334 Ma Kanigiri ophiolitic mélange, within the NSB, indicates that a ca 50 Ma gap exists between Mesoproterozoic subduction-accretion. Although Kanigiri granite occurs close to alkaline plutons (1250–1400 Ma) in Prakasam alkaline province, A-type granite appears unrelated to intra-plate rift magmatism (Sain et al., 2017).

Intra-continental mafic dykes, dyke swarms and the LIP

Regionally extended dyke swarms of tholeiitic affinity are ubiquitous in Dharwar craton (French and Heaman, 2010; Halls et al, 2007, Srivastava, 2012). The intrusion ages of these dykes range in three groups: 2.37-2.22 Ga, 2.21-2.08 Ga, and 1.90-1.78 Ga (Table 1). However, paleomagnetism support two episodes (~2370 and ~1890 Ma) of ~E-W-trending dyke swarms (Piispa et al., 2011). The mafic dykes to the south of the Dharwar craton in the high-grade terrain of northern Tamil Nadu are also dated to be ~2.3 Ga (Dash et al. 2013). The paleopole positions of these dykes match with that of the ~2.3 Ga Dharwar dykes confirming the contiguity of the Dharwar craton and the northern block of SGT at ~2.3 Ga (Dash et al. 2013, Pivarunas et al., 2019). Two new swarms, the N–S trending ca. 2.25 Ga Ippaguda-Dhiburahalli and NW–SE trending ca. 1.79 Ga Pebbair swarms, have been recognized (Söderlund et al., 2018). These dykes lack significant Eu-anomaly, and appear originated from mantle source within intra-continental rift environment and crustally contaminated (French and Heaman, 2010).

Comparison of Dharwar dykes with dykes of other cratons

Söderlund et al. (2018) have found that no mafic events are reported yet from the Bastar or the Singhbhum craton to match 2.37-2.22-2.21 Ga dyke swarms of Dharwar. Further there are no matching of dyke events between Dharwar and Bundelkhand cratons except those of 1.10-1.12 Ga. Bundelkhand craton experienced two major dyke events, 1.98 Ga and 1.11 Ga, for Jhansi and Mahoba swarms respectively (Pradhan et al., 2012; Ernst, 2014; Samal et al., 2019). Mahoba swarm is comparable with 1.10-1.12 Ga kimberlites of Dharwar craton (Rao et al., 2013) and 1.05 Ga lamproites of Bastar craton (Sahu et al., 2013; Rao et al., 2016). There is no match found for 1.98 Ga Jhansi dyke event in any of the Indian cratons.

Proterozoic magmatism in the Cuddapah Supergroup

Tadpatri Formation is comprised of ultramafic-mafic sills (1817±24, Bhasker Rao et al., 1995; 1.9 Ga, Anand et al., 2003; 1885.4±3.1 Ma, French et al., 2008) contemporaneous with sedimentation. These and associated olivine gabbro, rhyolite, felsic tuff (1862±9 Ma, Sheppard et al., 2017) and albite rich volcanics seem to be formed in extensional setting (Sesha Sai et al., 2017).

Mesoproterozoic to Neoproterozoic kimberlite intrusions

Near synchronous kimberlites having common mineral assemblage were emplaced in Wazarakarur (ca. 1083-1134 Ma, $\epsilon\text{Nd}^{(t)}=2.08$ to 2.51; $\text{SrI}=0.702$ -0.703), Narayanpet (ca. 1126-1141 Ma, $\epsilon\text{Nd}^{(t)}=0.68$ to 1.99; $\text{SrI}=0.703$ -0.704), Raichur (ca. 1089 Ma; $\epsilon\text{Nd}^{(t)}=1.72$; $\text{SrI}=0.704$; Rao et al., 2013) and Siddanpalli (ca. 1090 Ma, $\text{SrI}=0.703$; Kumar et al., 2007) regions of the eastern Dharwar craton. Enriched metasomatic SCLM overprinted by asthenosphere within a short span can account for distinct isotopes of these kimberlites (Rao et al., 2013). Majhgawan and Bunder lamproites of Bundelkhand craton and Nuapada lamproites of the Bastar craton are synchronous to those of Dharwar, but are much younger than ca. 1.50–1.22 Ga old lamproites of Krishna-Cuddapah fields (Rao et al., 2013). Tokapal kimberlite pipes were emplaced much later during Neoproterozoic (ca. 620 Ma; Lehmann et al., 2007).

Most kimberlites bear diamondiferous mantle xenolith, which designate a thickened (>140 km) lithosphere at the time of eruption (Lehmann et al., 2010). The synchronous intrusions of 1.1 Ga old kimberlites in India coincide well with the assembly of Rodinia supercontinent between 1.3 and 1.0 Ga (Dalziel et al., 2000).

Proterozoic magmatic components in Himalaya

Proterozoic felsic magmatism in the Himalaya

Felsic magmatic belt (ca. 1800 Ma) in the Himalaya (Table 1) represents northern extremity of Indian plate, which is part of Paleoproterozoic continental arc system, not a passive margin (Kohn et al., 2010). Palaeoproterozoic (1800±50 Ma, 1900±100 Ma, Trivedi et al., 1984; 1880±40 Ma, Varadarajan, 1978; 1888±46 Ma, Trivedi and Pande, 1993) S-type, ilmenite-series granites occur in the Amritpur region of Kumaun Lesser Himalaya (Kumar et al., 2006) forming part of Ramgarh-Chail nappe. Ramgarh gneiss (ca. 1765 Ma, $\text{SrI}=0.724$, Trivedi et al., 1984) is derived from crustal sources. Celerier et al., (2009) suggested ca. 1856 Ma and 1865 Ma ages for Debghur and Berinag gneisses respectively. Granite gneisses (ca. 1857 Ma, $\epsilon\text{Hf}^{(t)}=-5.5$ to -1.2; 1857-1878 Ma, $\epsilon\text{Hf}^{(t)}=9.6$ to 1.1; Mandal et al., 2016) from Askot-Chiplakot regions were formed from ancient crustal and juvenile sources in arc setting.

Peraluminous meta-rhyodacite-rhyolite (ca. 1840±16 Ma, $\epsilon\text{Nd}^{(t)}=-8.8$ to -5.8, $\text{SrI}=0.711$ -0.721; 1860±42 Ma) and tholeiitic metabasalt (1800±13 Ma, $\epsilon\text{Nd}^{(t)}=-0.7$ to +5.04) in Larji-Kullu-Rampur window were derived from crustal source and depleted-mantle source contaminated with crust, respectively (Miller et al., 2000). Granites (1.86–1.84 Ga, Nd model ages extended to 2.63 Ga) in Rampur window were formed by recycling of Neoproterozoic crust. Bandal orthogneiss (ca. 1860 Ma, Singh et al., 2009), leucogranite

(ca. 1810 Ma, Chambers et al., 2008), and Wangtu orthogneiss (ca. 1.8 Ga, $\epsilon\text{Hf}^{(t)}=-4$ to -1, Richards et al., 2005) in the MCT zone of Himachal Himalaya represent S-type magmatism formed from sedimentary sources (e.g. Sharma and Rashid, 2000).

Leucogranite-pegmatites (ca. 1850 Ma, Acharyya et al., 2017) from Rangit window, Lingtse orthogneiss (ca. 1840 Ma, Mottram et al., 2014) in the MCT zone of Darjeeling-Sikkim Himalaya also formed in the range of 1850-1810 Ma. Bomidila gneiss (1743±4 Ma, Yin et al., 2010; 1752±23 Ma, $\epsilon\text{Hf}^{(t)}=-1.67$ to -7.99, Pathak and Kumar, 2019) and its equivalent zero gneiss in Lower Subansiri form integral part of basement-involved imbricated thrusts in the Arunachal Lesser Himalaya (Goswami et al., 2009; Yin et al. 2010), which are equivalent to the Lesser Himalayan crystalline thrust sheets of the Himachal, Kumaun and Nepal Himalayas. Most of them were formed in syn- to post collision settings from melting of heterogeneous crustal sources evident by three-stage zircon Hf-model ages (2818, 2586–2424 and 2393–2250 Ma). Hornblende-biotite granites (~1750 Ma) in Salari region, however, represent calc-alkaline I-type, adakite-like magma formed in arc regime (Kumar and Pathak, 2010; Pathak, 2012). Proterozoic magmatic components (713–952 Ma, 1933 Ma, inherited zircons) partly contributed in the genesis of calc-alkaline Tirit granites (110-105 Ma) of Trans-Himalaya (Kumar et al., 2017b). Sporadic Neoproterozoic S-type granites (ca. 816-838 Ma, Singh et al., 2002) in Chor-Himachal and Sikkim-Bhutan Himalaya (Table 1) were formed by melting of metasediments.

Paleoproterozoic granites of Himalayan belt belong to calc-alkaline (Fig. 8a) granodiorite and granite (Fig. 8b). REE patterns exhibit mild fractionation ($\text{La}_N/\text{Yb}_N=7.05$ -45.94; avg. 16.78) with negative Eu anomaly ($\text{Eu}_N/\text{Eu}^*=0.16$ -0.73; avg. 0.53) (Fig. 8c). Chondritic to sub-chondritic $\epsilon\text{Hf}^{(t)}$ and $\epsilon\text{Nd}^{(t)}$ values (Fig. 8d, e) show crustal and mantle involvement in their origin. Neoproterozoic felsic rocks exhibit moderate LREE to HREE fractionation with negative Eu anomalies (Fig. 8c). Super- to sub-chondritic zircon $\epsilon\text{Hf}^{(t)}$ (Fig. 8d) suggest role of ancient crustal sources with small amount of mantle input in their genesis.

Proterozoic mafic magmatism in Himalaya

The mafic volcanics in the Garhwal (Ahmad and Tarney, 1991), Rampur (Bhat and Le Fort, 1992) and Mandi-Darla (Ahmad and Bhat, 1987), Bhimtal (Pandey, 2005) and Berinag (Pandey and Kumar, 2006) regions occur as inter-layered sequence of volcanics and sediments. They appear to be parts of a large volcanic province, and some were essentially erupted under shallow water condition, now exposed in different segments of NW Himalaya. Miller et al., (2000) suggested ca. 1800 Ma as minimum age of these volcanism. The provenance of quartzite occurring in association with volcanics could be the proximal >1800 Ma old felsic magmatic rocks, which may also have served as a potential source of zircons later entrapped into the volcanic flows. Gabbro (ca. 1907 Ma, $\text{SrI}=0.7022$, Ahmad et al., 1999) from Budhakedar, Chail Group formed in rift-setting. Tholeiitic to alkaline meta-mafics (ca. 1742 Ma, $\epsilon\text{Nd}^{(t)}=-3.3$ to +8.4, Chakungal et al., 2010) from NW Bhutan were extracted from SCLM source. Mafic dykes in Almora region of Kumaun Lesser Himalaya are crustally-contaminated tholeiitic basalt magma derived from enriched mantle source, which are geochemically identical to mafic dykes of Nainital, but are unrelated to Precambrian mafic volcanics of NW Himalaya and dykes of Salma and Rajmahal regions (Singh and Kumar, 2010).

Figure 8. Proterozoic rocks of Himalaya (a) AFM plot (b) TAS plot (c) REE patterns (d) $\epsilon Hf(t)$ vs Age (Ma) plot. (e) $\epsilon Nd(t)$ vs Age (Ma) plot. Data source: Bhat and Le Fort 1992; Le Fort and Rai, 1999; Sharma and Rashid, 2000; Miller et al., 2000; Pandey, 2005; Singh et al., 2009; Rao and Sharma, 2009; Chakungal et al., 2010; Kohn et al., 2010; Rao and Sharma, 2011; Mandal et al., 2016; Ding and Zhang, 2016; Sen et al., 2018; Pathak and Kumar, 2019. The abbreviations and references used for various plots are the same as given in Figure 4.

Paleoproterozoic mafics are tholeiitic gabbros/basalts of subalkaline affinity (Fig. 8a, b), and exhibit REE patterns ($La_N/Yb_N=1.15-14.36$; avg. 5.34) with variable Eu anomalies ($Eu_N/Eu^*=0.62-1.54$; avg. 0.84) (Fig. 8c). They measure chondritic to sub-chondritic $\epsilon Nd(t)$ values (Fig. 8e) due to likely derivation from enriched mantle.

Conclusions

Proterozoic mafic-felsic magmatism have played vital role in the stabilization of cratons and mobile belts of India. These constitute syn-collision, subduction to post-collision, rift related, moderate to high-K calc-alkaline felsic to intermediate volcano-plutonic complexes with variable contribution of coeval mafic magma formed during Columbia and Rodinia supercontinent assembly and growth. Predominant tholeiitic and subordinate alkaline magmas formed the mafic dykes, dyke swarms in the extensional setting and volcanics penecontemporaneous with sedimentation in marginal rift basins. Kimberlites and lamproites are common in Dharwar and Bastar cratons. Proterozoic magmatism has equivocally contributed in the geodynamic evolution of Himalayan belt. Neoproterozoic calc-alkaline to alkaline magmatism as discrete plutonic bodies and LIP (e.g. Malani Igneous Suite) with dominant volcanics mainly constitute the Aravalli-Delhi fold belts in NW India.

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