Plutonism and Precambrian Magmatism in India

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We summarize the work done by various workers on plutonism and Precambrian magmatic activities in India. During the last four years (2004-2007) several integrated studies on plutons (including Archaean-Proterozoic magmatism) involving field-based strain fabrics mapping, petrology, geochronology and whole-rock geochemistry including isotopes have been carried out and published in peer-reviewed international and Indian journals. Archaean geological period represents one-third history of our planet. Paradoxically despite the fact that much of the growth of continental crust and important mineralization probably occurred at this time, little is known about this period. Numerous studies suggest that Archaean represented a period during which crust formed and stabilized into cratons. All the exposed Archaean cratons are dominated by three lithological associations: (i) tonalitic-trondhjemitic-granodioritic (TTG) assemblages which represents first differentiates of the continental crust, (ii) volcanic-sedimentary greenstone associations (greenstone belts) which contain ultra-high-temperature lavas, the best witness of Archaean mantle, and (iii) voluminous late potassic granite plutons, which are often associated with high-grade metamorphism, that provide information on crustal reworking, granite-greenstone tectonics and cratonization of Archaean crust.

The greenstone belts comprise volcanic and sedimentary sequences found in all Archaean cratons. Their age is generally ranging between 3.5-2.5 Ga. The geochemical characteristics of the volcanics are comparable from one craton to another. They usually comprise mafic volcanics belonging to tholeiite-komatiite lineage which pass towards summits dominated by felsic volcanics. Archaean sedimentary sequences are crucial to our understanding the nature of primitive Earth's atmosphere, composition of seas and oceans, weathering patterns and crust-hydrosphere interactions. Archaean greenstone belts are most intensely mineralized continental fragments and much of the worlds ferrous (Fe, Mn, Cr, Co, Ni) non-ferrous (Au, Ag, Cu and PGE) metals come as well as from Archaean greenstones. The report on plutonism and Precambrian magmatism has been sub-divided into the following geographical terrains:

1. Himalayan region (including Nagaland ophiolite, Andaman Islands)
2. Northwestern Indian Shield
3. Central Indian Shield (Bundelkhand and Bastar)
4. Eastern Indian Shield (Chotanagpur, Singhbhum, Eastern Ghats and Shillong Plateau)
5. Southern Indian shield

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1. HIMALAYAN REGION

In the Himalayan region most of the studies on the plutons are concentrated in the Trans-Himalayan region of Ladakh where ophiolitic rocks are exposed along the Indus and Shyok suture zones. Ophiolitic rocks from Nagaland-Manipur and further to the south is another region where some studies have been done. Some studies have also been done in the Higher and Lesser Himalayan sequences of the Kumaun Himalayas. Following are the significant contributions from the Himalayan region for the period of this review.

Ahmad et al. (2005) have shown that Nubra ophiolitic suite of the Shyok suture zone and the Nidar ophiolitic complex of the Indus suture zone, eastern Ladakh depict sub-alkaline basalt, basaltic-andesite, andesite and rhyolitic composition. Nubra ophiolitic series have light rare-earth element (LREE) and large-ion lithophile element (LILE)-enriched and high field strength element (HFSE)-depleted trace-element characteristics. They probably represent continental arc. The Nidar ophiolitic complex on the other hand have nearly flat to slightly depleted LREE-LILE characteristics, with strong negative anomalies for the HFSE (Nb, P and Ti). These incompatible elemental characteristics for the Nidar ophiolitic rocks indicate that they probably represent intra-oceanic supra-subduction zone island-arc setting. Thus, the Shyok and Indus suture zones are probably unrelated and may represent contrasting tectonic settings.

Ahmad et al. (2008) have shown that Nidar ophiolitic complex from eastern Ladakh represents an intra-oceanic arc system that extended from Kohistan (northern Pakistan), where it is best developed, through Dras (western Ladakh) to at least up to Nidar (eastern Ladakh) during the late Jurassic-early Cretaceous. Mineral whole-rock isochron age for the Nidar Gabbro indicate that intra-oceanic subduction in the Neo-Tethyan ocean must have started as early as 140±32 Ma. Age data indicate evolution of the intra-oceanic arc system is marked by episodes of magmatism varying in composition from more basic at around 140 Ma through intermediate represented by Ladakh batholith at around 103 Ma to more acidic at around 50 Ma when the Indian and the Asian plates collided. There appears to be some sort of directional sense of maturity from south (less mature) towards north (more mature) based on the compositional variation of the arc magmatic rocks which may well support the earlier view of northward dipping subduction during the Cretaceous-early Tertiary period.

Singh et al. (2007) have shown that the Andean type Ladakh batholith intruded the Nidar-Dras arc which are now south of the main batholith. The SHRIMP – II U-Pb zircon age for the batholith range from 60.1 ±0.9 Ma to 58.4 ±1.0 Ma. These authors have also carried out pressure estimation based on Al content in hornblende for the batholith that indicates the depth of crystallization of the diorite at 16 ±1 km and for the granodiorite to be around 8 ±1 km. Their study suggests northward tilting of the batholith.

Bhutani et al. (2004) have carried $^{40}Ar/^{39}Ar$ dating of the Ladakh batholith and the basic magmatic rocks of the Indus suture zone. The typical granodiorite of the Ladakh batholith near Leh has given a plateau age of 46.3±0.6 Ma, biotite from the same rock has given a plateau age of 44.6±0.3 Ma. The youngest phase of the batholith represented by leucogranite near Himya has given a cooling age of ~36 Ma and muscovite from the same sample has given a plateau age of 29.8±0.2 Ma. These post-collisional ages probably indicate that post-collisional tectonothermal activity may have caused partial melting of the thickened crust. Basic volcanics with pillow lava near Chiktan (western Ladakh) has given an emplacement age of 128.2±2.6 Ma. This age is similar to those reported by Ahmad et al. (2008) for the Nidar ophiolitic complex of eastern Ladakh.

According to Maheo et al. (2004) Sapi-Shergol ophiolitic mélange preserves accretionary prism and ophiolite of the Neo-Tethyan ocean. The ophiolitic rocks represents intra-oceanic arc that was incorporated in the accretionary prism during imbrication of the arc. These authors have shown that the precursor for the blue schist rocks in this area was arc-related rather than Oceanic island arc considered earlier. Their study suggests complete closure of the Neo-Tethyan ocean during Eocene.

Ravikant (2006) has carried out Rb-Sr whole rock and mineral isochrones for different units of the Karakoram batholith and has been able to identify various phases that are known to exist based on earlier studies. Thus he is of the opinion that the Rb-Sr technique can be useful to date such younger events. The tonalite enclave within the Karakoram batholith has given an age of 118±15 Ma and whole-rock biotite age of 115±18 Ma. Phlogopite from an ultrapotassic lamprophyre dyke within Ladakh batholith has been dated at 24.3±2.2 Ma. A muscovite whole-rock age of 13.3±0.6 Ma for Durbuk leucogranite and whole rock-biotite age of 12.4±0.7 Ma has been obtained for a foliated granite at Muglib near the NE strand of the Karakoram fault.

Acharyya (2007) has described dismembered late Mesozoic Naga-Andaman ophiolite occurring in two sub-parallel belts along the eastern margin of the Indian plate. The eastern belt coincided with zone of positive gravity anomaly and comprises steeply dipping mafic-ultramafic rocks and continental metamorphic rocks. The western belt follows the eastern margin of the Indo-Burma range and the Andaman outer-island arc broadly following a zone of negative gravity anomaly. The ophiolitic rocks occur here as rootless sub-horizontal bodies overlying the flyschoidal sediments of Eocene-Oligocene age. Ophiolitic rocks of the western belt are interpreted as oceanic crust accreted due to prolonged subduction west of the island arc.

Srivastava et al. (2004a) have studied the basaltic rocks from south Andaman ophiolitic suite. The ophiolitic rocks comprise ultramafic cumulates, serpentinised mafic plutonics and dykes, pillow lavas, radiolarian chert and plagiogranite. These rocks have seen alteration and metamorphism. Geochemical studies indicate that the basaltic rocks are both alkaline and sub-alkaline. Some samples also show basaltic andesite, trachy-basalt and basanitic composition. Geochemical characteristics indicate their emplacement along the ridge axis from high-Ti MORB source.

Alam et al. (2004) have studied the prehistoric lavas and dykes from the Barren Island, Andaman sea to understand their tectonics of eruption and source characterization. The Barren island arc developed mostly during prehistoric period, is still active in the fumarolic stage with small mud volcanism in the historic past. Geochemical characteristics indicate their generation in an arc environment and they resemble the Sunda arc in terms of their chemical characteristics and evolution.

Recently Haldar et al. (2007) have given a detailed account of the Quaternary volcanism on the Barren and Narcondam islands in the Andaman Sea. They describe the volcanism on the Barren Island represented by prehistoric (1^{st} cycle), intermittent volcanism between 1787 and 1832 AD (2^{nd} cycle) and eruptions between 1991 and 2006 (3^{rd} cycle). The Narcondam island is considered extinct now. The 1^{st} ans 2^{nd} cycle of the Barren Island volcanism were initially olivine-bearing basaltic andesite followed by olivine basalt. The 3^{rd} cycle is again olivine basalt. The Narcondam island volcanism is represented by silicic andesite to dacites with cognate xenoliths of basalt and basaltic andesite. These authors suggest that Barren-Narcondam islands have arc-magmatism signatures across mixed oceanic and continental lithosphere.

Gururajan and Choudhuri (2007) have carried out geochemical studies of the Lohit plutonic complex in eastern part of Arunachal Pradesh. These authors have identified three major phases of magmatism that were related to arc magmatism. These phases are: (1) an early phase of metaluminous, tholeiitic to calc-alkaline gabbro-quartz diorite and hybrid rocks, (2) an intermediate phase of calc-alkaline, metaluminous, leucotonalite of high Al-trondhjemitic or adakitic composition and (3) a last phase of peraluminous leucogranite and associated veins of pegmatite and aplite. The earlier phases are characterized by enriched lithophile elements and depletion of high -field elements, low Sr-isotopic ratios (0.70-0.704). These authors suggest the melts were generated in a subduction zone setting and derived via fractionation of basaltic parent under high water pressure. The trondhjemitic rocks are suggested to have formed by melting of oceanic crust or basaltic rocks that underplated the arc leaving garnet and amphibole in the residue. The leucogranite have formed by anatectic melting of a mixture of leucotonalite and metasediments during the collision event.

Bose et al. (2004) have studied the Lingtse granite to understand its genesis and tectonic setting of emplacement using field, petrographic, mineralogical, chemical and experimental approach. Their study suggests that the granite closely follow the schistose rocks that it intrudes at many places and many structural elements pass from the schist to the granite. Geochemical data indicate open system behaviour represented by metasomatism/hybridization. Their experimental results indicate alkali-silica metasomatization of chlorite-biotite-muscovite schist could have given rise to these granitic rocks. Thier study indicates generation of these rocks in an anorogenic syn- or post-collisional tectonic setting of the host.

Patel et al. (2007) have reported fission and confined track studies in apatite from Chiplakot crystalline belt of the Kumaon Lesser Himalaya. Fission-track ages for this crystalline body exposed south of the Main Central Thrust represented by Munsiari thrust along the Kali-Darma valleys fall into two distinct groups. In the northern part the fission-track age ranges from 9.8±0.6 to 7.6±0.6 Ma with a weighted mean of 9.6±0.1 Ma while in the southern part the FT ages vary between 17.9±0.9 and 12.9±1.1 Ma with a weighted mean of 14.1±0.1 Ma. This bimodality of ages according to these authors indicates mixing rather than simple cooling ages. These ages indicate that Chiplakot crystalline belt was thrusted over the Lesser Himalaya before the Middle Miocene MCT activation. Since that time this crystalline belt has remained within the upper three kilometre crust. This would indicate moderate to slow erosion and exhumation of this body as they were thrust over the Lesser Himalayan sedimentary zone.

The early Paleozoic Akpa granitoids (477±29 Ma) and Rakcham granitoids (453±9 Ma) of Kinnaur district intruded the Vaikrita Group rocks of the Higher Himalayan Crystalline. These granitoids bodies are emplaced south of the Tethyan sedimentary sequence. Detalied geochemical and isotopic studies indicate their derivation from sedimentary protoliths, thereby, being classified as two mica-monzogranite (*sensu stricto*). These authors conclude that these two granitoids represent typical S-Type granite that were generated by partial fusion of sedimentary protoliths, prior to Caledonian but later than Pan-Indian thermal orogenic event.

2. NORTHWESTERN INDIAN SHIELD

In the NW Indian shield significant studies on the plutonic and Precambrian magmatic rocks have been concentrated on the Banded Gneissic Complex in central Rajasthan, basal Aravalli magmatic rocks in the Udaipur-Nathdwara sector, Phulad ophiolitic complex and the Malani igneous complex.

Buick et al. (2006) have carried out LA ICP-MS U-Pb dating of zircon from the western Indian shield. They have reported some interesting age data that questions the status of the Banded Gneissic Complex in the Central Aravalli mountains. The granulite-facies Sandmata complex and the amphibolite-facies Mangalwar complex were earlier considered to be of Archaean age. New age data presented by these authors indicate ~1720 Ma age for Sandmata granulite-facies metamorphism and charno-enderbite magmatism. It has been shown that igneous protolith to migmatitic felsic orthogneiss of Mangalwar complex have similar ages as the Sandmata charno-enderbite magmatism. It has also been found that the deposition of the protoliths of the metasediments of the Sandmata and Mangalwar complex took place during the Proterozoic rather than the earlier held view of Archaean age. An age of 950-940 Ma have been suggested for amphibolite metamorphism and anatexis in this region. Presented data questions the validity of equating the basement of the north-central Aravalli mountain with those of Archean crust further to the south.

Ahmad et al. (2008) studied the basal Aravalli volcanics including komatiites, komatiitic basalt and tholeiites for their Nd-isotopic characteristics and petrogenesis. The highly negative ε(Nd) (t=0) as low as –28 indicate long crustal residence. Calculated model ages of komatiitic basalts and tholeiites cluster between 2.2 and 3.0 Ga and the komatiites show older model ages between 3.5 and 3.8 Ga. The whole-rock Sm-Nd isochrons for komatiite samples indicate an age of ~2300 Ma and those for the komatiitic basalt and tholeiite indicate ~2000-1800 Ma. Collectively, therefore the age of basal Aravalli volcanism is constrained between ~2300 and ~1800 Ma. The epsilon Nd (t=2000) for all the samples clusters around -5 to -15 indicating derivation of the basal Aravalli samples from enriched mantle sources. Such enriched mantle sources are known to be less common in Precambrian rocks. However, the new data from Rajasthan and critical review of data from Himalayas, other parts of the Indian shield and some components of the Gondwanaland including Sudbury Igneous Complex, Roccamonfina lavas and Karoo basalts in southern Africa, Parana tholeiites in southern Brazil and early Cretaceous Rio Cear´a–Mirim Swarm tholeiites, northeastern Brazil do suggest the existence of such enriched pockets in the mantle. This observation leaves the possibility open for further research and evaluation of data from other less-studied terranes world over.

Khan et al. (2005) have studied the Phulad ophiolitic complex of the NW Indian shield. Field relationship and geochemical studies indicate variation in lithology with stratigraphic heights. The sequence begins with plastically deformed harzburgite representing mantle component followed by layered cumulus gabbroic rocks representing crustal component. This is followed upsection by hornblende schist, sheeted dykes and pillow basalt. These rocks have been intruded by dioritic intrusives. Geochemical studies of the non-cumulus rocks indicate their tholeiite-calc-alkaline characteristics. These authors interpret all these data to suggest that the Phulad ophiolite complex represents fore-arc tectonic regime.

Sharma (2005) has carried out geochemical studies of the Neoproterozoic Malani igneous province of ~ca. 750 Ma age. The magmatism started initially with basaltic volcanism followed by predominantly acidic volcanism. End of the magmatism is marked by granite plutonism and dyke emplacement. The effusive phase was sub-aerial but sub-aqueous eruption and associated sedimentation is also recorded. The large expanse of the magmatic suite has been interpreted by many workers to involve plume tectonics. However, Sharma (2005) suggests rift-tectonic environment for the magmatism and he does not subscribe to the plume tectonic model for this magmatic province.

Singh et al. (2006) have carried out geochemical studies of the Neoproterozoic (725±7 Ma) Malani Igneous Suite of western Rajasthan. The rocks are dominantly porphyritic and non-porphyritic rhyolite with minor amount of trachyte, welded tuff and ash beds. Basic dykes and gabbro also occur as enclaves/xenolith in the dominant rhyolite indicating the formers to be older. Geochemical characteristics of these rocks indicate A-type characteristics; however, the authors also suggest that they may represent arc-crustal rift. These authors have suggested that these acidic volcanics were derived from melasyenite source by 5-20% partial melting at ~8 kb pressure and ~1000^{0}C temperature. The Malani Igneous Suite may represent a major Pan-African magmatic episode in this region.

Ray et al. (2006) have described Sadara sill from the Pachham uplands of the northern Kachchh region. This sill has alkaline chemical characteristics transitional between alkali basalt and basanite. These rocks have enriched Sr, Ba, Pb and LREE and depleted Nb, Cr, Y, Cs and Lu. The chemical variation of these rocks has been explained through their generation by low degrees of partial melting of mantle peridotite followed by fractional crystallization of olivine and clinopyroxene. Paleomagnetic data indicate that this sill was emplaced during 85 Ma, much before the main phase of Deccan Trap volcanic activity. The geochemical characteristics and field data indicate the emplacement of the sill in a rift-tectonic environment.

Ray and Shukla (2004) have studied the trace-element characteristics and have compared it with the coeval alkaline silicate rocks from Amba Dongar area to assess if these two suite of rocks have any genetic links. Their results indicate that the carbonatite and alkaline rocks are products of fractional crystallization of two distinct parental melts. Their study also support liquid immiscibility of silicate and carbonate melts that evolved independently to give rise to these two rock suites.

Chatterjee and Bhattacharji (2004) have studied chemical and morphological characteristics of zircon and monazite from felsic dykes from Rajula, Gujarat to understand their genesis in relationship with the associated Deccan Traps. Their study indicate generation of the rhyolitic and trachytic magma from crustal melting. These authors suggest that passage of Deccan Trap magma through the basement rocks cause melting of the crust to give rise to these acidic melts. Some of the zircon grew during the evolution of the melt but many have inherited zircon from the crust.

3. CENTRAL INDIAN SHIELD

Studies on the plutonism and Precambrian magmatic rocks in the central Indian shield is restricted in the Bundelkhand Gneissic Complex and its equivalents in Tirodi gneisses within the Central Indian Tectonic Zone, the Amgaon gneissic complex and the Bastar craton south of the central Indian shear zone. Following are the significant work from this region:

Mallikharjuna Rao (2004) has carried out geochemical and Ar-Ar studies of the mafic dyke swarm of the Bundelkhand craton. He has identified quartz-normative tholeiitic dykes and ultramafic dykes are of komatiitic and komatiitic basalt composition with normative olivine. The tholeiites are enriched in terms of LREE and LILE and have both negative and positive Eu anomalies. Ar-Ar ages suggest two phase of dyke activities at c. 2150 Ma and 2000 Ma. This is the period when major magmatic activities are reported from adjoining regions and also coincides with major global magmatic events.

Mondal et al. (2007) have studied the Bundelkhand mafic dyke swarms that traverse extensively through the Bundelkhand granitoids and gneisses. Minor units of mafic dykes include basaltic komatiitic composition which has many characteristics similar to boninites. The dominant unit of this dyke swarm is basaltic and basaltic andesites that show enriched LREE-LILE and HFSE-depleted characteristics. Geochemical characteristics indicate their derivation from enriched mantle sources in a rift-tectonic environment. These authors have suggested enrichment of the mantle sources by subduction of sediments and by crustal components and are of the opinion that the Bundelkhand mafic dyke swarm has many common characteristics with those from the Aravalli craton and the Lesser Himalaya. Emplacement of these mafic bodies may have some common driving source.

Shrivastava et al. (2004) have studied the Bundelkhand granitoids from Shivpuri. They reported orbicular structures in the granitoid; these structure show no chemical variation so they are classified as homo-thrausmatic and iso-thrausmatic. The granitoid containing this structure is classified as quartz-monzonite and perthitic intergrowth indicates their igneous origin for the orbicular structure. These authors have suggested emplacement of water-saturated aplitic magma in the cooling granitic body, which loosened part of the crystallized material that acted as nucleus for the development of the orbicular structure. Similarity of composition caused by assimilation of the nucleus material giving rise to a homogeneous orbicules.

Stein et al. (2004) have carried out Re-Os dating on molybdenite from Cu-Mo-Au mineralization of the Malanjkhand deposit of the central Indian shield. The data suggest late Archaean - early Proterozoic (2490 ± 8Ma) deposition age for the deposit and therefore, the age of the host calc-alkaline Malanjkhand granitoids is also constrained to be older than the deposit. Detailed petrographic studies and high Re concentrations for molybdenites (400–650 ppm) indicate that Malanjkhand is a subduction-related stockwork-porphyry-style Cu–Mo–Au deposit which probably also had influence of mantle sources. Their studies suggest that Central Indian Tectonic Zone (CITZ) has formed by amalgamation of the southern and northern terranes during the late Archean - early Proterozoic period; thus, CITZ came into being from this period onwards. These authors have also suggested that this late Archaean - early Paleoproterozoic belt preserves sutures within an ensemble of Late Archean continent that included east Antarctica (Napier and Vestfold Hills complexes) at about 2.5 Ga.

Kumar et al. (2004) have described microgranular enclaves and xenoliths in the Paleoprotorozoic (~2400 Ma) Malanjkhand granitoids. The microgranular enclaves are rounded, ellipsoidal, discoid, elongated, lenticular, tabular, commonly up to 2 metres across. The enclaves have sharp and diffuse contacts with their host granitoids. These features indicate contemporaneous flow and mingling of partly crystalline felsic-mafic magmas. Some of the enclaves exhibit dark crenulated margins giving a pillow-like form that has been attributed to undercooling of a mafic magma as globules intruded into the consolidating granitic magma.

Sensarma (2007) has reported bimodal large igneous province represented by the Paleoproterozoic (2500 Ma) Dongargarh Group rocks from the central Indian shield. This province has sub-equal volumes of coeval felsic-mafic volcanic rocks. Although many features of this suite of rocks indicate plume-tectonic setting for generation of this large igneous province, the longer time of magmatic activity (~30 – 70 Ma) is too long for the contemporary plume models. The author has suggested extensional tectonic regime in which crustal and mantle sources were mobilized simultaneously to give rise to this large igneous province in the central Indian shield.

Wanjari et al. (2005) have carried out geochemical studies of the Amgaon gneisses north of the Bastar craton and south of the central Indian shear. Their study has indicated presence of high-Al_2O_3 trondhjemite along with calc-alkaline and peraluminous granites from the Amgaon gneisses. These chemical characteristics are similar to those of the ~2.5 -2.6 Ga granitoids of the Dharwar craton. These authors suggest that these two cratons were nearest neighbour at least during late Archaean.

Wanjari and Ahmad (2007) have studied part of the Amgaon Gneissic Complex well exposed in a quarry near Kalpatri village, ~20 km NE of Amgaon, south of the CITZ. The granitic rocks exposed on the quarry are massive to weakly deformed. Geochemically these rocks are per-aluminous granite with typical calc-alkaline lineage. These rocks have been intruded by synplutonic basic dyke when the pluton was still undergoing consolidation. This has given rise to excellent magma-mingling features between felsic and mafic magma. The mafic rocks have typical continental tholeiitic characteristics with enriched LREE-LILE and depleted Nb, Ti, Sr and Eu. These characteristics are also observed in the mafic enclaves in the neighbouring Dongargarh granite, probably indicating their consanguinity. However, there are also highly deformed mafic enclaves /xenoliths within the Amgaon Gneissic Complex which could be older components of the latter.

Ray et al. (2008) have studied two basaltic dykes from Rajmane and Talwade areas from the central Deccan Traps. These dykes are extremely rich in crustal xenoliths of great variety including gneisses, quartzites, granite mylonite, felsic granulite, carbonate rock, tuff. These xenoliths provide clear evidence for small-scale lithological heterogeneity and strong tectonic deformation in the Precambrian Indian crust beneath. Geochemical characteristics and isotopic ratios for the xenoliths are similar to the basement rocks of the Dharwar craton. The basaltic dykes have characteristics similar to lavas of the Mahabaleshwar Formation. Based on the study of the xenoliths, these authors suggest extension of at least 350-400 km of the Dharwar craton under the Deccan Traps.

Gregory et al. (2006) have carried out $^{40}Ar/^{39}Ar$ phlogopite dating of the Majhgawan kimberlite near Panna in central India. The kimberlite sample has been precisely dated at 1073.5±13.7 Ma (2σ). This date is very significant in terms of constraining the age of Upper Vindhyan (Rewa and Bhander) sedimentation to be younger than ca. 1075 Ma.

Hussain et al. (2004) have studied the basement gneisses and granitoids from the Bastar craton. These two rock units have some distinct characteristics but both are enriched in lithophile elements and depleted in P and Ti. The latter is interpreted due to retention of these elements by titanites and/or apatite during partial melting of the source region. These authors suggest derivation of older gneisses by partial melting of an oceanic slab due to subduction. The gneisses were formed when the slab was much shallower and not much interaction with the mantle wedge was possible. On the other hand the younger granitoids were generated by partial melting of the oceanic slab but at greater depth, thereby, allowing the melt to interact with the mantle wedge, hence having higher abundances of compatible elements compared to the gneisses.

Srivastava et al. (2004b) have studied the Neo-Archaean mafic magmatic rocks from southern Bastar craton. These rocks overlie the granite gneiss basement. Geochemical studies indicate three distinct types including sub-alkaline basalt, basaltic andesite and boninite. These authors have suggested that these three distinct suites are related by fractionation from boninite to basaltic andesite that goes into sub-alkaline basalt. They have also suggested rift-tectonic environment rather than subduction-related scenario. Trace-elements criteria indicate their derivation from lherzolite mantle source.

French et al. (2008) have carried out U-Pb (baddeleyite and zircon) dating of the two NW-SE trending mafic dykes from southern Bastar that has given 1891.1±0.9 Ma and 1883.0±1.4 Ma ages respectively. Another mafic sill from Cuddapah basin has given an age of 1885.4±3.1 Ma (baddeleyite). The authors have suggested that their study indicate mafic magmatism in the age range of 1891-1883 Ma in an area of at least ~90,000 km^2. If all these mafic magmatic episodes are related then they may represent a large igneous province. Existence of large igneous provinces nearly in the same age range from Superior Province and Kaapvaal craton probably indicate a global-scale mantle upwelling or enhanced mantle plume activity during this period.

4. EASTERN INDIAN SHIELD

Studies on the plutonic and Precambrian magmatic rocks in the eastern Indian shield are concentrated mostly on the alkaline complexes exposed at the contact of the Eastern Ghats and the southern Indian basement rocks. Some works are also reported from the Chotanagpur Gneissic Complex and its extension in the Shillong plateau, Singhbhum and the Eastern Ghat Granulite terrains.

Bhadra et al. (2007) have carried out detailed structural, microtextural and thermobarometric studies of the Ranmal migmatite complex to understand their genesis. Their study indicates that syn-deformational segregation-crystallization of *in situ* stromatic and diatexite leucosomes occurred at 800^0C and 8 kbar. The protoliths, neosome and mesosome comprise quartz, K-feldspars, plagioclase, hornblende, biotite, sphene, apatite, zircon, and ilmenite with large variation in modal mineralogy. Geochemical studies indicate dynamic melting that can explain the abundance better than batch partial melting in a deforming crust. According to these authors disequilibrium-accommodated dynamic melting followed by equilibrium crystallization of the melt led to uniform composition of plagioclase composition in migmatites and causes REE depletion in leucosomes.

Nasipuri and Bhattacharya (2007) have studied anorthosite pluton from Bolangir. The massive anorthosite in the interior of the pluton passes into margin-parallel foliated anorthosites. Their study indicate deformation of the pluton closer to the magmatic conditions of about 950^0C temperature and 6-12 kb pressure. The interior of the pluton shows deformation of larger than centimetre sized plagioclase crystals to aggregates of finer dynamically recrystallized internally–strained grains. Closer to the boundary of the pluton finer-grained plagioclase crystals are of two types. First type is strain-free rectangular-shaped indenting neighbouring plagioclase grains supposed to have formed by diffusion creep. The other unstrained end-to-end touching euhedral plagioclase grains show tilling representing magmatic flow textures. The difference in the deformation of the plagioclases from centre to margin is interpreted to reflect increasing melt fraction during syn-deformational pluton emplacement.

Chatterjee et al. (2008a) have carried out U-Pb zircon dating of the Balugaon Anorthosite Massif of the Chilka lake domain, Eastern Ghats belt to constrain their emplacement age. The new data indicate that this massif crystallized at 983±2.5 Ma, about 200 Ma earlier than that was previously thought. Available and present structural data indicate that the country rock was deformed twice before the intrusion of the massif. U-Th-Pb chemical dating of monazite cores (714±11 Ma) and rims (655±12 Ma) is consistent with progressive high-grade metamorphism of the anorthosite, and monazite-allanite rims (463±22 Ma) around apatite record low-grade Pan-African thermal activity. According to these authors the 714-655 Ma dates correlates with collision of Eastern Ghats–Rayner Block and Western Australia in the mid-Neoproterozoic.

Nagaraju et al. (2008) have carried out structural and Anisotropy of Magnetic Susceptibility (AMS) studies to understand the tectonic setting of emplacement of the Pasupugallu Gabbro–Anorthosite Pluton. The pluton has intruded the transition zone between the Mesoproterozoic Eastern Ghats granulites and the late Archaean amphibolites and migmatitic gneisses of east Dharwar craton, southern India. Their study suggest that this magma was emplaced into a chamber (dilational jog) induced by crustal-scale dextral transpressional tectonic regime, probably during the onset of Grenvillean event.

Upadhyay et al. (2006) have studied the Khariar alkaline complex which is one of the several Mesoproterozoic (1,480±17 Ma) alkaline and tholeiite intrusives that have been deformed during the Pan-African tectonothermal event. Geochemical characteristics indicate rift-tectonic environment of their emplacement. These authors suggest derivation of primary basanitic magma by partial melting of enriched lherzolite mantle source within the lithosphere. The basinitic primary magma fractionated within mantle clinopyroxene and Ti-rich amphibole to give rise to nepheline syenite. According to these authors these Mesoproterozoic alkaline magmatism trigerred initiation of a NE-SW rift that formed several marginal basins and an ocean towards the south. K-Ar ages of 1330±53 Ma for the glauconites in sandstone suggests that NW-SE-trending Godavari–Pranhita graben formed at nearly the same time and may be related. In that case the Godavari–Pranhita graben represents failed arm of a rift system.

Bhattacharya and Kar (2005) studied the Koraput Alkaline Complex within the high-grade Eastern Ghats belt. Their study indicates that this alkaline complex was intruded synkinematically in a pull-apart structure far away from Bastar cratonic margin. The alkaline suite comprises four distinct members viz. mafic syenite, felsic syenite, nepheline syenite and perthite syenite. Fe-enrichment trend may be related to evolution of alkali basalt series. Negative Nb in the multi-element patterns indicate crustal influence on their genesis. These authors suggest emplacement of the alkaline complex in a rift-tectonic environment along the continental margin.

Upadhyay (2008) has discussed about 1.5-1.3 Ga alkaline complex at the sheared contact between Eastern Ghat belt and Archaean cratons of southeastern India and the geodynamics in terms of crustal evolution in this region. Mesoproterozoic rifting and alkaline magmatism are correlated with breakup of the supercontinent Columbia and opening up of ocean between eastern India and east Antarctica. Metasedimentary sequence of Eastern Ghats Province was deposited during 1.4–1.2 Ga. Closure of the ocean during Mesoproterozoic (~1 Ga) caused collision of eastern India and eastern Antarctica during assembly of Rodinia. The collision caused development of Grenvillean Eastern Ghats-Rayner Complex orogen where sediments were metamorphosed to granulite-facies conditions. The craton-Eastern Ghats belt suture was modified subsequently during Pan-African (0.5-0.6 Ga) tectonism when the Eastern Ghats granulites were thrusted westward over the cratonic foreland. The author suggests that the present crustal geometry exposes only the eroded Pan-African thrust contact between the craton and the Eastern Ghats belt and not the original Grenvillean suture, which may be underlying the granulite thrust sheets.

Upadhyay and Raith (2006a) have carried out geochemical and geochronological (Sr-, Nd-Pb) studies of the Kunavaram Alkaline Complex near the craton-Eastern Ghats Belt (EGB) contact in SE India. Their study indicates emplacement of the alkaline magma along the Mesoproterozoic (ca. 1384 Ma) rifts at the cratonic margin. These paleo-rifts can be traced along the EGB-craton boundary by the presence of alkaline suite along Khariar, Kunavaram, Jojuru, Elchuru areas. Present study of alkaline rocks of Kunavaram region indicate evolution of the alkaline magma through assimilation fractional crystallization involving fractionation of clinopyroxene–amphibole, apatite, titanite, zircon. The craton margin EGB rocks have been overprinted by amphibolite-grade metamorphism during the Neoproterozoic–Paleozoic (611–484 Ma) when Pan-African tectonism thrust the EGB granulites westward over the cratonic foreland along a number of northwest-vergent shear zones. These authors suggest that the craton-EGB contact represents a rifted Mesoproterozoic margin deformed subsequently during Pan-African collisional tectonics.

Upadhyay and Raith (2006b) have studied monzosyenite rocks from Jojuru near Kondapalle along the boundary between Archaean cratons and Easten Ghats belt. Their U-Th-Pb SHRIMP zircon age of 1263±23 Ma is considered by these authors at the lower bracket age. Geochemical studies indicate rift tectonics for emplacement for these bodies. Geochemically these rocks are comparable to nepheline syenite, recorded all along the Mesoproterozoic continental margin that was overprinted by a Pan-African collision during westward thrusting of Eastern Ghat Granulite Belt over the cratonic foreland.

Bhattacharya et al. (2004a) have shown based on geochemical and isotopic studies that the syenite complex around Rairakhol in Orissa are derived from the crust rather than mantle as others have proposed for many of the alkaline plutons from this area. Their suggestion is based on negative-epsilon Nd values for these rocks that suggest longer crustal residence time for their protoliths. Their study also indicates emplacement of this pluton could be related to latest deformation / folding of the host granulitic country rocks.

Roy et al. (2004) have studied ultramafic (harzburgite and lherzolite) dykes which is part of the Newer dolerite. Rb-Sr isochron age for this dyke is 2613±177 Ma, probably indicating the stabilization age of the craton. These rocks have enriched LILE and depleted Ba, Nb and Sr with high concentration of Cr and Ni. REE patterns show enriched LREE and nearly-flat HREE. Epsilon Nd (t) varies from +1.23 to –3.27 and $\delta^{18}O$ vary between +3.16‰ to +5.29‰ which is lighter than mantle value. All the data indicate that~2.6 Ga the mantle below eastern Indian shield was nearly chondritic in terms of isotopic characteristics but got metasomatised/enriched in incompatible trace elements probably due to subduction of the early crust.

Bhattacharya et al. (2004b) have studied the granitic rocks exposed at the northern margin of the Eastern Ghats Mobile Belt against the Singhbhum craton. Field studies show similar structural features in the granite and the host rocks indicating syn-deformational emplacement. Geochemical studies indicate that while some of the granites formed/from high-grade protoliths by dehydration melting others could have been derived from low-grade protoliths, indicating heterogeneous sources for these granites.

Dobmeier et al. (2006) have carried out U-Pb (zircon), Rb-Sr (mineral) and whole-rock Sm-Nd and Lu-Hf systematics of the Vinukonda meta-granite, Eastern Ghats, India to date their emplacement, their genesis and the regional tectonics. Their studies indicate that this granitic magma intruded the granitic gneiss of Vinjamuru domain of the Krishna district that was already deformed under epidote-amphibolite peak metamorphism. Sm-Nd and Lu-Hf whole-rock systematics indicate isotopically homogeneous crustal source and multi-stage evolution. U-Pb zircon indicate age of emplacement at 1588.4±7.1 and 1589.7±5.7 Ma. Their synthesis suggests that thrusting in the Krishna Province reflects intracratonic deformation in response to the amalgamation of the Eastern Ghats-Rayner Province with subcontinental India in early Palaeozoic time.

Chatterjee et al. (2008b) have carried out U-Pb zircon of the Bengal anorthosite massif and U-Th-Pb chemical dating of monazite in metapelite granulite of the Chotanagpur Gneissic Complex of the eastern Indian shield to understand the thermal-tectonic history of the region. It has been shown that gabbroic anorthosite was emplaced at 1550±12 Ma, which is about 50-150 Ma subsequent to the earlier metamorphic event when the northern and southern continental blocks collided. Zircon overgrowth in anorthosite records subsequent metamorphism in the Chotanagpur Gneissic Complex around 947±27 Ma and 950±20 Ma and 995±24 Ma monazite growths in the matrix and within garnet of metapelite-granulite located north of the Bengal anorthosite. It has been discussed by these authors that Grenvillean granulite-facies metamorphism played an important role in the thermal-tectonic evolution of the Chotanagpur Gneissic Complex similar to that of the Eastern Ghats Granulite Belt. These authors have shown that Singhbhum Shear Zone shows multiple reactivation, the oldest being at ~3.09 Ga, followed by Palaeo- to Mesoproterozoic period.

Kumar and Ahmad (2007) have studied the field relationships and geochemical studies of the Precambrian dykes intruding the Chotanagpur Gneissic Complex. There are two major sets of mafic dykes, one set also traverses through the Gondwana sediments, whereas the Precambrian dykes are restricted within the Chotanagpur gneisses . Their study is concentrated on the Precambrian dykes only. These rocks have undergone greenschist to lower amphibolite grade of metamorphism. These rocks are shown to have enriched trace-element characteristics, high LILE-LREE/ HFSE and strong negative Sr anomaly in multi-element patterns, similar to rift basalts. Trace-element modelling indicates their derivation from variably enriched mantle sources followed by assimilation fractional crystallization. These authors suggest that these dykes within the Chotanagpur Gneissic Complex mark continental rifting during the Proterozoic period.

Srivastava and Sinha (2004a) have studied the early Cretaceous alkaline ultramafic-mafic complex that intruded the the Proterozoic rocks of the Shillong Plateau. These alkaline bodies followed Barapani-Tyrsad shear zone, Kopali faults, and Um Ngot lineaments at Jasra, Karbi Anglong district of Assam. These rock suites essentially comprise pyroxenite, gabbro and nepheline syenite. The nepheline syenite occur as small dykes within the pyroxenite or as differentiated units within the gabbroic rocks. Mineralogical and chemical characteristics clearly indicate their alkaline nature. These authors suggest derivation of these rocks from primary carbonatitic magma that were generated by lower degrees of partial melting of metosomatised mantle peridotite.

Chatterjee et al. (2007) have carried out electron microprobe (EPMA) monazite dating and paragenesis of granulite-facies metapelites from the Shillong-Meghalaya Gneissic Complex. The latter is considered as the extreme northeastern portion of the Indian shield closest to the

Australian-Antarctic block during the assembly of the Neoproterozoic-Cambrian Rodinia supercontinent. Their study provide well-constrained age of 1596±15 Ma (n=103) for the Garo-Golapara hills that corresponds to counter-clockwise pressure-temperature path with near-peak conditions of 7-8 kb and 850^0C. Some rare monazite rims have given younger ages of 1032-1273 Ma. At Sonapahar, west of Shillong, the EPMA monazite age cluster around 500±14 Ma (n=3). This age corresponds with 880-480 Ma Rb-Sr dates of the porphyritic granite that intrudes the Shillong-Meghalaya Gneissic Complex in its eastern-central portion. These authors have suggested that a Pan-African amalgamation of the Indian plate with the Australian-Antarctic plate and a northward extension of the Prvdz Bay suture through Shillong-Meghalaya Gneissic Complex. They also suggest that the western boundary of the suture lies between Garo-Goalpara hills and Sonapahar regions.

Kumar et al. (2005) have carried out field studies of magmatic interaction between Khasi hill granitoids and basic magma giving rise to microgranular enclaves. These authors have shown how in a crystallizing granitic magma body a basic magma intrudes and mingles and mixes to some extent to give rise to a hybrid rock. They have described the microgranular enclaves, best recorded between Mawthaphdah and Jashiar villages, are 3 to 30 cm across with varying shapes and sizes from subrounded, ovoid to ellipsoidal and show sharp to crenulated contact with the granitic magma. In the hybrid rocks the large crystals of K-feldpars, mafic and felsic xenocrysts were in disequilibrium and got corroded along the margin because of the changing composition of the hybrid magma.

5. SOUTHERN INDIAN SHIELD

The southern Indian shield is divided into two broad crustal domains, Archaean to the north and Proterozoic to the south. Both of these domains are being separated by a transcrustal E-W-running Palghat-Cauvery Shear (PCZ) zone. The Archaean domain is classically termed as 'Dharwar craton' corresponds to protocontinent that exposes a large tilted section of continental crust whilst to the south metasedimentary rocks associated with quartzo-feldspathic charnockite and mafic granites are dominant lithologies with small discrete alkali granite or syenite plutons. The Dharwar craton of southern India exposes a large natural section of Archaean continental crust and provides a unique opportunity to study crustal accretion patterns, mantle evolution and sedimentary environments through time. The Dharwar craton comprise vast areas of TTG gneisses (regionally known as Peninsular gneisses), two generations of volcanic-sedimentary greenstone sequences (>3.0-Ga Sargur Group and 2.9-2.6-Ga Dharwar Supergroup) and late calc-alkaline to high-potassic granite plutons. The craton is commonly divided into two sub-blocks (western and eastern) based on the nature and abundance of greenstones, degree of regional metamorphism, melting as well as nature and age of their surrounding basement. The steep mylonitic zone along the eastern boundary of the Chitradurga greenstone belt is generally considered as the dividing line between two cratonic blocks. The western Dharwar craton dominated by 3.4-3.2Ga Peninsular gneisses which are interlayered with >3.0 Ga Sargur Group greenstone belts which together forms basement for younger Dharwar Supergroup greenstone belts. On the other hand the eastern Dharwar craton contains minor older (>3.0 Ga) basement and dominated by c. 2.7 Ga TTG - greenstone associations and most voluminous calc-alkaline plutons.

Jayananda et al. (2006) present combined field-based tectonic fabric data, spot image analysis, petrography, U-Pb zircon ages, Nd isotopes and whole-rock geochemical data for the late Archaean granite plutons in the western Dharwar craton (WDC) from Arsikere-Banavara and Chitradurga-Hosdurga area. Structural data show that Arsikere-Banavara plutons are syn-kinematic with respect to development of dome-and-basin structures resulting from partial crustal diapiric overturn (D1), whilst Chitradurga-Hosdurga plutons show deformation patterns resulting from the superimposition of large-scale regional strike-slip shearing (D2) onto D1 syn-emplacement fabrics. SIMS U-Pb zircon ages of 2614±10 Ma for the Chitradurga pluton and of 2617±3 Ma for the Arsikere pluton define minimum age of the D1 strain pattern. Based on whole-rock geochemistry and Nd isotopes (εNd = -6 to 0) they attributed the petrogenesis of Chitradurga-Hosdurga and Arsikere-Banavara granites to partial melting of old (>3.0 Ga) depleted lower crust of intermediate composition. Their heterogeneous chemical compositions indicate involvement of various sources and also significantly different depths of partial melting to generate those melts. The production and emplacement of granite melts correspond to regional partial reworking associated with HT event prior to 2.61 Ga and thus are different from 2.55 to 2.51Ga granulite-facies metamorphic episode associated with regional strike–slip shearing (D2) that affected the entire craton (Jayananda et al., 2006). Partial reworking of lower crust at 2.61 Ga and associated deformation explained by heat advection and/or crustal thickening related to voluminous mafic greenstone volcanism at that time.

Chardon and Jayananda (2008) discussed fabrics development and juvenile pluton emplacement (Closepet granite) across the tilted crustal section of the EDC and show that horizontal constrictional pure shear strain affected large volumes of the mid and lower crust at the time of regional melting and magmatic accretion. Bulk constriction explained by a combination of coeval shallow and steep planar fabrics sharing common horizontal elongation direction, two sets of conjugate strike-slip shears and extensional shear bands.

Lopez et al. (2006) reviewed the published geochemical data of Archaean granitoids (including Archaean granitoids of southern India) in the light of experimental data and discussed the evolution of Archaean continental crust. Their proposed petrogenetic model suggest progressive decrease of geothermal gradients through time during Archaean. Lopez et al. (2006) visualized thermal structure of the early Archaean down-going plates tobe favourable for melting at shallow depths in plagioclase stability field (P<10 k bar) to generate TTG magmas without interaction with the mantle during ascent. These TTG magmas are characterized by lower Fe, Mg, and higher Na/Ca ratios. On the other hand the cooling of the Earth during late Archaean produced an increase in dip of subducting slab, favouring partial melting of down-going slabs at greater depths (P>10 k bar) and the generated magmas interacted with overlying mantle during their ascent to crust thus accounting for higher Fe, Mg, low Na/Ca ratios. They suggest the formation of voluminous K-rich granites at the Archaean-Proterozoic boundary through mantle-derived hydrous sanukitoid magmas with tonalitic crust.

Chadwick et al. (2007) documented structural and SHRIMP U-Pb zircon ages for granites adjacent to Chitradurga schist belt NW of Chitradurga town in the western Dharwar craton. Zircon U-Pb SHRIMP dates of mylonitized granites indicate 2648±40 Ma, 2598±19 Ma and ca. 2600 Ma respectively. The large errors in the zircon ages have been attributed to radiogenic Pb-loss during an unidentified Neoproterozoic event. They describe magmatic as well as solid-state fabrics in granites outlasted by sinistral and dextral strike-parallel shears. Chadwick et al. (2007) explain structural data by emplacement of granite above the hanging wall of the duplex in the NW of the schist belt outlasted by top-SW displacement. The structural relationship of the Chitradurga belt with the granites in the west modelled as mid-crustal imbricate fold thrust. The thrust thickening, granite emplacement in the foreland accretionary complex occurred as multiphase injections during orogen-parallel sinistral and dextral shears.

Rogers et al. (2007) have presented SHRIMP U-Pb zircon ages together with whole-rock geochemical data for granitoids adjacent to the Hutti-Muski schist in the eastern Dharwar craton. They show two phases of plutonism intruded into Hutti-Muski belt, the syn-tectonic porphyritic Kavital granitoid that define an age of 2543±9 Ma followed by post-tectonic fine-grained Yelagatti granite defining minimum ages of 2221±99 Ma. The tectono-magmatic evolution of Hutti-Muski schist belt and adjoining plutons attributed to collision of eastern and western blocks of the Dharwar craton subsequent to 2658 Ma and accounted by combining uniformitarian and non-uniformitarian models (Rogers et al., 2007).

Vasudev and Chadwick (2008) presented lithological and fabrics data on the granite plutons and surrounding TTG-Hutti greenstone belt in the northern part of the eastern Dharwar craton (EDC) and discuss spatial relationship between regional deformation, metamorphism, pluton emplacement and gold mineralization. They attributed sedimentary and volcanic facies in the unstable marine environments, and high-temperature – low-pressure metamorphism spatially associated with emplacement of granites which coincided with emplacement of granite plutons but outlast D1 schistosity. Vasudev and Chadwick propose island-arc setting to explain volcano-sedimentary greenstone basin formation, granite emplacement and metamorphism.

Devaraju et al. (2007a) have presented petrologic, geochemical and Nd-isotope data for the Archaean TTG and potassic granites from the northern part of the western Dharwar craton (WDC). They classified the granitoids of the northern part of the WDC into several types including Anmod Ghat trondhjemite, Chandranath granite, Dhudsagar granite, Ramnagar migmatite, Ramnagar granitic gneiss, Ramnagar porphytitic granite, Annigiri-Majjigudda granite and Hatalgiri-Naregal migmatite. Their petrologic data on these granitoids indicate greenschist – lower amphibolite facies metamorphism. Sm-Nd isotopic data indicate three major groups:

i) Older trondhjemite-tonalite-monzogranite providing model ages around 3.3Ga;

ii) Suite of granitoids (Chandranath granite, Dudhsagar granite, Ramnagar granite gneiss and Ramnagar porphyritic granite with model ages range from 2.96 Ga to 2.83Ga, and

iii) Younger granite viz Annegeri-Majjigudda granite with model age of 2.68 Ga.

Isotopic and geochemical characteristics of the gneisses and granites are marked by depletion in REE and distinctly different from gneisses and granites of eastern Dharwar craton (EDC). Based on chemical and isotopic characteristics they conclude that the gneisses and granites derived from igneous protoliths in syncollisional and plume settings.

In the northeastern part of EDC, Singh et al. (2004) have dated a pink potassic granite from Dharmawaram in Karimnagar district of Andhra Pradesh by Rb-Sr whole-rock method which define an age of 2232±46 Ma with initial Sr ratio of 0.71052 ±0.00084 indicating its derivation by reworking of older crustal source.

In the Eastern Ghat Mobile Belt (EGMB) Chetty and his co-workers carried detailed integrated studies involving strain fabrics analysis, AMS and geochemistry on the Pasupugallu gabbro pluton (Nagaraju et al., 2005, 2008). The magnetic fabrics correspond well with the field measurements and petrographic data. Their structural analysis and AMS data show that the magma emplaced into a magma chamber (dilational jog) induced by crustal-scale transpressional tectonic regime probably during the onset of Grenvillean event.

In the Southern Granulite Terrain (SGT), Pandey et al. (2005) present Rb-Sr, Sm-Nd and Pb-Pb isotope data on the granites and associated granulites of Usilampatti area. Granite plutons and associated leptynitic gneisses yielded 823±38 Ma (initial ratio 0.713) and 894±82 Ma respectively. Microcline and muscovite from pegmatite indicate 532 and 491 Ma respectively. They interpret granulite metamorphism and granite emplacement as an early phase of metamorphism and magmatism during Pan-African orogeny whilst younger ages corresponds to later decompression and exhumation. On the other hand Upadhyay et al. (2006) document petrologic, geochronologic and whole-rock geochemical data for Neoproterozoic-Cambrian alkaline plutons along the southern margin of Cauvery shear zone at Sivamalai. U-Pb TIMS dating of zircons from syenite yield a concordant age of 590.2±1.3 Ma which was interpreted to date the intrusion of alkaline plutons. These alkaline plutons were affected by Pan-African thermal event and ductile deformation as evidenced by recrystallization textures observed. Major-and trace-element data reveal the presence of both enriched and depleted rock types in alkaline pluton. The distinct trace-element depletion interpreted to be result of fractional crystallization involving removal of accessory phases like zircon, titanite, apatite and allanite.

Suresha and Srikantappa (2005) have described igneous charno-enderbite and charnockite (C-type magmas) from Dindigul, Tamil Nadu. According to these authors these rocks comprise pyroxene, plagioclase, alkali feldspar, quartz, biotite, titanomagnetite, ilmenite and apatite. The bulk rock is characterized by high K, Ti, P and low Ca for their Si abundance. These characteristics are similar to those of the Ardery charnockite from Antarctica. Studies of these charnockitic rocks will help us understand the tectonic assembly of the southern Indian block and fragmentation of the Gondwanaland.

Rajesh and Santosh (2004) have characterized charnockitic magmatism for the southern Indian granulite terrains. The older Archaean - early Proterozoic charnockite occur in the northern part and the younger late Proterozoic ones occur towards south. Older charnockite from Biligirirangan hill, Shevroy hill and Nilgiri hill are of intermediate composition and those from Pallavaram are dominantly felsic charnockites. The northern Kerala and Cardamom hill have intermediate but the youngest Nagercoil massif are felsic charnockite. Their generation is undoubtedly igneous but at two stages as suggested by these authors. First basaltic magma underplated the lower crust and caused melting of the lower crust with low water content giving rise to the intermediate charnockite followed by melting of the lower crust in the presence of water that gave rise to felsic charnockite.

Further south in the Trivandrum block, Rajesh (2004) present geochemical data for 640-Ma Chengannoor granite that intrudes the NW margin of the Neoproterozoic high-grade metamorphic terrain of Trivandrum block. Geochemical data of Chengannoor granite characterize as high-K alkali-calcic I-type granite. Other characteristics such as anhydrous high-K nature and comparison with experimental studies on various granitoid compositions together with trace-element modelling reflect source rock of igneous charnockite nature. Rajesh (2004) proposes a petrogenetic model where basaltic underplating caused the melting of lower crust forming the charnockite massifs and remelting of charnoenderbites from charnockite generate Chengannoor granite. In the regional context Chengannoor granite is considered as significant heat source for near-UHT metamorphism.

Rajesh (2008) has conducted detailed geochemical studies on Kalpatta and Munnar granites from southern part of Nilgiri hills and Madurai blocks. Geochemical characteristics of Kalpatta granites are similar to high-K calc-alkaline magnesian granitoids whilst those of Munnar granites are similar to A-type alkali ferroan granitoids. Trace-element modelling together with constraints from experimental studies suggest derivation of two granites from charnockite source. Rajesh (2008) proposes petrogenetic model involving partial melting of north Kerala massif charnockite to generate high-K magnesian Kalpatta granite whilst partial melting of Cardomom hill charnockite followed by fractional crystallization for A-type ferroan Munnar granite.

Recently, Jayananda et al. (2008) presented field, petrographic, Sm-Nd whole-rock isochron and whole-rock geochemical data for komatiites from Sargur Group greenstone belts (Ghattihosahalli, Jayachamarajapura, Bansandra, Nuggihalli, Kalyadi and Nagamangala belts) of western Dharwar craton. Field data such as pillow structures indicate their eruptions mainly in marine environment. Petrographic data reveal that igneous mineralogy has been altered during post-magmatic hydrothermal alteration processes corresponding to greenschist- to lower amphibolite-facies conditions with rarely preserved primary olivine and orthopyroxene. A sixteen point whole-rock Sm-Nd isochron gives an age of 3352±110 Ma for timing of eruption of komatiite lavas. The studied komatiites show both Al-depletion and Al-undepletion characteristics. The Al-depleted komatiites are characterized by high CaO/Al_2O_3 ratios (>1.0) and low Al_2O_3/TiO_2 (5-16) whereas Al-undepleted komatiites show lower CaO/Al_2O_3 ratios (<1.0) and higher Al_2O_3/TiO_2 (17-26) values. Trace-element distribution patterns of komatiites suggest that most of the primary geochemical and Nd isotope compositions are preserved with only minor influence of post-magmatic alteration processes and negligible crustal contamination. The chemical characteristics of Al-depleted komatiites such as high $(Gd/Yb)_N$ (>1.0) values together with lower HREE, Y, Zr, and Hf imply their derivation from deeper mantle with garnet (majorite?) involvement, where as lower $(Gd/Yb)_N$ (<1.0)values together with slightly higher HREE, Y, Zr and Hf suggest derivation from shallower mantle without garnet involvement. Nd-isotope data of the komatiites indicate depleted mantle reservoirs which may have evolved by early (>4.53 Ga) global differentiation of silicate Earth. The observed chemical characteristics attributed to derivation of komatiite magmas from mantle at different depths in a plume setting whereas sub-contemporaneous felsic volcanism and TTG accretion explained by arc setting. They have explained komatiite volcanism and associated sub-contemporaneous TTG accretion in the WDC by a combine plume-arc model.

Bidyananda and Mitra (2005) have studied crystal chemistry of chromites from Nuggihalli greenstone belt. Crystal chemistry indicate komatiitic affinity of chromitite and P-T calculations of the chromite-hosted peridotites yielded pressure range of 13-28 kbar and temperature ranging from 775° to 1080°C; the oxygen fugacity (log fO_2) varies from +0.5 to +1.6 above QFM buffer. The P-T and fO_2 data indicate that Nuggihalli chromitites crystallized in an environment similar to upper mantle.

Devaraju et al. (2007b) presented mineral chemistry of Cr-spinels from ultramafic complexes of older Sargur Group (Nuggihalli and Rangapura – Shivani) as well as younger Dharwar Supergroup (Channagiri-Shankaraghatta-Usgao) in western Dharwar craton (WDC). They have carried out EPMA analysis for more than 200 spots and show compositions of Cr-spinel and whole range of aluminous chromite. In rare instances titanium chromite is found in PGE mineralized Channagiri complex. The chemical variations of Cr-spinels have been attributed to distinct petrogenetic processes of ultramafic complexes. These authors conclude that the chemical characteristics of Cr-spinels of WDC are similar to well-known layered/podiform/ophiolitic suites and do not permit characterization exclusively as layered or podiform.

Naqvi et al. (2007) for the first time documented adakitic magmatism from the younger Dharwar Supergroup Shimoga greenstone belt near Ranibennur in the WDC. The adakites consists mainly of quartz, plagioclase and amphibole. They show low Y (8-14 ppm) and Yb (0.85 – 1.47 ppm) typical of high SiO_2, low Mg#, Ni and CR type adakites. Other chemical characteristics such as Na_2O, K_2O, Nb, Zr, LREE and HREE also closely resemble high-silica adakites. These adakites show compositional similarities with Meso- and Neoarchaean tonalite-trondhjemite-granodiorite (TTGs). Such rocks have been experimentally generated by partial melting of hydrous melts that are similar to adakitic glass veins in peridotite xenoliths of Kamchatka arc lavas, which imply derivation from wedge mantle. These authors attribute similar chemical characteristics of TTG and adakites to their common petrogenetic mechanisms to rapid subduction and faster continental growth during Archaean.

Alapieti et al. (2008) document PGE mineralization in ultramafic rocks from Hanumalapur area of Shimoga greenstone basin of the WDC. The PGE mineralization divided into four mineralogically distinct types in descending order of PGE content are: 1) a silicate-hosted Pd type, 2) a silicate-hosted Pt type, 3) a base-metal sulphide hosted Pd type and 4) an oxide-hosted PGE type. These authors attribute the origin of mineralization to magma mixing and resultant sulfide immiscibility during crystallization of ultramafic magmas.

Sunder Raju et al. (2006) discuss shear zone-hosted gold mineralization in the BIFs of Chitradurga greenstone belt (CGB). They document highly deformed and sheared BIFs which are metamorphosed under greenschist facies conditions. These shears in BIFs occupied by syntectonic quartz-carbonate veins are favourable loci for gold mineralization. The primary gold in BIFs is enriched with intense fracturing controlled by major shear systems extending from Gadag in the north and Dodguni in the south. The authors attribute accretionary processes and associated fluid movements in active convergent setting for gold mineralization.

Naqvi et al. (2006) presented detailed geochemical data for the volcanic rocks of the Kustagi-Hungund greenstone belts of the (EDC). The volcanic rocks show extreme geochemical diversity due to the presence of high-Mg, high-Fe, high-Fe-Mg basalts, high-Mg dacites and andesites (boninitic affinity) and sodic-palgioclase-quartz-rich felsic rocks (adakite with 4-6 wt% Na_2O). Some of the rock types (adakites) were reported for the first time. Geochemical characteristics of different volcanics rocks explained by partial melting of different mantle sources as well as slab source which generate collage of compositionally different rocks within island-arc setting.

Manikyamba et al. (2004a) have investigated amphibolite facies tholeiitic basalts from Ramagiri-Hungund greenstone belt of EDC for petrology and geochemistry. They have documented pillowed basalts, compositionally uniform with Mg# ranging from 0.60-0.64. REE patterns are coherent with no Eu anomalies, near-flat REE patterns and systematically depleted LREE (La/Sm_{cn} = 0.68-1.08). Cr (284-671 ppm), Co and Ni contents are relative to Phanerozoic arc tholeiites. Dominant negative Nb-Ti anomalies compared to REE attributed to convergent setting whilst high Mg# and Cr, Co, Ni contents may be indicative of plume influence on mantle wedge. The compositional variations of basalts have been interpreted by two-stage melting in arc environments; first-stage depletion of incompatible elements in wedge, leaving positive anomalies of Nb and Zr-Hf inherited by second-stage melting.

Manikyambha et al. (2004b) discuss gold mineralization in late Archaean (2.7 Ga) Penakacherla greenstone belt of the EDC. The observed chemical and carbon isotope values have been explained by dehydration of an oceanic slab which contributed mineralizing fluids.

Manikyamba et al. (2005) reported boninites from late Archaean Gadwal greenstone belt in the EDC. These boninites are characterized by slight enrichment in LREE, depletion of MREE compared to LREE and MREE resulting in U-shaped patterns and negative Nb, Ta, Zr, Hf, Ti and V anomalies despite depletion in MREE. Such characteristics are similar to those found in modern and ancient island arcs from intraoceanic subduction settings. Geochemical characteristics of boninites of Gadwal belt have been attributed to melting of depleted refractory-depleted mantle wedge in tectonic settings similar to Cenozoic subduction complexes. Further, Manikyambha and Khanna (2007) also presented geochemical data for different kinds of volcanic rocks from Gadwal belt including boninite, Nb-enriched basalts, andesites, dacite, rhyolite and adakites. They attributed spatial association of these compositionally different volcanic rocks to arc processes where melting of refractory mantle wedge, down-going slab and residue of adakite-wedge hybridization (Nb-enriched basalts) play significant role in the growth of the continental crust in EDC during late Archaean.

Rogers et al. (2007) documented U-Pb zircon age of 2586±59 Ma for the felsic volcanics from Hutti-Maski greenstone belt in the northern part of EDC. They also present U-Pb zircon ages for two phases of granitoids intruding the greenstone belt, an early syntectonic Kavital granite indicate 2543±9 Ma whilst a post-tectonic Yelagatti granite define an imprecise age of 2221±99 Ma. They attributed tectono-magmatic evolution of Hutti-Muski belt to collision between eastern and western blocks of the Dharwar craton subsequent to 2658 Ma and cratonwide magmatism from 2613 to 2513 Ma within the general framework of uniformitarian and non-uniformitarian models.

Vasudev and Chadwick (2008) describe lithology and structure of the auriferous Hutti greenstone belt. They document four different kinds of metabasalts including massive, jointed, schistose and carbonate-rich schistose and chlorite schists. Based on chronological relationships between quartz-carbonate vein systems and pervasive schistosity and linear fabrics showing a tectonic continuum of NE-SW stretching, which corresponds to D1, it is believed to have given rise to a large-scale anticline-syncline pair in the east of the belt and an apparent tectonic discontinuity in the NE of the belt that separates the SW-younging

Palakanmardi fining-up sequence and metabasalts with a total strike-normal thickness of ca. 3.5 km from the metabasalts. Felsic volcanics and the Gagalghatta complex in the central and southern part have total strike-normal thickness of ca. 15 km. This anomalous thickness has been interpreted to be consistent with tectonic thickening of other Neoarchaean schist belts. The authors attribute the lithologies and structures to island-arc setting.

Kolb et al. (2005) discuss relative timing of deformation and two-stage gold mineralization in the Hutti greenstone belt. They concluded that gold mineralization that occurred in two tectonic events affected the EDC during c. 2550-2530 Ma (1) The assemblage of various terranes of the eastern block, (2) a tectono-magmatic event which caused late- to post-tectonic plutonism and a thermal perturbation. It differs from pre-peak metamorphic gold mineralization at Kolar and single-stage mineralization at Ramagiri. They also note that greenschist-facies gold mineralization in Hutti greenstone belt occurred 35-90 Ma later than in western Dharwar craton.

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