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Mafic and Ultramafic Magmatism and Associated Mineralization in the Dharwar Craton, Southern India

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Abstract: Evidence of mafic and ultramafic magmatism exists in many parts of the Dharwar craton which is divided into two blocks, the West Dharwar Craton (WDC) and the East Dharwar Craton (EDC). The mafic-ultramafic rocks occur in supracrustal/greenstone belts and in numerous enclaves and slivers in the WDC. The oldest recorded mafic-ultramafic rocks, which are mainly komatiitic in nature, are preserved in the Sargur Group which is more than 3.3-3.4 Ga old, the youngest being manifested by 63-76 Ma old mafic dyke magmatism, possibly related to Deccan volcanism.

In the Sargur Group, ultramafics rocks greatly dominate over mafic lithological units. Both extrusive and intrusive varieties, the latter in the form of differentiated layered complexes, occur. Mafic volcanics exists in all the greenstone belts of the eastern block and in the Bababudan and Western Ghats belts of the western block. In addition to the Sargur Group where stratigraphic sequences are unclear, mafic magmatism is recorded in three different formations of the Bababudan Group and two sub-divisions of the Shimoga and Chitradurga Groups where basaltic flows are conspicuous. In the well studied greenstone belts of Kolar and Hutti in the EDC, three to four different Formations of mafic volcanic rocks have been mapped. Isotopic dating has indicated that while mafic magmatism in the greenstone belts of the EDC covers only a short time span of between 2.65 to 2.75 Ga, those in the Dharwar Supergroup of the WDC cover a much longer time span from 3.35 to 2.5 Ga.

Mafic dyke magmatism has taken place repeatedly from 2.45 Ga to about 1.0 Ga, but, the peak of emplacement was between 1.8 and 1.4 Ga when the densely developed swarms on the western and south western portions of the Cuddapah Basin and in the central part of Karnataka, were intruded. Emplacement of potassic ultramafic magma in the form of kimberlite-lamproite which is confined to the EDC, is a later magmatic event that took place between 1.4 Ga and 0.8 Ga.

From a mineralization perspective, mafic magmatism of the supracrustal groups of the WDC and the greenstone belts of the EDC are the most important. *V-Ti- magnetite* bands constitute the most common deposit type recorded in the mafic-ultramafic complexes of the Sargur Group with commercially exploitable *chromite* deposits occurring in a number of belts. *PGE* mineralization of possible commercial value has so far been recorded in a single mafic-ultramafic complex, while *copper-nickel* mineralization occurs at certain localities in the Sargur and Chitradurga Groups. *Gold* mineralization hosted by mafic (occasionally ultramafic) rocks has been noted in many of the old workings located in supracrustal groups of rocks in the WDC and in the greenstone belts of EDC. Economically exploitable mineralization, however, occurs mainly in the greenstone belts of the Kolar, Ramagiri-Penkacherla and Hutti-Maski and along the eastern margin of the Chitradurga belt, where it is associated with a major N-S striking thrust zone separating the WDC from the EDC. Gold deposits of the eastern greenstone belts are comparable to those of the younger greenstone belts of Canada, Zimbabwe and Australia where the mineralization is associated with quartz carbonate veins often in iron-rich metabasic rocks. The gold was emplaced as hydrothermal fluids, derived from early komatiitic and tholeiitic magmas, and injected into suitable dilatent structures.

The other common type of mineralization associated with the ultramafic rocks of the Sargur Group and supracrustal belts, particularly of the WDC, are *asbestos* and *soapstone*, related to autometamorphism/metasomatism. *Ruby*/*sapphire* deposits occur in places at the contacts of ultramafic rocks with the Peninsular Gneiss, and are related to contact metamorphism and metasomatism. Mineable *magnesite* deposits related to low-temperature hydrothermal/lateritic alteration exist in the zone of weathering, particularly in the more olivine-rich rocks. Recent spurt in diamond exploration is offering promise of discovering economically workable diamondiferous kimberlite/lamproite intrusions in the EDC.

Keywords: Mafic magmatism, Mafic dykes, Kimberlite-lamproite, Mineralization, Dharwar craton.

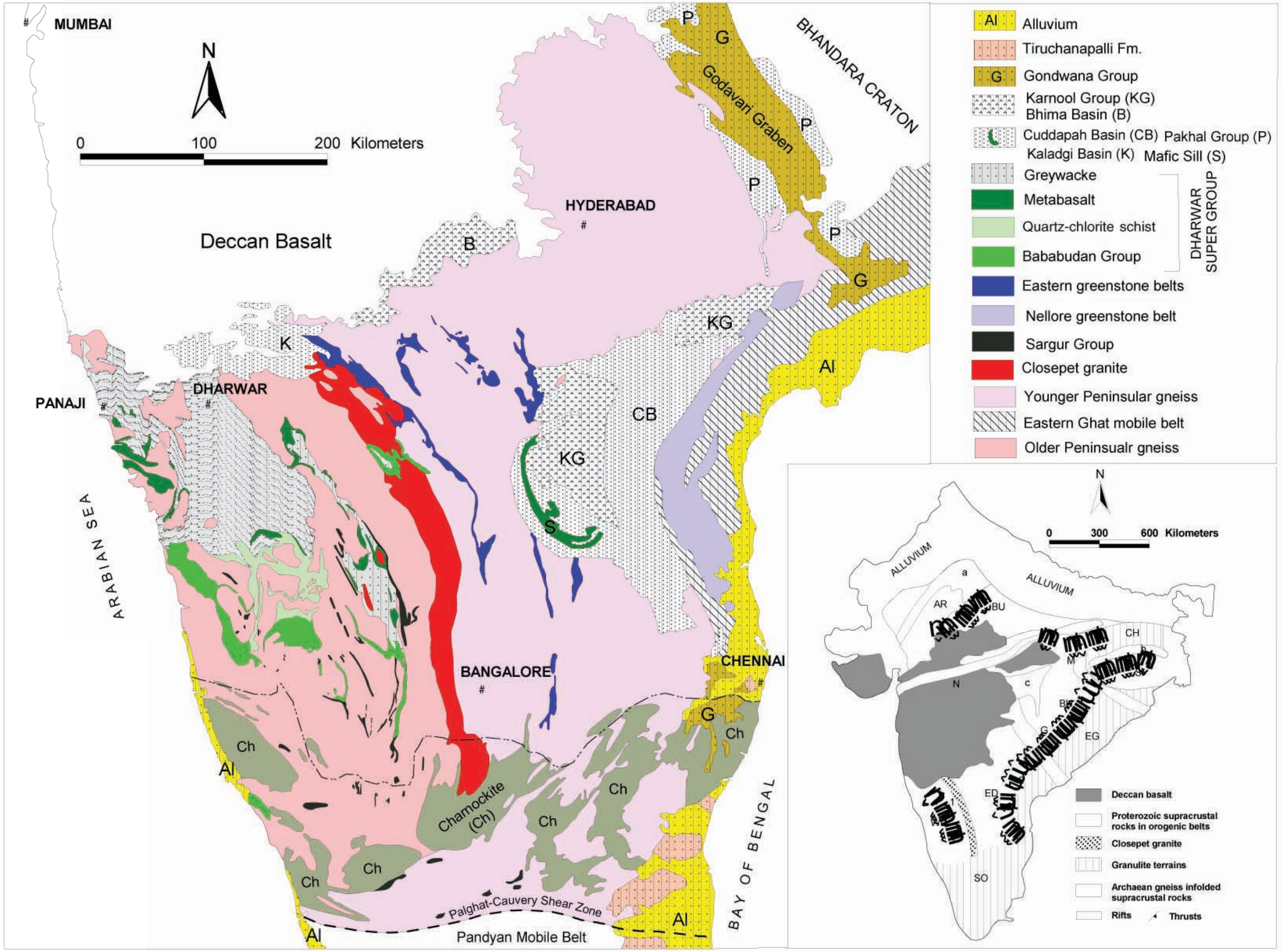


Fig.1. Map of Dharwar craton showing the broad geology of the western and the eastern blocks (adapted from project Vasundara map of GSI, 1994) *Inset:* Generalized geological map of India showing several of the cratons and regional structures (*after* Rogers, 1990) a - Delhi Supergroup; b - Singhbhum orogeneic belt; and c – Granulite terrains. CH – Chotanagpur; EG – Eastern Ghats; and SO – Southern granulite terrains, separated from the Dharwar Cratons (ED and WD) by a non-tectonic transition zone. Archaean gneissic terrains with infolded supracrustal rocks: AR – Aravalli; BU – Bundelkhand; SI – Singhbhum; BH – Bhandara; ED – Eastern Dharwar; WD – Western Dharwar. Rift valleys: N – Narmada; S – Son; M – Mahanadi; and G – Godavari. *Major thrusts:* 1 – unnamed thrust in Western Dharwar Craton, 2 – Eastern Ghats front; 3 – Sukinda; 4 – Singhbhum (copper belt); 5 – thrust south of Son valley; and 6 – Great Boundary fault.

INTRODUCTION

Mafic and ultramafic magmatism constitutes an integral part of the evolution of the Dharwar craton, having taken place repeatedly at various stages of its development. Evidence of mafic-ultramafic magmatism exists in the oldest to the youngest rock groups and is an indication of mantle involvement in the processes of crustal evolution. The major tectonic movements associated with the development of the crust have not only triggered the generation of mafic magmas in the mantle but also the emplacement of derived magmas at various crustal levels. It is also possible that early plume activity might have played an important role, particularly in komatiitic magmatism. The scale and style of mafic-ultramafic magmatism varies greatly both in space and time.

Mafic and ultramafic rocks of the Dharwar craton are hosts to diamond, PGE, Au, Ni-Cu, Cr, and V-Ti magnetite mineralization. The nature of mineralization associated with these rocks is determined among other factors by their geological setting, overall form of emplacement, crystallization of magma, geochemistry, source and the initial composition of the magma.

Mafic and ultramafic magmatism in space and time and also the associated mineralization, are highly debated issues and we do not propose to present here an overall synthesis of the topic. Neither, do we attempt to present a review of mafic and ultramafic magmatism in the entire Indian subcontinent. Our discussions are confined to mafic magmatism and associated mineralization in the Dharwar craton. We have done so because of our familiarity with the craton.

GEOLOGY OF THE DHARWAR CRATON

The Dharwar craton lies between longitudes 72°45'- 80° and latitudes 11° - 19°. It preserves within it, the geological history of one of the earliest continental crusts, covering a time span of over 3.3 Ga of earth history. It is sub-divided into Western and Eastern blocks, popularly designated as the •Western Dharwar Craton• (WDC) and the •Eastern Dharwar Craton• (EDC). It is now interpreted that the western block forms an older Archaean gneissic nucleus, older than 3.0 Ga, and the eastern block consisting mainly of gneissic rocks is a mobile belt made up largely of younger more potassium-rich granites and reactivated gneisses ranging in age from 2.5 to 2.6 Ga (Jayananda et al. 2008). The craton is bound on the south by the granulite terrain of Tamil Nadu–Kerala. Rogers (1990) (Fig.1: inset) fixed the southern boundary to coincide with the northern limit of southern granulite belt, whereas the Geological Survey of India extended the southern limit of the craton further south to coincide with the Palghat-Cauvery shear zone (Project Vasundara map of G.S.I, 1994). The Eastern Ghat mobile belt and the Godavari Basin mark the boundary on the east and northeast, while a steep dipping fault plane marks the western boundary of the craton with the Arabian sea (Fig. 1). The northern limit of the craton lies well north of present exposures, below the Deccan basalts, and has been defined by regional aeromagnetic and gravity surveys (Mishra, 2002). There are distinct changes in regional geology, lithology, volcano-sedimentary environments, magmatism and grade of metamorphism between the WDC and EDC. A 5 km wide and almost 400 km long, steeply dipping, mylonite belt separates the two blocks of the craton.

Among the Supracrustal groups of the WDC, the oldest recognized Sargur Group occurs as widely dispersed enclaves within the gneisses whereas the younger supracrustals (3 to 2.5 Ga old i.e., essentially Late Archaean) of the Dharwar Supergroup, namely the Bababudan, Shimoga and Chitradurga Groups, occur as large belts comparable to •*Proterozoic basins*• and •*Geosynclines*•. In the eastern block, there are younger greenstone belts comparable and similar to those in Australia and Canada and South Africa.

From north to south in the craton, there is progressive increase in the grade of metamorphism from greenschist facies to granulite facies. Both the blocks of the craton are affected by 2.5 Ga old granulite facies metamorphism at their southern margin. The southern granulite belt exposes 5 to 25 km deep crust and is regarded by some of the leading workers as an extension of the Dharwar craton, differing largely in level of exposure. The Eastern Ghat belt is lithologically similar to the southern granulite terrain, both areas being characterized by anorthositic rock suites. The Eastern Ghat is separated from Archaean-Lower Proterozoic rocks on the west by a major thrust fault that took place during Middle Proterozoic times.

The rocks of the Dharwar craton show evidence of intense E-W compression, but, do not appear to form part of a major orogenic belt. The Archaean gneissic complex of the Dharwar craton includes several supracrustal suites in the western block and isolated intricately folded mafic greenstone belts in the eastern block. Although lithologically dissimilar and geographically separated, the supracrustal belts of the western and eastern blocks are thought to have formed at the same time but evolved under different tectonic regimes. Limited age data on orogenic activity and rifting has indicated that

Table 1. Lithostratigraphic sequence in the western Dharwar craton

Felsic magmatism related rocks	Age (in Ga)	Mafic dyke intrusions and Supracrustal Groups				Age(in Ga)
Neoproterozoic lamprophyre-diorite-monzonite-tinguite dyke intrusions	~ 0.8 [7,8]	U. Cretaceous – Early Tertiary			Mafic dykes related to Deccan volcanism	0.063 – 0.076 [13, 14]
Chamundi granite	~ 0.8 [6]					
		Mesoproterozoic			Younger mafic dykes	1.4 – 1.6 [12]
		Palaeoproterozoic			Older mafic dykes	1.9 – 2.4 [9,10,11,12]
		Shimoga Supracrustal Group	Ranibennur Fm. : *Phyllites with local intercalations of dolomitic limestone, ultramafic schists, BIF, acid volcanics*			
			Channeshpura Fm.= Tuppadahalli Fm.: Phyllites interbedd with quartzite & dolomitic limestones ← *conglomerate*			
Closepet Granite and other potassic-granites	2.5 – 2.6 [a, 6]			**Chitradurga Supracrustal Group**	Hiriyur Fm.: *acid volcanics* ← ***mafic volcanics*** ← *pyroclast* ← *cherts* ← *polymict conglomerate*	2.46 – 2.52 [6]
Charnockites and Peninsular Gneiss Phase III	2.5 – 2.6 [a, 5]				Ingaldhal Fm.: *cherts* ← *phyllite* ← *acid volcanics* ← ***mafic volcanics***	2.65 [a]
			Channagiri Fm.: *Phyllites with dolomitic lenses* ← *quartzite* ← *conglomerate*			
			Devara Gudda Fm.: Phyllites interbedded with quartzite and dolomitic limestones ← congl.		Vanivilas Fm: *Fe-Mn fm.* ← *carbonates* ← *phyllite* ← *cherts* ← *Talya-Dodguni polymict conglomerate*	
			Kur Gudda Fm.: *Phyllites with BIF, dolomitic limestone, quartzite interbands, polymict conglomerate*	**Bababudan Supracrustal Group** (Western Ghat belt, northern part of Holenarasipur belt)	Mulaingiri Fm: *BIF interbeded with chlorite and graphitic schist*	2.72 [a]
					Santaveri Fm.: Acid volcanics ← *pyroclast* ← *cross bedded quartzite* ← ***mafic volcanics***	2.85 [a]
			Hegdale Gudda Fm.: ***Ultramafic-mafic complexes with magnetite seams*** *and minor phyllites & quartzite*		Allampura Fm.: ***Metapyroxenite and gabbro*** ← *with interbedded quartzite*	
					Kalasapura Fm.: ***Amygdoiladal basalts*** ← *interbedded with quartzite & phyllite*	2.91 [a]
Peninsular Gneiss Phase II (and older charnockite)	2.9 – 3.2 [a,4]					
Peninsular Gneiss Phase I	3.3-3.4 [2, 3]	**Sargur Group**	Nuggihalli, Krishnarajpet, Holenarasipur, Nagamangala, Javanahalli and Ghattihosahalli belts		**- Ultramafic complex** - *Fe-Mn formation* ← *carbonates* ← *metapelites* ← ***amphibolites – pyribolites.*** *Cr-quartzite with local barite and chromite layers*	> 3.3 – 3.4 [a, 1]

a. Quoted by Radhakrishna and Vaidyanadhan (1997); 1. Jayananda et al. (2008); 2. Dhoundial et al. (1987); 3. Devaraju et al. (2007c); 4. Mojzsis et al. (2003); 5. Hansen et al. (1997); 6. Crawford (1969); 7. Ikramuddin and Stueber (1976); 8. Devaraju et al. (1995); 9. Bhaskar Rao et al. (1992); 10. Devaraju et al. (2002); 11. Balasubrahmanyam (1975); 12. Gopalan and Anil Kumar (1989); 13. Anil Kumar et al. (1988); 14. Widdowson et al. (2000).

the Dharwar craton became a stable block about 1.5 Ga ago.

MAFIC-ULTRAMAFIC MAGMATISM IN THE DHARWAR CRATON

General Observations

The Dharwar craton has witnessed repeated mafic and ultramafic magmatism from pre 3.4 Ga to about 62 Ma. The oldest recognized stratigraphic event was the formation of the Sargur Group, while the youngest was the eruption of the Deccan volcanics during early Tertiary times (see Tables 1-4). Magmatism is represented in the form of lava flows, plutonic intrusions of various sizes, some of which have undergone magmatic differentiation, plugs and hypabyssal dyke/sill-like bodies. No batholithic intrusions of mafic-ultramafic magma comparable in magnitude to the Bushveld Complex or the Great Dyke of southern Africa, are known in the craton. Magmatism has taken places in several cycles, with the time span covered by each cycle and the scale of magmatism of each cycle being variable.

As noted from Table 1, mafic-ultramafic rock formations exist in the WDC in the Sargur Group of the type area (Fig.2a), in the three lower, Kalasapura, Allampur and Santaveri Formations of the Bababudan Group, constituting a large proportion of the Hegdale Gudda Formation occupying the lowermost sections of the Shimoga Group and in the Ingaladhal Formation of the Chitradurga Group.

Mafic-Ultramafic Magmatism of the Sargur Group

Sargur Group rocks occur as slivers, dismembered enclaves and belts varying in size from a few meters to tens and hundreds of meters in strike throughout the largely tonalite-trondhjemite terrain of the southern portion of the WDC. As in other parts of the world, such as South Africa, these very old greenstone remnants have in many instances been intruded by a variety of sodium-rich trondhjemite-tonalite gneisses (TTG•s) which are a widely developed component of the Peninsular Gneisses.

As a consequence of the dismemberment of the Sargur greenstones, it is difficult to reconstruct a definitive stratigraphic section. The belts are however dominated by ultramafic and mafic lithologies mainly of komatiitic affinities with lesser tholeiitic volcanics and subordinate felsic volcanics, fuchsitic quartzites, cherty quartzites, banded iron-formation and barite beds (Jayananda et al. 2008).

Massive and schistose komatiites are the dominant ultramafic-mafic rock types of the Sargur Group and vary from relatively fresh to serpentinized and carbonated varieties. Besides serpentinites, talc-tremolite-actinolite-chlorite schists as well as amphibolites (hornblendites) are characteristic rock types of these greenstones. Pillow structures as well as nodular ocelli structures consisting of spherical nodules, 1-2 cm in diameter are conspicuous in many of the belts. In addition, quench or spinifex textures, a characteristic feature of both peridotitic and basaltic komatiites (Viljoen and Viljoen, 1969a), have been reported from the Ghattihosahalli (Viswanatha et al. 1977) J.C. Pura (Venkata Dasu et al. 1991), the Kibbanahalli limb of the Chitradurga belt in the Bansandra area (Seshadri et al. 1981; Srikantia and Bose, 1985) and the Nuggihalli (Jaffri et al. 1997) greenstone belts. Komatiitic rocks, sometimes without characteristic spinifex or ocelli textures, also occur in the southern limb of the Holenarasipur, Krishnarajpet, Nagamangala and Javanahalli belts (Jayananda et al. 2008).

Dating of detrital zircons from sediments interlayered with Sargur volcanics of the Holenarispur belt have yielded ages of between 3090 – 3580 Ma (Nutman et al. 1992) but the age of the ultramafic and mafic rocks of the Sargur Group have not as yet been accurately established. However, Jayananda et al. (2008) have carried out Sm-Nd isotopic analyses on a number of komatiite samples from the Ghattihosahalli, J.C. Pura, Banasandra, Kalyadi and Nuggihalli greenstone belts. A whole rock isochron age of 3352±119 Ma is interpreted by them as the average age of komatiitic volcanism in the Sargur greenstone belts of the WDC. This age suggests that the Sargur komatiites probably represent the oldest known ultramafic-mafic magmatic event in India. Furthermore, the ages are slightly older or contemporaneous with the age of the oldest TTG•s and felsic volcanics of the Sargur Group of the WDC. These ages as well as the association of komatiitic volcanism with the oldest TTG•s are features characteristic of similar terrains in other parts of the world, notably in the southern portion of the Barberton greenstone belt of South Africa (Viljoen and Viljoen, 1969b).

Major element geochemistry indicates that most of the Sargur samples analysed by Jayananda et al. (2008) are of peridotitic komatiite composition with MgO contents varying between 22.9 to 41.3 wt%. Two samples analysed by them have MgO contents of 11.9% and 17.2% respectively and are thus komatiitic basalts according to the definition of Viljoen and Viljoen (1969).

The komatiitic nature of the Sargur samples is reflected in the Al_2O_3 – Fe_2O_3 and TiO_2 – MgO diagram of Jenson (1976), modified by Viljoen et al. (1982). The same characteristics are demonstrated by the CaO–MgO–Al_2O_3

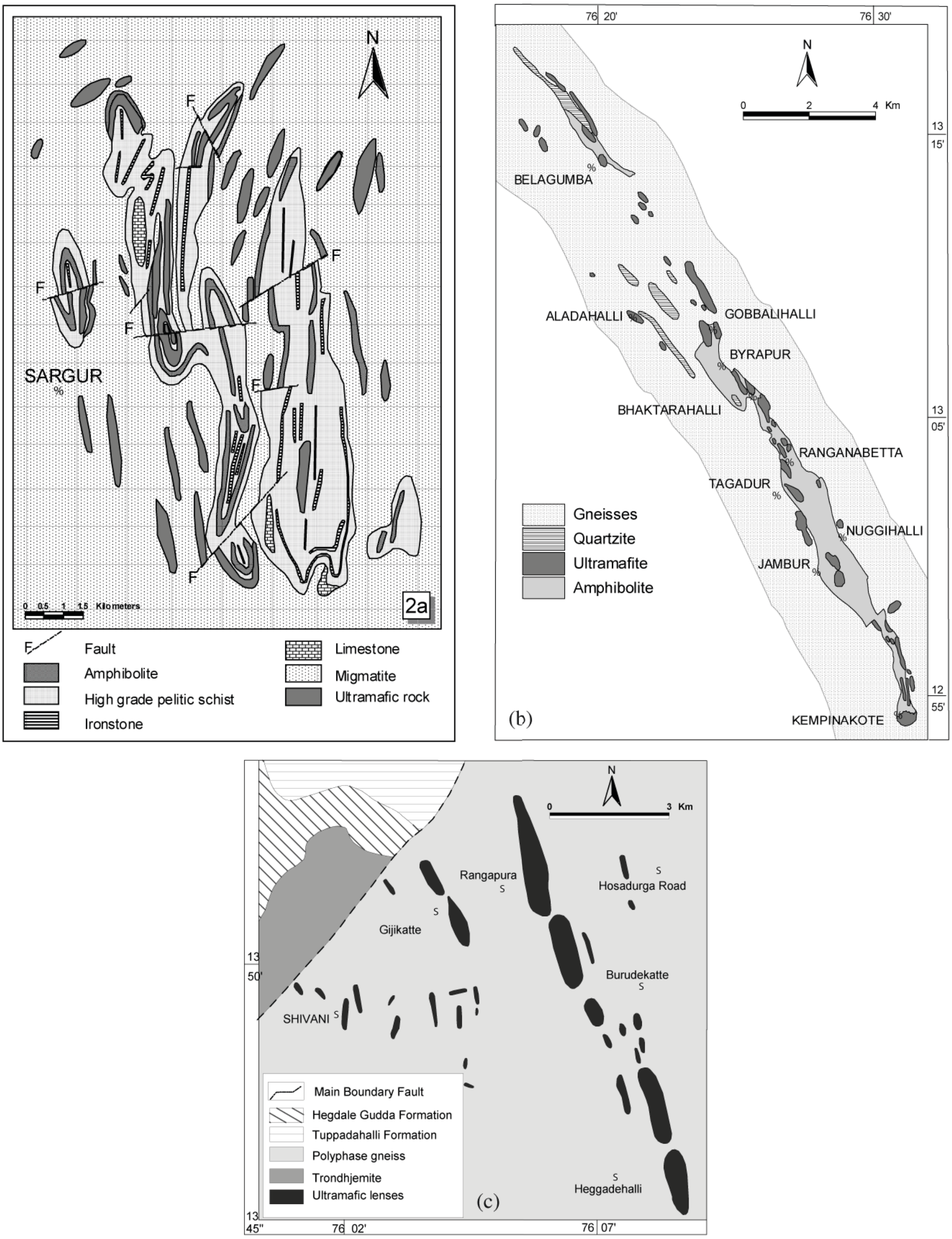


Fig.2. **(a)** Geological map of Sargur Supracrustal Group of the type area (*after* Swami Nath and Ramakrishnan, 1981). Note the typical dismembered occurrence of a large number of ultramafic-mafic bodies and other lithologies **(b)** Geological map of Nuggihalli schist belt showing the more important ultramafic lenses/pods hosting chromite deposits (*after* Jafri et al. 1983) **(c)** Geological map of Shivani-Rangapura-Heggadehalli area showing a linear array of dismembered ultramafic lenses (Sargur equivalents) within the Peninsular gneissic complex constituting southeastern flanks of the Shimoga supracrustal belt (*after* Devaraju et al. 2004a). The ultramafic lenses contain subeconomic pods, mm-cm scale layers of chromitite.

diagram used by Viljoen et al. (1982) to illustrate the unique features of the komatiite chemistry. The Sargur komatiites of the WDC also show characteristics of the aluminium depleted Barberton type komatiites and the aluminium–undepleted Munro Township type komatiites (Jayananda et al. 2008).

A number of investigators (e.g. Srinivasan and Srininvas, 1972; Naqvi et al. 1978; Jayananda et al. 2008) have described the extrusive nature of komatiites. It is evident that, as in similar settings elsewhere in ancient cratonic areas, komatiitic magmas have frequently been emplaced as concordant or semi-concordant bodies into the developing pile of flows with subordinate sediments. In many instances these intrusive komatiitic magmas have undergone magmatic segregation giving rise to a number of differentiation products including dunites, harzburgites, ortho- and clino-pyroxenite, gabbros and anorthosites. Chromitite and chromiferous magnetite as well as vanadium and titanium bearing magnetites are also characteristic of some of the layered bodies of the Sargur Group.

Widespread ultramafic and mafic magmatism of the Sargur type has been interpreted in other parts of the world as an event which built up the very early earth crust. The komatiitic magmas were probably emplaced along suture zones or spreading centres where they built up linear belts. At a somewhat younger stage in crustal development, parts of the ultramafic-mafic crust were subducted resulting in partial melting and the production of more evolved basaltic to felsic volcanics. Large quantities of partial melt did not reach the surface but intruded the earlier komatiitic crust and formed a number of sodium-rich tonalitic, trondhjemitic and at times granodioritic batholiths. The komatiitic greenstones sank into and formed cusps between rising granitic plutons, becoming extensively folded and deformed. Greenstone fragments of all sizes were torn off by the granitic intrusions, heated and plastically transformed in places into complex mixed rocks or migmatites. These inclusions and xenoliths (dismembered Sargur Group) are to be seen in many parts of the Peninsular gneiss.

Mafic-Ultramafic Rocks of the Eastern and Western Dharwar Craton

In the EDC, as noted from the information compiled in Table 2, the •Sakarsanite Association• is correlated with the Sargur Group of the WDC, with subordinate mafic-ultramafic rocks occurring in the upper columns of the sequence. The •Kolar Group• of the EDC is correlated with the Bababudan Group of the WDC and contains mafic-ultramafic rock formations at three different stratigraphic levels, one in the lower Kalhalli Formation, the second in the overlying Yerra Konda Formation (here the metabasalt, metapyroxenite and metagabbro sheets are associated with BIF and carbonaceous-argillaceous schists) and the third at the top of the•Gold Field volcanics• division (Fig.4a).

The Hutti-Maski belt, the only major gold producing belt at present, is comprised mainly of metabasic volcanic rocks with felsic volcanics and fine clastic-chemical sediments occurring in subordinate proportions. The thick pile of metabasalts which host gold mineralization are classified from the base to the top as the Hussainpur Formation (almost entirely comprised of varieties of amphibolite), the 530 Hill Formation (largely pillowed metabasalt with lensoid amphibolite), the Bullapur Formation (predominantly amphibolites with some sediments) and the Buddinne Formation consisting of massive, vesicular, pillowed and coarse grained metabasalts with local fine clastic and chemical sediments (Fig.4b).

With regard to the other greenstone belts of the EDC, the Nellore belt (Fig. 1) is located along eastern margin of the EDC. It occupies the middle transition zone (MTZ), which separates the eastern portion of the EDC from the Eastern Ghat mobile belt (Ramam, 1997). Based on the evidence of high-grade metamorphism, dominance of mafic lithologies, occurrence of anorthosite with pelitic sediments containing barite, this belt is correlated with the Sargur Group of the WDC. Metabasic rocks occur in the lower and upper portions of the stratigraphic sequence in the other greenstone belts of the EDC. These include the Veligallu, Jadcherla, Gadwal and Kadiri belts. In these belts too metabasic volcanics occur in the basal portions of the stratigraphic sequence, and the upper stratigraphic sections typically include an association of felsic volcanics, fine clastics and chemical sediments.

The Chitradurga, Shimoga, Bababudan and Western Ghat belts of the WDC have been called the •Dharwar type schist belts• by Shackleton (1976) and Goodwin (1977), by virtue of their geological setting and evolution, while the Bababudan Group (Fig.3a) is comparable to •*early Proterozoic belts*•. According to Ramakrishnan (1981) the supracrustal groups of the Shimoga (Fig.3a) and Chitradurga belts (Fig.3b) resemble the so called •*geosynclines*• of the ancient shield areas of Canada, Africa and Australia. The greenstone belts of the EDC are comparable to classical early greenstone belts of the world with some important differences. Large volumes of ultramafic flows and intrusives do not occur at the base of these belts as in the case of the Barberton greenstone belt of South Africa. Late Archaean-early Proterozoic K-granite without co-genetic mafic rocks are particularly common in the eastern block. However, batholithic suites showing calc-alkaline trends from gabbro

Table 2. Stratigraphic succession in the eastern Dharwar craton

Formation	Main Divisions			Age (in Ga)
Kurnool – Bhima Group				0.98 – 0.55 [a]
Kimberlite-lamproite dyke				0.84 – 1.4 [j - m]
Younger Mafic dykes				1.1 - 1.7 [e, g - i]
Cuddapah Group				1.6 – 1.8 [j, l]
Vempalle lava				1.75 - 1.8 [I, k]
Older mafic dykes				1.8 - 2.45 [d-h]
Granitic plutons of Hyderabad, Perur, Tirumala, Lepakshi, Kadiri, Gangam complex, Chenna gneiss				2.52 – 2.6 [a, d-j]
	[Classification of amphibolites/ metabasites of Au-mineralized Kolar and Hutti Groups]		*Other belts (generalized)*	
Greenstone belts of Veligallu, Kadiri, Pedavuru, Gadwal, Jonnagiri, Raichur, Hutti-Maski, Kushtagi-Hunugund, Penkacharla, Ramagiri, Kolar	*Kolar*	*Hutti*	BIF	2.7 – 2.75 [b-d]
	Gold Field Amph	Buddinne Fm.	Carbonates	
	Champion Gneiss	Bullapur Fm.	Pelitic-siliceuos sediments & felsic volc.	
	Yerrakonda Fm.	530 Hill Fm.		
	Kallahalli Fm.	Hussainpur Fm.	Metabasites (largely metabasic volcanics)	
Basement Gneisses (TTG) banded gneiss of Kolar				~ 3.2 [a] (?)
Enclaves in TTG (Sargur equivalents)				> 3.2 [a] (?)

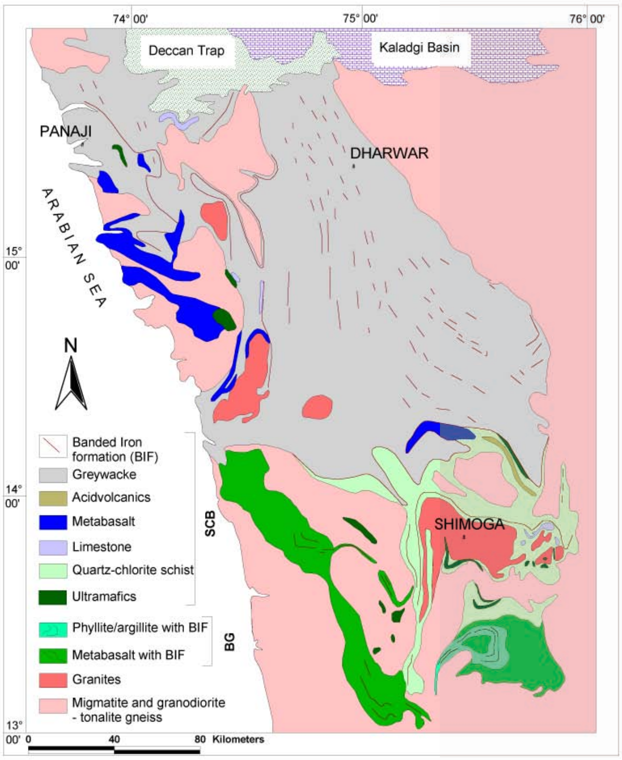
b-d are the ages obtained for Kolar and Ramagiri amphibolites

a. Quoted by Ramam and Murthy (1997); b. Krogstad et al. (1989); c. Zachariah et al. (1995); d. Balakrishnan et al. (1999); e. French et al. (2004); f. Halls et al. (2007); g. Murthy et al. (1987); h. Murthy and Sarma (1992); i. Mallikarjuna Rao et al. (1995); j. Amitab Sarkar and Mallik (1995); k. Bhaskar Rao et al. (1995); l. Crawford and Compston (1973); m. Paul et al. (1975)

to granite are virtually missing from the Dharwar craton as a whole.

Bhaskar Rao and Naqvi (1978) have shown that the Bababudan volcanics are, in places, nepheline normative and spilitic in character. They have attributed this to soda metasomatism. They are also of the opinion that the Chitradurga volcanics evolved synchronously under differing tectonic environments. The Chitradurga volcanics are interpreted as fractionated tholeiite-andesite-spilite of calc-alkaline affinity, indicating a submarine geo-synclinal environment similar to that of island arcs (Naqvi and Hussain, 1973) or oceanic ridges (Yellur and Nair, 1978). Recent geochemical studies carried out on metabasic volcanics in the Goa and Dharwar sector of the Shimoga belt (Devaraju, 2003) has revealed that these volcanics range in chemistry from picro-basalt to andesite, subalkaline, show an overall tholeiite trend, and compare with extension related island arc tholeiites in terms of many different chemical parameters. The Dharwar volcanics on the whole are more evolved as compared to the mafic rocks of the Sargur Group (Naqvi et al. 1978) being mainly tholeiitic as compared to the preponderance of komatiites in the Sargur Group. The greenstone belts of the EDC are essentially volcanic belts with voluminous basaltic flows and subordinate fine clastic and chemical sediments. Geochemical studies carried out on metabasalts of the Hutti-Maski belt have indicated that they are tholeiitic with significant iron enrichment. In addition, as compared to mafic volcanics of the Chitradurga-Shimoga Group, these have higher Rb:Sr, Ba:Sr and lower K:Ba and K:Rb with some LREE enrichment patterns and are similar to basalts erupted in basin margin environments (Anantha Iyer et al. 1980). The Kolar amphibolites, which are also closely comparable to the Hutti-Maski metabasalts, are predominantly tholeiitic. They contain minor inter-bands of komatiitic basalts derived from a mantle source with a much greater Mg:Fe ratio than the dominant tholeiitic basalts (Balakrishnan et al. 1988; Subramanyam et al. 1991).

Available isotopic data suggests that the ages of the mafic rocks of the supracrustal groups of the WDC and greenstone belts of EDC are closely similar, ranging mainly between 2.9 and 2.7 Ga. Near identical isotopic ages 2.65-



in the Bababudan Basin and the localization of the mafic-ultramafic complexes along the southern and western border areas of the Shimoga Basin (from 1981 map of GSI).

2.75 Ga obtained for the Ingaladhal metabasalts of the Chitradurga Group in the WDC and the Sandur, Kolar and Ramagiri belts of the EDC, reflect, as suggested by some workers (e.g. Ramakrishnan, 1981), synchronous and coeval development of the groups but, in different tectonic regimes. As in the case of post-Archaean mafic dyke magmatism, which took place over a protracted period from 2.4 to 1.4 Ga, late Archaean mafic magmatism also appears to have occurred over a protracted period of time from 2.9 to 2.5 Ga. Magmatism took place in several pulses, resulting in the development of mafic-ultramafic complexes/formations at different stratigraphic levels from the basal sequences of the Bababudan Group to the upper portions of the Chitradurga Group.

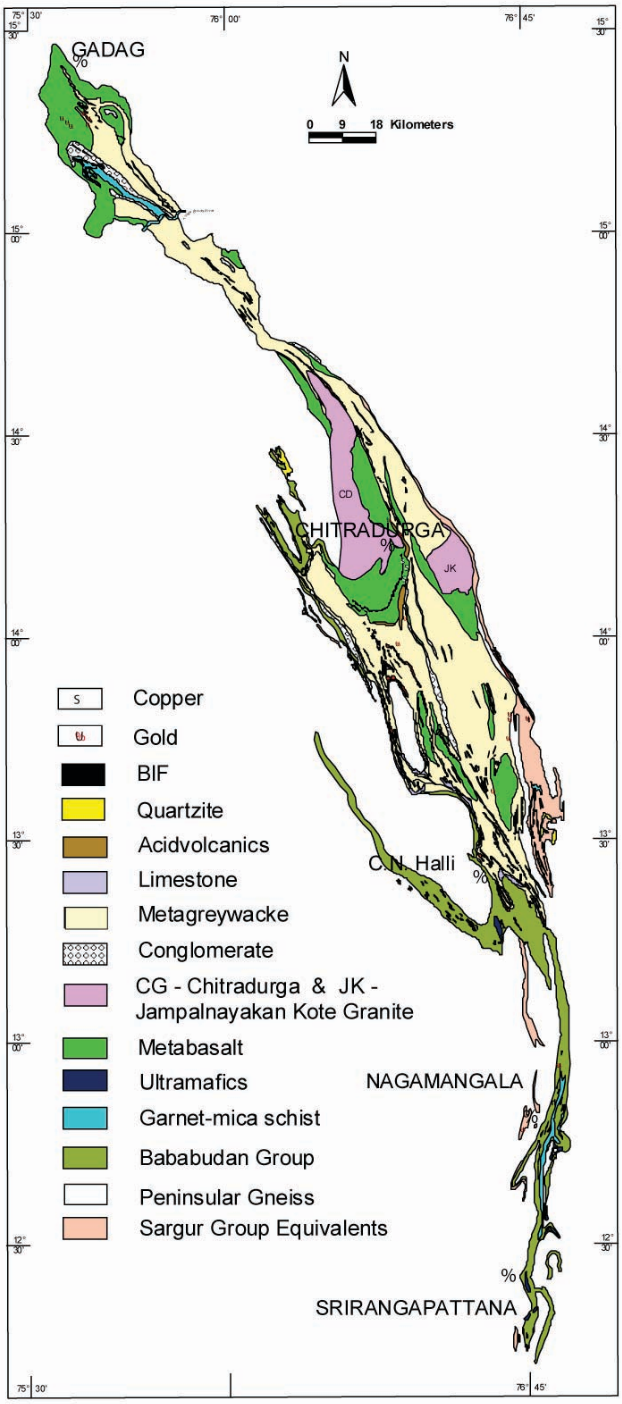
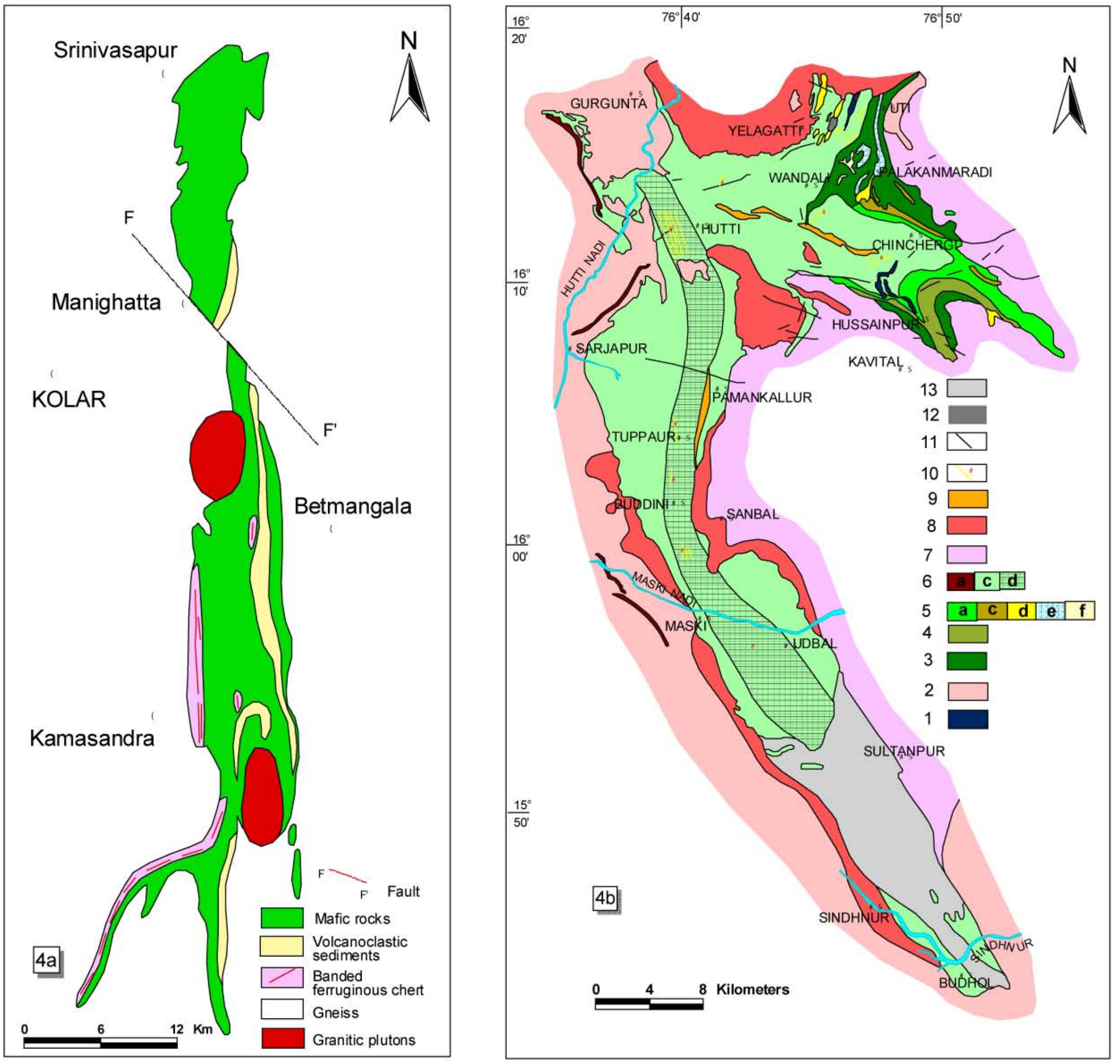


Fig.3b. Geological map of Chitradurga belt showing distribution of the more important mafic-ultramafic rock occurrences. The map also includes the Kibbanahalli arm and the adjoining Nagamangala, Javanahalli and Ghattihosahalli belts which are greatly dominated by mafic-ultramafic complexes (adapted from 1981 map of GSI).

Mafic Dyke Magmatism

The stabilized rigid crust of the Dharwar craton became brittle and fractured resulting in episodic emplacement of mafic dykes over a protracted period from 2.4 Ga to about 1.0 Ga (Tables 1 and 2). Mafic dyke intrusions occur throughout the Dharwar craton where they intrude all the granites-gneisses and supracrustal belts older than about 2.5 Ga. Their frequency, however, varies greatly. The most spectacular development of mafic dykes occurs on the

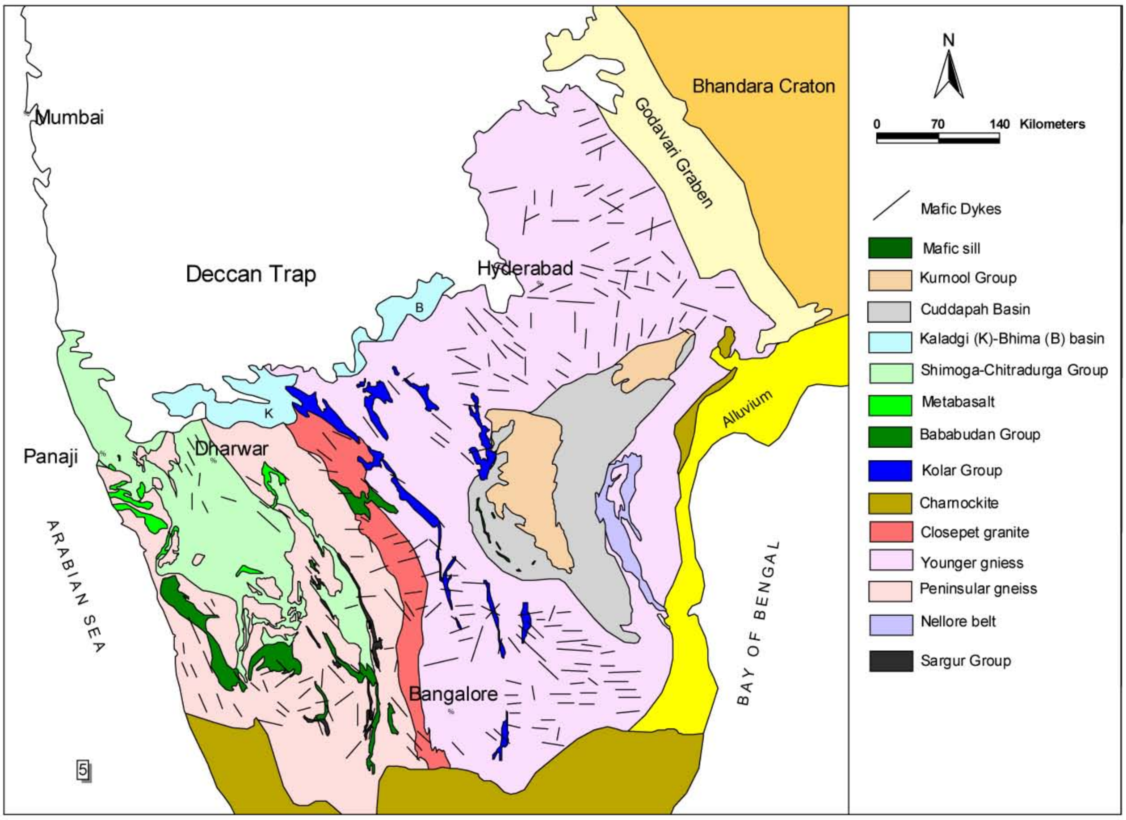


main gold-quartz reefs**. (b)** Geological map of Hutti-Maski schist belt, Eastern Dharwar Craton (adapted from compilation of S.V.Srikantia (GSI); *In:* Curtis and Radhakrishna, 1995). **1.** Metaultramafites (Sargur equivalents), **2.** Peninsular Gneissic Complex, **3.** Hussainpur Fm., **4.** 530 Hill Fm., **5.** Bullapur Fm., **6.** Buddinne Fm. (Formations 3 to 6 constitute the Hutti Group), **7.** Kavital Granitoid, **8.** Yelgatti Granitoid, **9.** Chinchergi Granophyre, **10-G.** Quartz-gold-sulphide lodes, **11.** Basic dykes, **12.** Basalt, **13.** Black soil (Deccan?).

western and southwestern portions of the Cuddapah Basin where an ENE trending swarm is very prominent (Fig.5). The emplacement of these dykes and the formation of the Cuddapah Basin seem to be closely related. Somewhat less abundant and more widely spaced are the mafic dykes of the central portion of the southern Dharwar craton. It is probable that the dense swarms have formed in areas of distended crust due to mantle plume activity around hot spots. The consistent linearity of the dykes in one or two directions suggests emplacement at deeper crustal levels. Dykes trend in all directions but, E-W trends are the most common (Fig.5).

The main types of mafic dykes are dolerite, quartz-dolerite, olivine-dolerite and epidiorite with local gabbroic, pyroxenitic, lherzolitic and anorthositic dykes. They are generally fresh and show chilled margins. Pyroxenite granulite dykes are known to occur in Coorg, South Bangalore and in the southern granulite terrain. Some of the deformed, boudined and narrow elongated mafic lenses in the older gneissic complex possibly represent the oldest mafic dykes.

Most mafic dykes carry signatures of tholeiitic and sub-alkaline magmas of both continental and oceanic affinity. The bulk of the unmetamorphosed basic dykes of the



(updated from Murthy, 1987).

Dharwar craton are probably of Palaeo-Meso-Proterozoic age.

Kimberlite-Lamproite Potassic Ultramafic Magmatism

The East Dharwar Craton (EDC) with its vast granite-greenstone terrain and an ancient history of cratonization (~2.0 Ga), low surface heat flow regime and deep seated faults, offers an ideal geological milieu for kimberlite and lamproite emplacement, the two primary source rocks of diamond.

The eastern Dharwar craton was a locus of anorogenic igneous activity during the middle to upper Proterozoic period. It resulted in the emplacement of a number of smaller plutons of anorthositic rocks in the Eastern Ghats mobile belt, granite to syenite intrusions close to the eastern margin of the Cuddapah Basin and kimberlite diatremes and related lamproite dykes in three main clusters. The first of these occur in the Anantapur-Kurnool-Gulbarga-Raichur district, the second in the Mahboobnagar district and the third in the eastern Nallamalai portion of the Cuddapah Basin (Fig.6a). Kimberlites-lamproites of the craton are dated at between 840 to 1205 Ma (Table 2), which is essentially the time span during which the kimberlites in Madhya Pradesh-Chhatisgarh were also emplaced. To date, over 50 kimberlite and 30 lamproite intrusions have been found in the EDC, but, vast stretches of craton still remain unexplored for kimberlites-lamproites.

MINERALIZATION IN MAFIC-ULTRAMAFIC ROCKS OF THE DHARWAR CRATON

Western Dharwar Craton

Mafic-ultramafic rocks, whether of the Sargur Group, the Supracrustal Dharwar groups or the Kolar type greenstone belts, are hosts to a wide variety of minerals and ore deposits. These are discussed below.

Sargur Group

a. Syngenetic Mineralization**:** Chromite and V-Ti-magnetite in the form of bands/layers and lenses constitute the most important type of syngenetic mineralization associated with the ultramafic-mafic complexes of the Sargur Group of the WDC. Economically viable **chromite** deposits are known in the Sinduvalli-Talur belt (Mysore district) and the Nuggihalli belt (Hassan district) (Fig.2b), while sub-

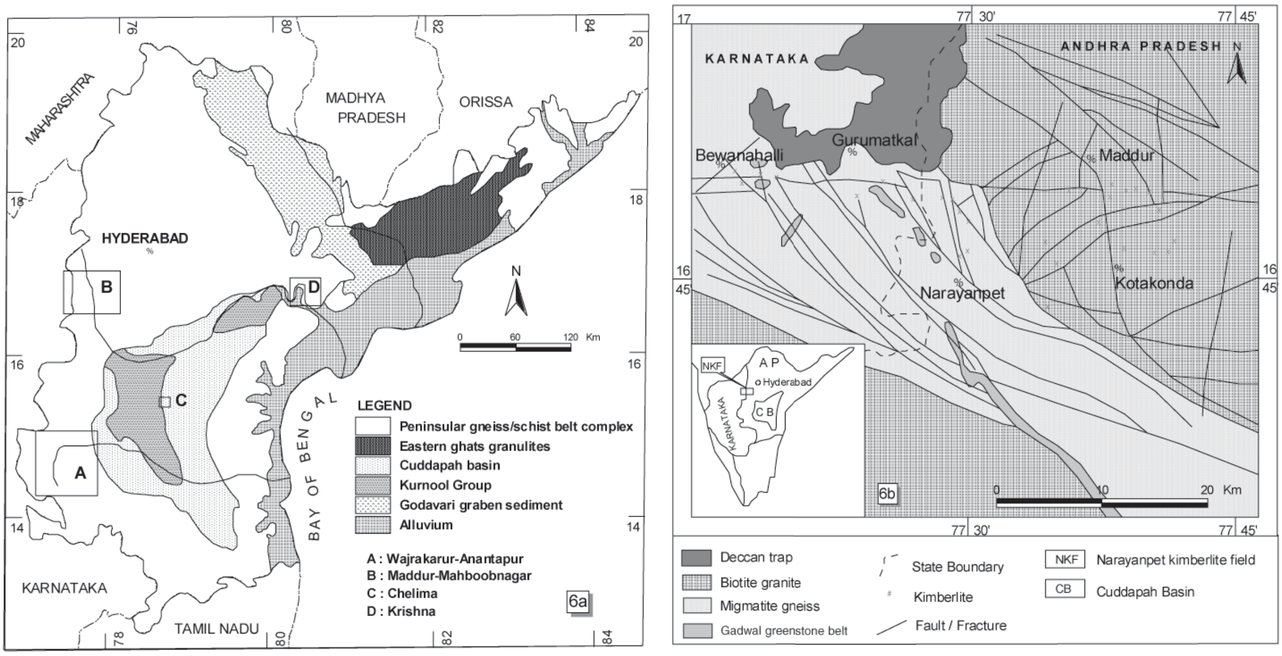


Fig.6. **(a)** Kimberlite and lamproite areas of the Eastern Dharwar Craton (*after* Babu, 1998). **(b)** Generalized geological map showing Maddur-Kotakonda, Narayanpet-Bevanahalli kimberlite clusters with reference to the prominent lineaments of the area (*after* Rao, 1998).

economic deposits exist in the Usgao complex in Goa, southern part of the Holenarasipur belt (Hassan district) and in several of the ultramafic enclaves around the Shivani-Rangapura-Heggadehalli sector (Fig.2c) (Chickmagalur-Chitradurga districts). The exploitable deposits of the former two belts are of medium to low-grade; with metallurgical grade material being very limited. Mining of chromite has been carried out at Byrapur, Jambur, Tagadur, Ranganbetta, Bhaktarahalli, Gobbalihalli, Aladahalli, Pensamudra and Sunkadahalli in the Nuggihalli schist belt. (see Fig.2b for the locations mentioned) and in the Sinduvalli, Talur and Marshettihalli, Solepur, Chickkatur and Dodkatur areas in the Sinduvalli-Talur belt. After economic liberalization and the removal of restrictions on imports, however, only the Byrapur, Jambur and Tagadur deposits have continued to be exploited. The Nuggihalli belt has an estimated chromite resource of more than 2.7 million tonnes (Radhakrishna, 1996), while the richest concentrations of 0.8 and 0.7 million tonnes (Cr:Fe ratios ~1.9) of proved resource occur in the Byrapur and Tagadur sector of the belt respectively. Chromite occurs as lenses and pods, nodular to mottled patches, veins and as non-persistent millimeter to centimeter scale layers. Chromite typically occurs in ultramafics (viz., dunite-peridotite-lherzolite-websterite) which are partially to fully serpentinized. Thicker, more persistent layers are rare and most bands and lenses are probably dismembered units of such layers. There are no large, chromite-bearing mafic-ultramafic complexes comparable to the Bushveld of South Africa or the Great Dyke of Zimbabwe or even in Orissa in the Dharwar craton (De Young et al. 1984; Stowe, 1987; Chakraborthy, 1965; Suryanshu Choudhury, 2006).

The mode of occurrence of chromite suggests its formation as early magmatic segregations. Isolated pods and lenses are perhaps the consequence of segregation around centers/or nuclei of crystallization and the elongation reflects lateral flow orientation parallel to the length of the intrusion.

V-Ti magnetite is the most common form of mineralization associated with the mafic-ultramafic complexes that host the chromite lenses. V-Ti magnetite has been recorded almost throughout the length of the Nuggihalli belt. It is, however, rare or abasent in the Holenarasipur belt, and in the Shivani-Rangapura-Heggdehalli sector (Chickmagalur -Chitradurga districts). Near Kurihundi, Duggahalli and Dadadahalli (Mysore district) and Annechakanahalli, Kommonahalli, Bellibetta and Teginahalli in the K.R. Pura belt (Mandya district) V-Ti magnetite lenses occur exclusively without a chromitite association.

The V-Ti magnetites occur as seams/ lenses and as narrow bands, typically located within the pyroxenite-gabbro-anorthosite portions of the mafic-ultramafic complexes. In the Nuggihalli belt, bands and lenses are found in the Belagumba, Byrapur, Chikkonhalli, Gobbalihalli, Tagadur and Jambur blocks. Preliminary investigation of the deposit occurring in the Tagadur block has indicated that it constitutes a resource of 8 million tonnes to a depth of 30 m, with an average of 10% TiO_2 and 61% Fe (Radhakrishna, 1996). The V_2O_5 content of the Nuggihalli titaniferrous magnetite ore is in the range of 0.4 to 0.8%.

Ti-magnetite layers and lenses are, like the chromite layers and lenses, also syngenetic in origin having formed as magmatic segregations during the later stage of differentiation in which gabbro and anorthosite began to crystallize.

PGE mineralization: Studies are presently being undertaken to locate PGE mineralization in the mafic-ultramafic complexes of the Sargur Group. Preliminary whole rock and mineralogical data obtained from the complexes of the Nuggihalli belt (Devaraju et al. 2007a), Shivani-Rangapura-Heggadehalli sector (Devaraju et al. 2004a) and the southern portion of the Holenarasipur belt (studies in progress) have not as yet indicated the presence of economic levels of PGE mineralization.

Epigenetic mineralization: Old workings for **gold** in the mafic-ultramafic rocks of the Sargur Group are located at Kempinakote (Hassan district), and at Wolagere, Amble, Hunjunkere, Butagahalli and Kollegal Taluk (Mysore district). In all these instances gold occurs in vein quartz associated with shear related fractures and alteration zones. The occurrences appear to be related to hydrothermal remobilization of gold present in the host ultramafic-mafic rocks of the Sargur Group. Occurrences of copper in ultramafic-mafic rocks of the Sargur Group are known at Kalyadi (Hassan district) and at Sovanahalli (Kanakanahundi complex, Mysore district) where old workings are present. In addition, the association of Cu with V-Ti magnetite seams of the Masanikere area (Davangere district) (Ramiengar et al. 1978) and in the Nuggihalli schist belt at Tagadur and Aladahalli (Vasudev et al. 1994) has been reported. At Kalyadi, where mining was in progress until the early nineties, copper mineralization in the form of disseminations and stringers is localized in quartz-carbonate veins that traverse talc chlorite-biotite-actinolite schist and wall rock alteration zones adjoining such veins. As in the case of gold, copper mineralization is also thought to be related to hydrothermally triggered remobilization of the metal from the host mafic-ultramafic rock. Cobalt in recoverable concentrations and the localization of quartz-carbonate veins carrying copper mineralization in mafic-ultramafic rocks, strengthen such an interpretation.

***Autometamorphism related mineralization*:** Chrysotile and amphibole asbestos and soapstone related to autometamorphic and metasomatic alteration of Mg-rich ultramafic rocks of the Sargur Group occur in the Hassan and Mysore districts. Small scale intermittent mining of asbestos has been carried out for more than four decades in the southern part of the Holenarasipur belt, particularly in the Yenneholerangana betta, Yedegondanahalli and Doddakadnur blocks and at Gopalpura and Mavinahalli in the Mysore district. The deposits occur as conformable stringers, laminations, lenses and patches replacing and pseudomorphing serpentinized dunite/ or peridotite and as well as tremolitic ultramafites. A number of soapstone occurrences have been reported, especially from Hassan district. This rock was quarried extensively to provide building stones for the famous temples of Halebidu, Belur and many others. Small quantities of soapstone are also produced from Konehalli, Bilenhalli and Jadgatta in the Hassan district, and from Kadehalli, Honnenhalli and Birasandra in the Tumkur district (Radhakrishna, 1996).

Contact metamorphic related mineralization: Gem varieties of corundum (ruby, sapphire) occur at the contacts of ultramafic rocks with the Peninsular gneiss. They are interpreted as a product of contact metamorphism, and have been exploited at Itna in the Sargur type locality and at several locations in the Nuggihalli belt.

***Low temperature hydrothermal and lateritic alteration related mineralization*:** Occurrences of magnesite in commercially recoverable concentrations associated with the weathered upper crust of Mg-rich ultramafics occur in the Mysore district (part of the type area of the Sargur Group) at Dodkanya, Hulhalli, Karya, Kakkeri and Hanagodu and the Holenarasipur belt at Doddakadanur, Hosur, Yedegondanahalli, Bantaratalalu and Yenneholerangana betta. The magnesite occurs as a network of veins, lenses and concordant fracture filings in the weathered zones (mostly limited to the upper 30 m layer) of Mg-rich dunites, harzburgites and peridotites. Magnesite formation is the result of the breakdown of serpentinized ultramafic rock by hydrothermal and/or meteoric carbonate solutions with concomitant release of silica which occurs alongside the magnesite as opal/chalcedony. A resource of 12.6 million tonnes of mineable magnesite has been reported from the Dodkanya deposit.

Bababudan Group

Asbestos mineralization is present in the metabasic rocks of the Bababudan Group. It occurs as one to two centimeter wide cross fibres in the metabasites lying at the base of thick sequence of BIF constituting the Muliangiri Formation. The asbestos mineralization is intermittently developed over a strike length of 5 km. Prospecting carried out by the State Department of Mines & Geology has indicated that the

Table 3. Stratigraphy of mafic magmatism related mineralization in the western Dharwar craton

Stratigraphic Groups	Stratigraphic sub-divisions of the main group	Age (Ga)	Ore level mineralization	Host rock	Genesis	Locality
Chitradurga Group	Ranibennur Fm. Hiriyur Fm. Channeshpur = Tuppadahalli Fm. **Ingaladhal Fm.** Channagiri Fm. Vanivilas Fm. Devara Gudda Fm. Mundre Fm. Kur Gudda Fm.	2.65-2.7	Au, Cu	Metabasalts	Hydrothermal remobilization & augmentation	***Au****:* Gadag- central & western reefs; *central*: Nabhapur, Kabulayakatti-Attikatti, Mysore-Sangli; *western:* Hosur-Shirunj, Yellisipur-Venkatapur ***Cu****:* Ingaladhal, Kunchiganhal, Gonur, Chicknayakanahalli, Kurumaradihalli
			Pyrite	Metabasalt	Hydrothermal fluids related to metabasalts	***Pyrite*****:** Ingaladhal
Shimoga Group	Mulaingiri Fm. Santaveri Fm. **Hegdale Gudda Fm.**	2.72 2.8	PGE	Fine-grained chromite-chlorite rock (metadunite)	Early magmatic	Hanumalapur (Davanagere dist.)
Bababudan Group	Allampur Fm. Kalasapura Fm.	2.9	Ni-Au-PGE	Sulphidic meta-dunite	Early magmatic sulphide segregation	Shankaraghatta (Shimoga dist.)
			V-Ti Magnetite	Metapyroxenite/ gabbro	Magmatic segregation/injection	Shimoga & Ulttara Kannada dists.
Sargur Group		>3.3-3.4	Chromite	Serpentinite-dunite-peridotite	Early magmatic segregation	Nuggihalli & Sindhuvalli-Talur belts
			V-Ti magnetite	Pyroxenite-metagabbro	(Late) Magmatic segregation/injection	„ „ do „ „ K.R. Pura belt and at Kurihundi-Duggahalli (Mysore dist.)
	Ultramafic-mafic intrusive complexes with anorthositic variations Amphibolite interbedded with met-pelites, carbonates & Fe-Mn formation Cr-quartzite with local interbands of barite & chromite		Au	Contact of ultramafite and lamprophyre	Syngenetic/ Hydrotheramal (?)	Kempinakote
			Cu	Altered ultramafic-mafic rock	Hydrothermal remobilization	Kalyadi
			Asbestos/ steatite	Mg-rich ultramafic rocks	Autometamorphism/ metasomatism	Southern part of Holenarasipur & Nuggihalli belts & near Gopalpura and Mavinahalli (Mysore dist.)
			Ruby, sapphire	Contact of ultramafics & Peninsular gneiss	Contact meta-morphism	Sargur type area & at several locations in Nuggihalli belt
			Magnesite	Weathered-altered ultramafic rocks	Low-temperature hydrothermal-lateritic alteration	Southern part of Holenarasipur belt and around Dodkanya, Hullhalli & Karya (Mysore dist.)

deposits are not economically workable (Radhakrishna and Venkob Rao, 1967).

Shimoga Supracrustal Group

Mineralization of commercial significance occurs in the mafic-ultramafic formations of the Shimoga Group and include PGE, gold, Ni, V-Ti-magnetite, chromite and copper. An association Ni-Au-PGE mineralization has recently been recorded by Devaraju et al. (2004b) in the ultramafic lens that underlies the Kuvempu University campus (Shankaraghatta), Shimoga district. The lens, which has been folded, is almost 12 km long and about 0.3 km thick. To the south and north of this occurrence are two other conformable ultramafic lenses which have greater strike lengths and are thicker than the Shankaraghatta lens. They are folded together with quartz-chlorite schist and metabasalt (Fig.7a) and are thought to occupy the same stratigraphic level as the mafic-ultramafic complex of Channagiri which constitutes the Hegdale Gudda Formation comprising the lower stratigraphic levels of the Shimoga supracrustal belt (Devaraju et al. 2007b). Sulphide mineralization occurs over a 3-5 m wide zone within the meta-ultramafite of Shankaraghatta (Fig.7b). Quantitative mineralogical as well as whole rock geochemical studies of this mineralization have been carried out by Devaraju et al. (2004b) whose work shows that the ultramafite is nearly massive or weakly foliated, with no layering or magnetite/chromite lenses having been noted. The mineralized ultramafite, a metadunite, contains about 94% serpentine (antigorite), 3% sulphide (up to 8%), 1% magnesite, and 0.5% Fe-Cr oxide (Fig.9a), *Millerite* and *pentlandite* are the main carriers of Ni. Gold varies in composition from nearly 100% *native*

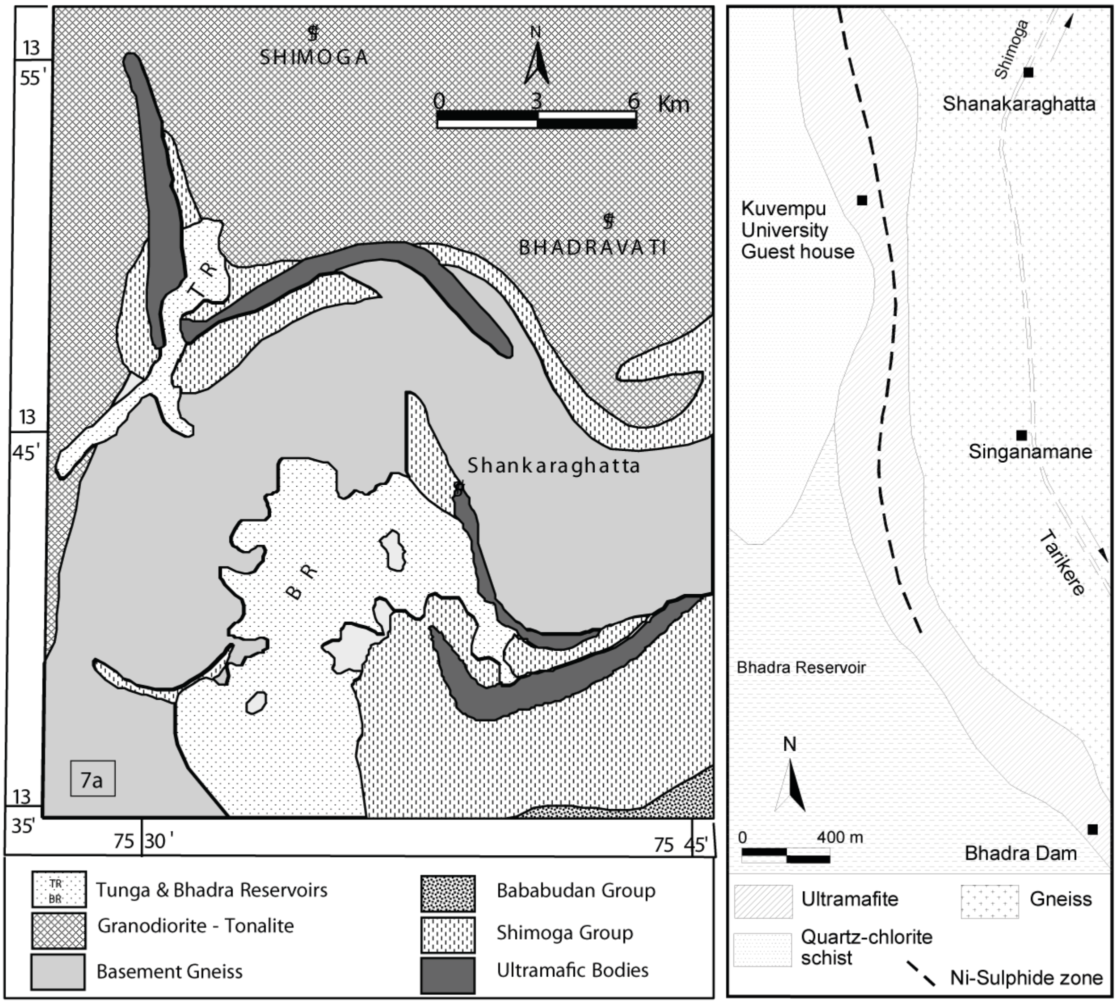
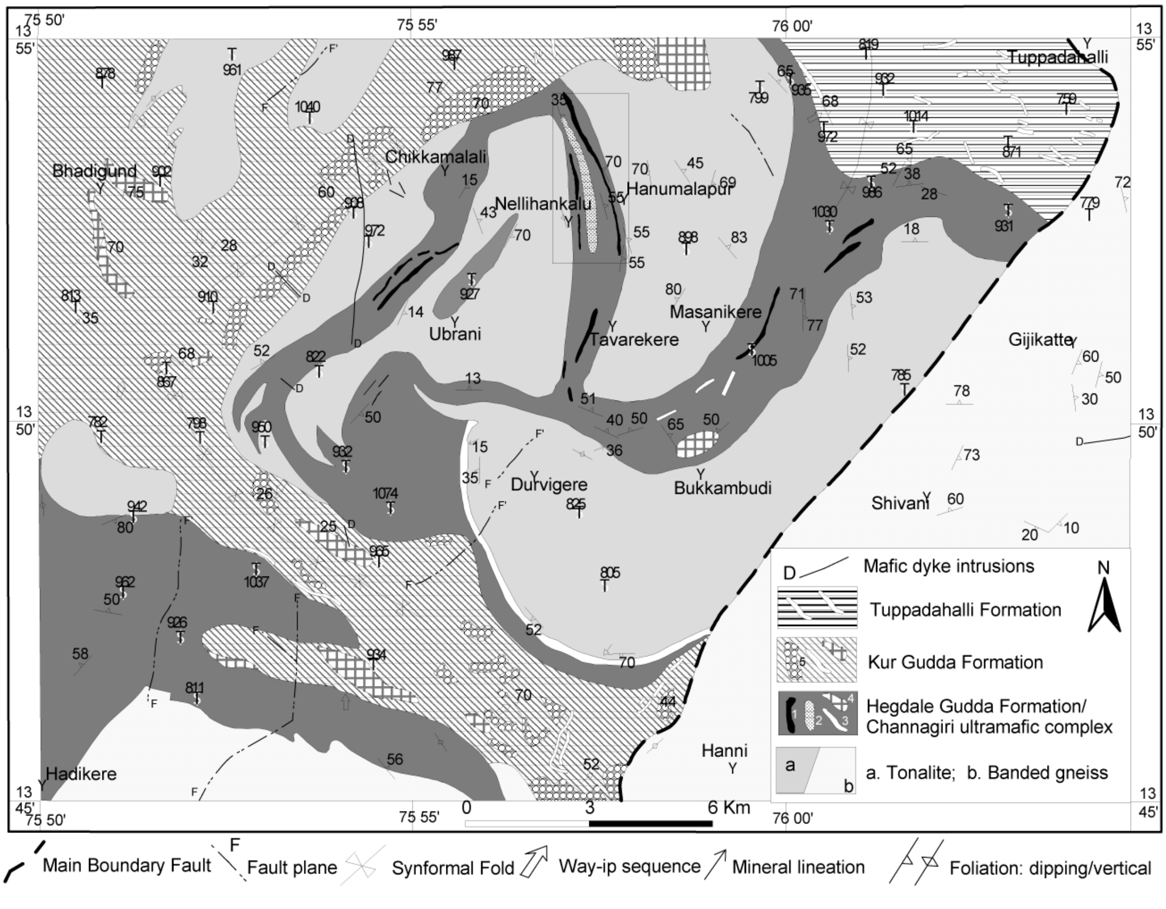


Fig.7. (**a**) Geological map of Shankaraghatta and adjoining areas showing the three prominent folded ultramafic lenses (adapted from Geological Survey of India Geological & Mineral Map of Karnataka & Goa, 1981). (**b**) Sketch map of northern part of Shankaraghatta ultramafic lens showing the centrally located sulphide zone comprising Ni-Au-PGE mineralization.

gold to *electrum* with 22.7% Ag (Fig.9b). *Melonite* greatly dominates *michenerite, mernskyite* and *Pd-Ti-Bi-Sb alloys* among the Pd minerals identified. Pt is present both as *sperrylite* and *irarsite*. Au as well as Pd-Pt minerals occur as 1 to 10 micron sized inclusions enclosed in sulphides (50%), silicates (10%) and along the contacts between sulphides and silicates (40%).

Ni-Au-PGE mineralization is stratabound and concentration of the metals in sulphide melt by liquid immiscibility is suggested. Whole rock analysis of a representative sample of mineralized metadunite has yielded values of 1.59% Ni, 2.7 ppm Au, 0.81 ppm Pd and 0.22 ppm Pt. Despite the potentially economic concentrations of Ni, Au, and PGE, further investigations have not been carried out because of its unfavorable location in the vicinity of the Bhadra dam, Kuvempu University campus, forest cover and several villages. The occurrence could however serve as an important guide to the location of similar sulphide-bearing ultramafic rock hosting Ni-Au-PGE mineralization.

An association of PGE, chromite and V-Ti-magnetite mineralization has been recorded in the mafic-ultramafic complex located about 15 km south of Channagiri and within the southeastern boundary limits of the Shimoga supracrustal belt (Devaraju et al. 1994) This complex has also been studied in detail to understand fully the petrology and mineralization pattern (Devaraju et al. 2005a, 2007b; Alapieti et al. 2008). The Channagiri mafic-ultramafic complex forms the main litho unit of the lowermost section of the Shimoga supracrustal sequence in the southeastern part of Shimoga belt which is classified by Chadwick et al. (1988) as Hegdale Gudda Formation. The complex is made up of several tectonically separated blocks extending over a strike length of about 40 km in a NE-SW directions (Fig.8a). While a large part of the complex is surrounded by tonalite, in the N-NE and S-SW, it lies in juxtaposition to the Tuppadahalli and Kur Gudda Formations respectively (Chadwick et al. 1988). Detailed 1:2000 scale mapping and lithogeochemical studies of the PGE mineralized Hanumalapur segment (Figs. 8a, 8b and 9c) of the



Formation of Shimoga sSupracrustal belt (*after* Devaraju et al. 2007b). 1-V-Ti-Magnetite, 2-Chromite, 3-Quartzite, 4-Limestone, 5-Conglomerate – these occur within Hegdale Gudda, Kur Gudda and Tuppadahalli Fornations.

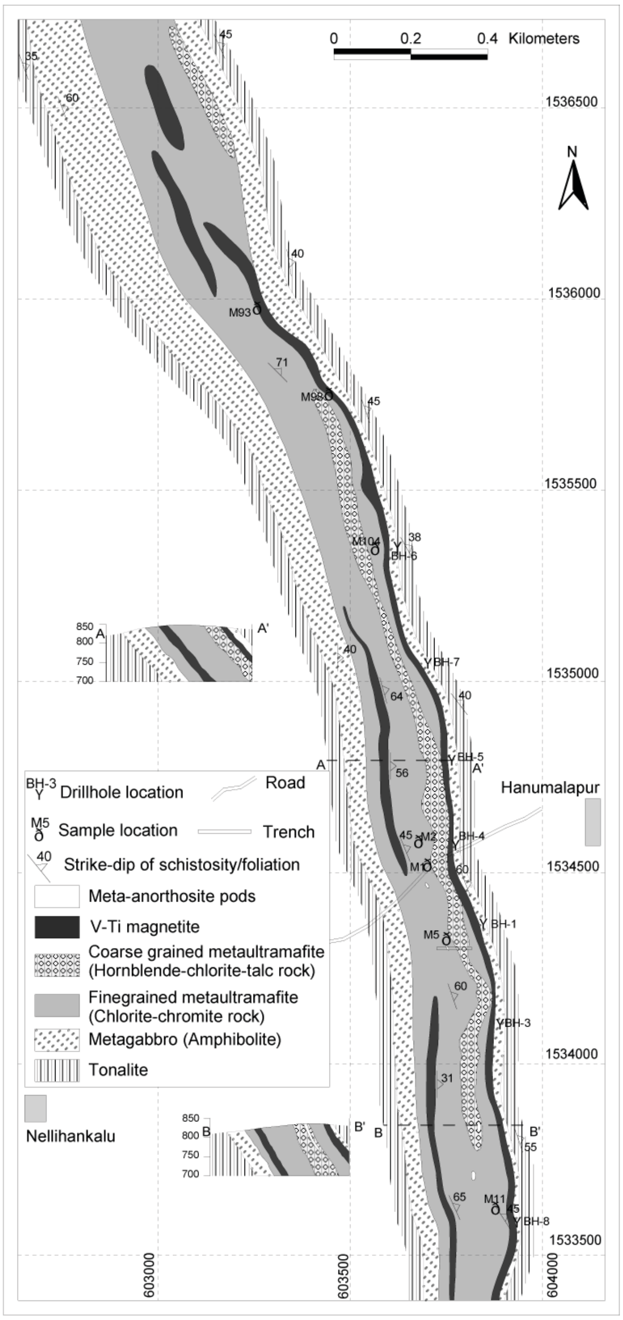


Fig.8b. Geological map of the northern about three km portion of PGE mineralized Hanumalapur segment of the Channagiri mafic-ultramafic complex (from Devaraju et al. 2007b).

Channagiri complex, together with a quantitative mineralogical evaluation, has indicated: (i) N-S to NNW strike, 55° to 70° easterly dip, penetrative deformation and greenschist-lower amphibolite facies metamorphism to result in complete obliteration of original textures and mineralogy; (ii) Layered character comprising of a central 100-150 m ultramafic zone, a narrow gabbroic outer zone and an interface zone between the two which includes V-Ti magnetite seams and small disconnected seams of anorthositic rock; (iii) Presence of an association of fine grained chromite-chlorite rock (metadunite) (Fig.9d) and coarse grained pegmatitic chloritic hornblendite (metapyroxenite) constituting the central ultramafic zone; (iv) Localization of PGE enriched zones to the central fine grained ultramafite and to the chromiferrous magnetite forming a part of the eastern magnetite seam; (v) Absence of PGE mineralization in the coarse grained ultramafite, western magnetite seam, anorthositic lenses and outer gabbroic zone; (vi) Existence of both Pt and Pd reefs, but the latter dominating over the former; (vii) Presence of more than 25 different phases of platinum group minerals as minute inclusions ranging in size from 2-3 microns to 10-15 microns in the main minerals of the rock (Devaraju, 2005b, Figs. 10a-d) viz., chromite (~60%) and chlorite and also occupying the boundaries between the two minerals (Figs. 10a-d); (viii) Absence of a Ni-base metal sulphide association; (ix) chromite controlled mineralization, being localized only to chromite bearing units of the complex, presumably related to the solubility of sulphur at the locus of chromite formation (x) Persistence of PGE mineralization over a strike length of 3 km and existence (determined by detailed study of drill core) of 3 closely spaced mineralized reefs in a 5 m wide zone analysing 3.7 – 5.0 ppm Pt+Pd and lower grade reefs analysing 1.3 – 1.8 ppm Pt+Pd and 0.7 to 1.8% Cu in a 50 m wide zone just above the main ore zone (Devaraju et al 2007b, Alapieti et al 2008); (xi) Rough similarity of Hanumalapur PGE mineralization with that of UG2 of Bushveld (Mclaren and DeVillers, 1982) and SJ reef of Penikat in northern Finland (Alapieti and Lahteinen, 1986; Halkoaho, 1994).

Chromite: Besides the Channagiri complex described above, where a chromite-PGE mineralization association is recorded, the Usgao complex in Goa, located at the northwestern portion of the WDC, also includes chromite mineralization. Detailed examination of these occurrences (Devaraju et al. 2007a) has revealed that while chromite in the Channagiri complex is very iron-rich and low grade, the chromite lenses in the Usgao complex are small and are located in the bio-reserve of Boundla. These factors have discouraged further exploration. For the same reason only a preliminary examination of the PGE potential of the latter complex, has been carried out (Devaraju et al. 2007a). As in the case of the chromite mineralization occurring in the Sargur Group, the chromite occurrences of the mafic ultramafic complexes of the Shimoga Group were concentrated by early magmatic segregation, forming lenses, pods and mottled aggregations. Penetrative hydrothermal and low-grade metamorphic alteration has affected even the

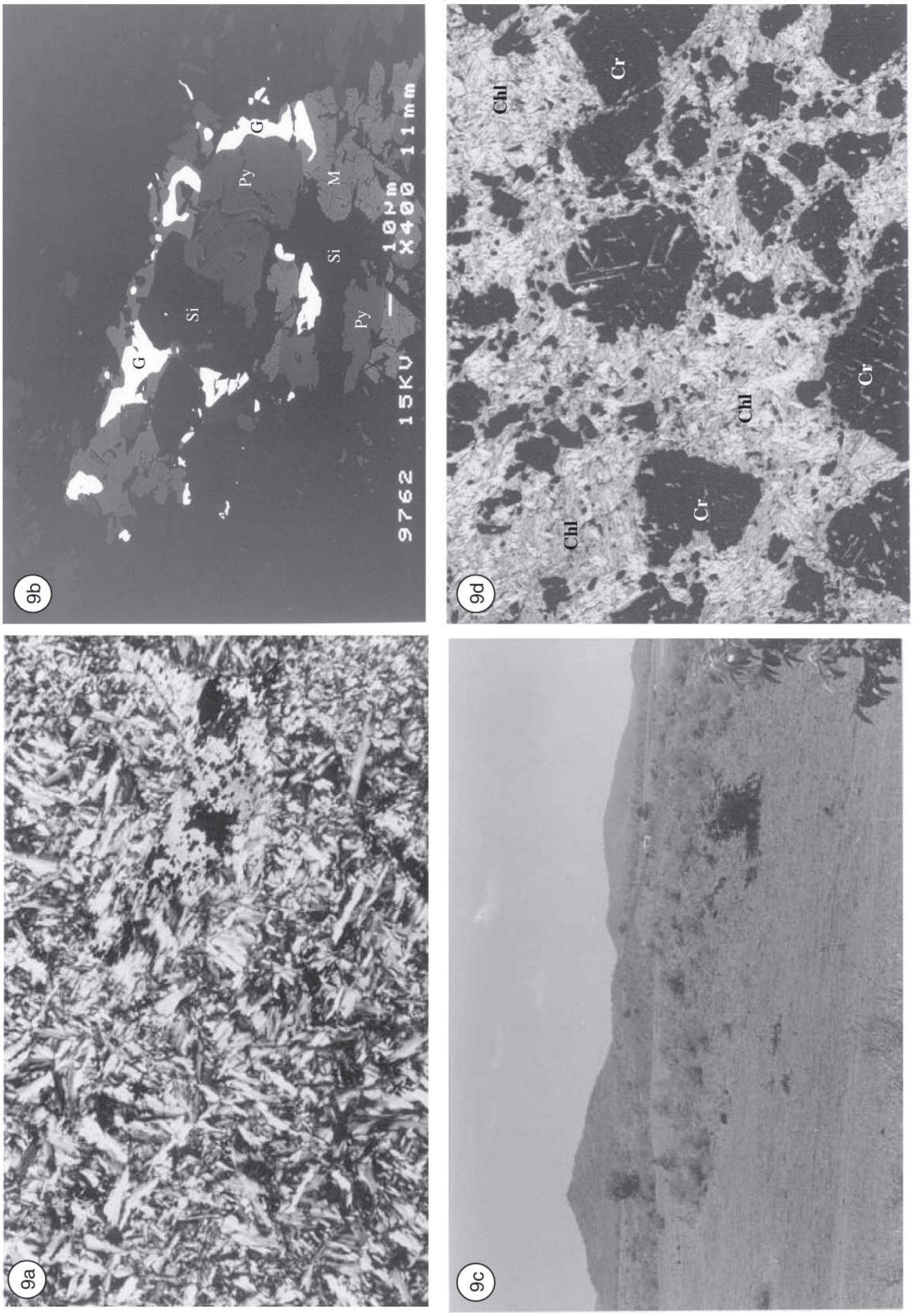


Fig.9. **(a)** Photomicrograph of Ni-Au-Pd mineralized meta-peridotite of Shankaraghatta: (scaly mineral: antigorite, black: largely sulphide and whitish: magnesite); **(b)** Back scattered electron micrograph showing occurrence of native gold (G) occupying generally the grain boundaries of base metal sulphides viz., millerite (M), pyrite /pyrrhotite (Py) and silicate (Si) (antigorite) (M-192); **(c)** Overall view of the PGE mineralized Hanumalapur mafic-ultramafic segment, viewed northwards from southern half of the segment (photo by TCD); **(d)** Photomicrograph of fine-grained ultramafic chromite (Cr)-chlorite (chl) rock comprising PGE ore of the Hanumalapur segment (sample M5). Ordinary light. Photomicrographs and back scattered SEM photos by Risto Kaukonen.

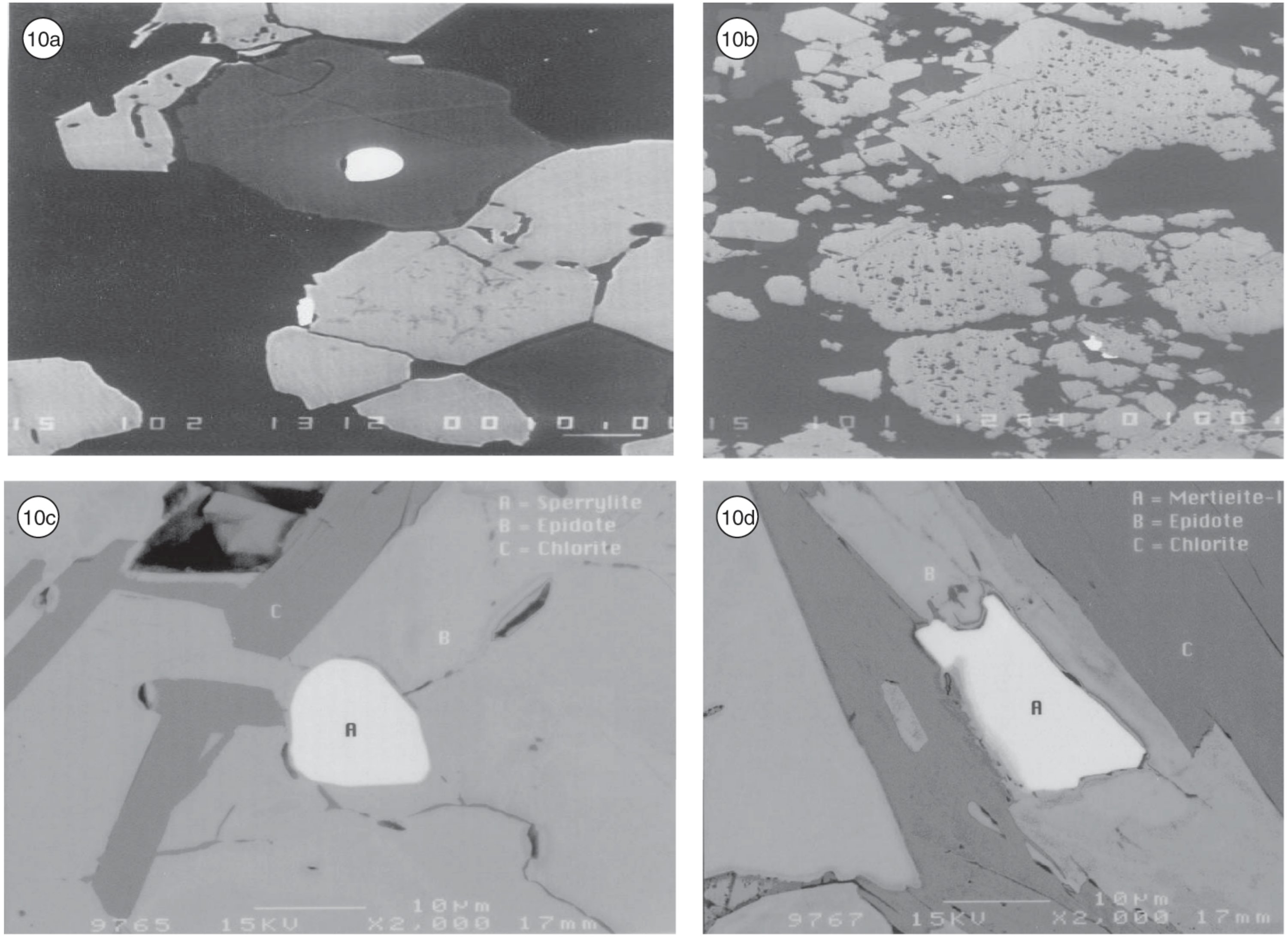


Fig.10. Back scattered electron micrographs (by Risto Kaukonen) of some of the common platinum-group minerals (bright white looking) in the outcrop (a & b) and silicate dominated core samples (c & d) from the PGE mineralized zone of the Hanumalapur segment: (**a**) *sperrylite* inclusion in chromite, sample M5:96: (**b**) *stibiopalladinite* occurrence along the grain boundary of chromite and within chlorite (black), sample M98:97; (**c**) inclusion of *sperrylite* in epidote; (**d**) inclusion of *mertieite-II* in epidote.

chromite resulting in variable degrees of oxidation and iron-enrichment in the mineral. The alteration of chromite is most pronounced and intense in the Channagiri complex (Devaraju et al. 2007a).

V-Ti-magnetite is the most commonly recorded type of mineralization in the mafic-ultramafic complexes of the Shimoga Group occurring at many different locations in Chikmagalur-Davanagere-Shimoga districts viz. Masanikere, Tavarekere, Ubrani, Gourapura, Chikkamalali, Hanumalapura, Devaranarasipura, Sakrebyle and Uttara Kannada district viz., Madanagere, Hiregutti, Morhalli, Markal, Hanotigadde, Kodsani, Sanyasigudda, Motigudda, Angadibail, Nursha, Subguli, Mulemane, Kaiga, Karansal, Honur, Hulsi, Suryakalyanigudda and Santepet. It is possible that all these occurrences are essentially related to the mafic-ultramafic magmatism which took place at the beginning of Shimoga Basin formation. Resource estimation on several of these deposits has resulted in an inventory of more than 30 million tonnes of magnetite ore. These magnetite ores are reported to contain 0.3 to 1% V_2O_5 and 5 to 15% TiO_2 and could be exploited as a source of V and Ti too.

Being resistant to weathering, V-Ti magnetite lenses are manifested as prominent outcrops at most of the localities mentioned. The host mafic-ultramafic rock is often very weathered, altered and covered by float of magnetite thus hampering identification and the establishment of field relationships. Where visible the host rocks consist of gabbro and anorthosite close to contacts with pyroxenitic-gabbroic rock types. As in the mafic-ultramafic complexes of the Sargur Group, the V-Ti magnetite layers in the Shimoga Group are a later differentiate as compared to PGE, Ni and chromite, having formed in that stage of differentiation during which the pyroxenitic-gabbroic units crystallized. Poor development of anorthositic layers in the mafic-ultramafic complexes of the Hegdale Gudda Formation of the Shimoga Group is an important difference when compared to the mafic-ultramafic complexes of the Sargur Group.

Old workings for **gold** are located at several places in the Shimoga basin, but, those at Kudurekonda-Palavanahalli (Davangere district), Jalagargundi and Bukkambudi (Chikmangalur district), Singanamane and Tammadihalli (Shimoga district), which are located in metabasic-ultramafic rocks, merit particular mention as they hold promise for reexamination and possible reopening. At these locations, gold mineralization was introduced in the form of hydrothermal quartz reefs and/or veins which also appear to have originated from remobilization of gold contained in the mafic host rocks.

Copper mineralization associated with V-Ti-magnetite deposits have been reported from Masanikere (Ramiengar et al. 1978) in the Shimoga belt and more detailed examination of several of the V-Ti-magnetite bodies for Cu mineralization is warranted. Indications of Cu and Ni mineralization occur in the sulphidic mafic-ultramafic rock (viz. metagabbro-metapyroxenite) occurring about 1.5 km west of Kaiga village (Uttara Kannada). The mineralized metabasic rock occupies over 1500 m^2 area with 0.6 to 0.8% Cu and 0.03 – 0.36% Ni having been reported. Factors such as its location in the midst of dense forest and close proximity to the Kaiga Atomic Power Plant, however, preclude more detailed investigations at this stage.

Chitradurga Supracrustal Group

Copper, *gold*, and *pyrite* are the more important mineralizations located in the metabasic volcanics of the Chitradurga Group. The Ingaladhal-Kunchiganal **copper** sulphide deposit (with minor Zn, Pb, As, Au, Co) occurs in the Jogimaradi volcanic suite, which forms the basal part of the Ingaladhal Formation (Fig.12). The Jogimaradi volcanic suite consists of about 85% tholeiitic basalt, 12% low silica variolitic andesite and 3% rhyolite (Ravindra et al. 1994). The Ingaladhal sulphide zone, consisting of stratabound concordant massive sulphide lenses, is confined to submarine volcanoclastics overlying the Jogimaradi pillow lavas and underlying variolitic andesitic lava horizons. Mookherjee and Phillip (1979) and Vasudev (1983) have considered the Ingaladhal sulphide deposits to be of the volcanogenic stratiform type and have envisaged syngenetic deposition of sulphide in a submarine environment. The underground workings for copper at Ingaladhal have in certain sections of the mine yielded 0.5 to 3 g/t of Au, 6 to 8.5 g/t of Ag and 130-500 ppm Co with some Pb and Zn. This also is substantiated by the quantitative mineralogical information obtained by Devaraju et al. (1997a, 1997b) for the sulphide ore samples collected from different levels of the Ingaladhal and Kalyadi mines. This multimetal sulphide zone is located close to the N-S trending fault/shear zone lying along the eastern margin of Chitradurga belt.

Gold: Numerous ancient old workings for gold in the Chitradurga belt are located adjacent to the well defined shear zone along the eastern margin of the belt and close to the contact of Chitradurga granite body. Of the several known occurrences, especially those located near Bellara, between Ingaladhal and Kunchiganhalu and forming the Western and parts of the Central lode systems of the Gadag belt, are largely confined to the metabasic volcanics. The mineralization is very similar to that in the greenstone belts of Kolar and Hutti. It is lithologically and structurally controlled being mostly confined to metabasic volcanics and

Fig.11a. Map of a part of Kolar greenstone belt showing the main gold-bearing lodes in the Gold Field Amphibolites (from Radhakrishna, 1996).

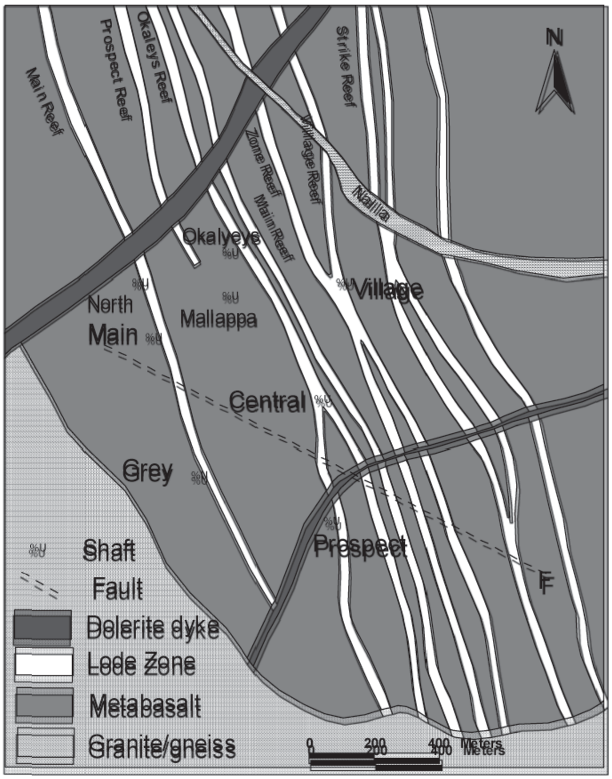


Fig.11b. Map of a part of the Hutti greenstone belt showing the main gold bearing lodes in the Buddinne Fm. of the Hutti Group (from Radhakrishna, 1996).

the shear/fracture system in the more competent mafic rocks. A possible genetic connection between the host metabasite and gold mineralization is suggested.

A **pyrite** deposit with a reserve of 3.5 million tonnes is located just south of Ingaladhal village. Pyrtiferrous bands have been traced through the entire sulphide-rich zone on the eastern side of the Chitradurga schist belt. Detailed exploration of this potentially economic zone is warranted.

Eastern Dharwar Craton

The most important ore minerals hosted by the mafic-ultramafic lithologies of the eastern block are *gold* and *diamonds*. While gold mineralization is localized in the greenstone belts of EDC, diamonds occur in several kimberlite/lamproite intrusions. There is also *copper* mineralization associated with a dolerite dyke intrusion located near Tinthini (Gulbarga district) (Table 4).

Gold: The best known gold deposits of the EDC are those hosted by the Kolar greenstone belt (Figs. 4a and 11a). These deposits were exploited continuously for over 125 years, the mine being officially closed in 2003 as a consequence of declining grades and the great depths of mining. In all, Kolar goldfield is reported to have produced 800 tonnes of gold.

The other important known deposits are in the Ramagiri-Penkacherla belt, located ~160 km NW of Kolar where intermittent mining is being carried out, and the Hutti belt (Figs. 4b and 11b), about 400 km NW of Kolar, the second largest gold deposit of the Dharwar craton. Hutti is presently the only major producing gold mine in India with an annual production of about 3 to 3.5 tonnes.

A careful study of all the locations in the Hutti-Maski belt has shown that most of the old workings, as well as presently working mines, fall within the stratigraphic unit known as the Buddinne Formation. The coarse and fine grained vesicular metabasalt of this formation is the host

Table 4. Stratigraphy of mafic magmatism related mineralization in Eastern Dharwar Craton

Stratigraphic position	Sub-divisions		Age (Ga)	Ore level mineralization	Host rock	Genesis	Locality
Neoproterozoic			0.84 – 1.2	Diamond	Kimberlite	Deep mantle crystallization in kimberlite magma	Vajrakarur cluster- 10 out of 15 intrusions forming Vajrakarur, Lattavaram and Venkatapalle subclusters
			~ 1.4		Lamproite		Chelima, Cuddaph Basin
Palaeo Proterozoic	Mafic Dyke		2.4 (?)	Copper	Dolerite/diabase	Hydrothermal fluids related to mafic dyke magamatism	Tinthini & Machanur
Late Archaean	**Kolar belt** = ***Gold field Amphibolites***	**Hutti belt** ***Buddinne Fm.***	~ 2.7	Gold	***Hutti:*** Coarse and fine grained vesicular metabasalt *(Buddine Fm.)* ***Kolar:*** Massive, schistose and granular amphibolite *(Gold field amphibolites)*	Reactivation, remobilization, scavenging of gold in the host basalt & augmentation by hydrothermal liquids derived from host basalt	***Hutti-Maski belt:*** Hutti, Wandalli, Chinchergi, Uti, Kadoni, Hira-Buddini, Tappaladoddi, Tuppadur, Virapur, Sanbal, Udbal ***Kolar belt:*** KGF, Shagitur, Manighatta, Ganacharpura, Tamadihalli, Arikere, Jaderi, Jayamangala, Nayakanahalli, Mallappa konda, Chigargunta, Surapalle, Bisanattam
	Champion gneiss Yerrakonda Fm. Kalahalli Fm.	Bullapur Fm. 530 Hill Fm. Hussainpur Fm.					

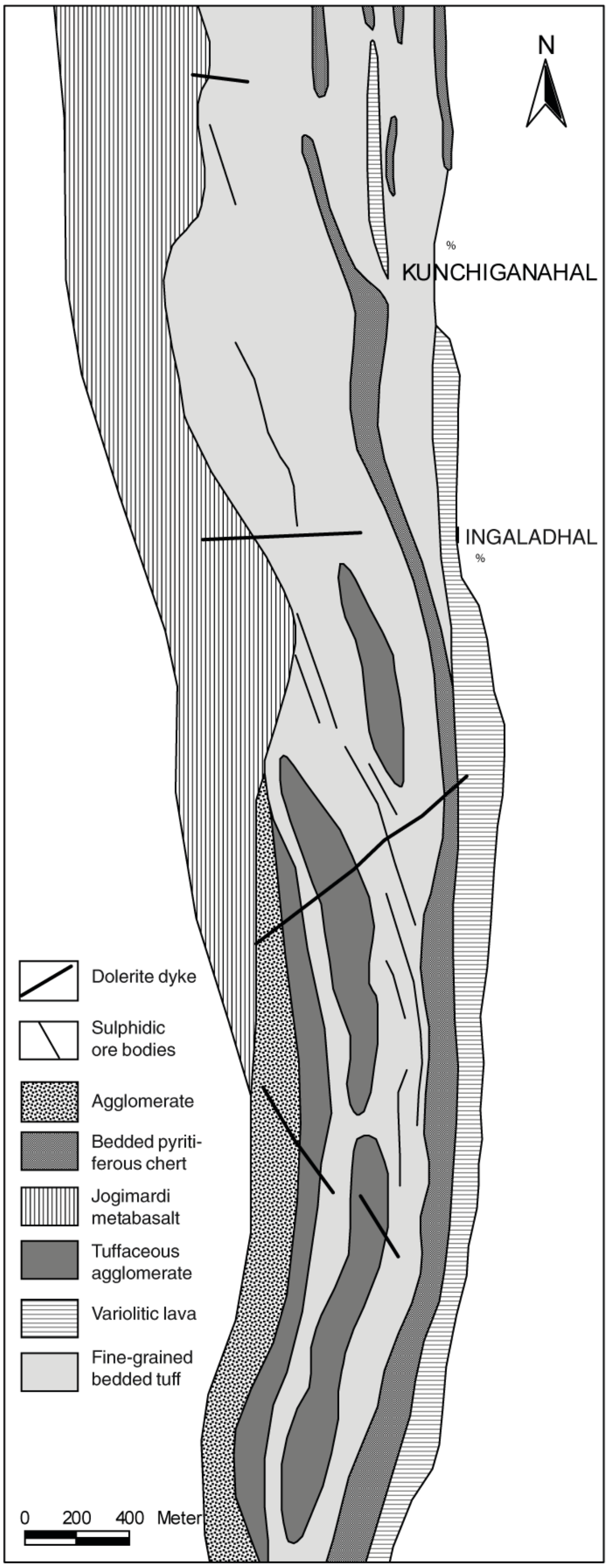


Fig.12. Geological map of the Ingaladhal sector of Chitradurga supracrustal belt showing the distribution of metabasic volcanic suite of rocks and copper sulphide mineralization zones (*after* Ravindra et al. 1994).

for the auriferous lodes which suggests a lithostratigraphic control for the mineralization. Gold mineralization is linked to several conformable quartz reefs which occupy shear planes. Wall rock alteration is common in all the nine gold-bearing quartz reefs that have been identified. At 50% payability, based on the present cut off grade of 2 gm/tonne, 15 million tonnes of mineable ore are estimated to be available for exploitation in this deposit (Curtis and Radhakrishna, 1995).

The Kolar, Ramagiri and Hutti deposits not only lie along the same strike but also bear close similarities in their overall geological settings. They are comparable even in terms of isotopic age data that has become available, being about 2.7 Ga, suggesting synchronous development. Lithologically these belts are greatly dominated by metabasic volcanics with only subordinate polymict volcanogenic conglomerate, fine clastics, chemical sediments (mainly BIF) and felsic volcanics. The broad variations displayed by the three belts could be explained as being related to temporal facies variations and increase in grade of metamorphism from the most northerly Hutti belt to the southern Kolar belt.

In the pattern of gold mineralization too there are great similarities among the three belts. In all three, metabasalt is nearly the sole host of gold-bearing quartz-carbonate reefs. The auriferous reefs occupy well defined fracture/shear planes which show an overall orientation parallel to the schistosity/foliation planes and lithological boundaries of the host metabasalt (Figs. 11a, b). Branching and interlacing of the reef system and also variable degrees of wall-rock alterations, which have widened the mineralized zones, are normal features. The host basalt has undergone extensive low-temperature fluid alteration. The auriferous grey to smoky quartz reefs with minor sulphides are localized along sheared and altered zones of metabasalts. With respect to primary gold mineralization, the greenstone belts in the eastern block of the craton are comparable to greenstone belts of similar age in Canada, Australia and Zimbabwe.

Furthermore, in all three of the important gold fields of EDC, the gold-bearing quartz-carbonate sulphide veins are generally localized along Fe-rich amphibolitic rocks suggesting stratabound mineralization both on a local and regional scale. A comparable pattern of mineralization is recorded in a number of other gold fields, notably at Kalgoorlie in Australia. Although the actual source of gold is not always convincingly established, the Fe-rich tholeiitic rocks seem to have appropriate chemical and physical characteristics to be a potential source as well as host rocks for gold-quartz vein mineralization (Giritharan and Rajamani, 1998). As observed by Raju and Sharma (1991) based mainly on the significantly higher gold content of the average host basalt of the Hutti Gold Field, the source of gold is thought to be in part, if not fully, the host metabasalt. Hydrothermal fluids emanating upon metamorphism from the basalt, were injected into the suitable dilatent zones in the basalt. These fluids caused alteration of basalt and also remobilization, scavenging and re-deposition of gold originating in the basalt.

Based on evidence from ancient/old workings in the Velligallu, Jonnagiri and Gadwal schist belts, the State Department of Geology and Geological Survey of India have carried out exploration for gold. These investigations have not however resulted in the identification of economic deposits.

Copper mineralization at Tinthini (Gulbarga district) located in the northwest sector of the EDC is localized along the sheared contact of EW striking dolerite dykes within pink granite. The mineralization is found over a strike length of 5 km, and, as per the estimations carried out by the HGML (during 1975-79), the deposit has an average Cu content of 0.6%. Regular mining operation did not materialize as the results of exploration did not confirm the economic viability. Localization of mineralization to the sheared and hydrothermally altered contact zones of dolerite, appears to suggest a genetic connection of mineralization to the hydrothermal fluids related to dyke magmatism.

A passing reference may also be made here to the small (syngenetic) **chromite** deposit of Kondapalle, Krishna district (with about 100,000 tonnes reserve), in the EDC (ore production from this deposit ceased as far back as mid nineties). The host mafic-ultramafic rock of this deposit is a sheet like body located along the contact between charnockite and migmatitic gneiss and occupies an area of about 100 km^2. The deposit occurs as small lenses/pods/pockets within what is considered as stratiform intrusion with a vertical variation from dunite to gabbro-norite and granophyre through harzburgite-bronzitite. However, the deposit is located within the Eastern Ghats Mobile Belt forming eastern rim of the EDC and is assigned Neoarchaean – Mesoproterozoic stratigraphic position (Ramam, 1999).

Kimberlite-lamproite related mineralization: These intrusions are well known hosts and the primary source rocks for diamonds. They have been found in the Anantapur, Prakasam, Mahboobnagar and Krishna districts. The well known 250 km^2 Wajrakarur diamond field in the Anantapur district includes the kimberlite and lamproite clusters of Wajrakarur, Lattavaram and Venkatapalle. Of the 12 pipes identified, two are of lamproite and micaceous kimberlite composition with the rest being typical kimberlites. All these pipes, except 2 are stated to be diamondiferous. They intrude Archaean granites and migmatites and have been emplaced along prominent lineaments (Fig.6b). The latest addition to this cluster is the Anumpalle pipe, the largest yet discovered, occupying an area of 60 hectares (Rao et al. 1997) and a diamond-bearing carbonatite-kimberlite (Rio Tinto – quoted by Radhakrishna 2007) in the Ramagiri gold field area of the Anantapur district. Seven kimberlite pipes have been reported from near Chigicherla, Pillapalle, Gollapalle and Ramagiri villages. Their diamond potential is still to be assessed. Occurrences of kimberlites in the 400 km^2 Maddur-Maboobnagar sector, is centred around Maddur, Kotakonda, Vanjamur and Narayanpet villages. Ten of these occur around Maddur, seven around Kotakonda, six around Narayanpet, three near Gurumatkal and four in the vicinity of Bewanahalli (the last two villages are in the Gulbarga District of Karnataka adjoining Mahboobnagar). De Beers have recently discovered 29 more intrusions which occur in a cluster in the border area of the Raichur and Gulbarga districts. They are referred to as the •Bhima cluster•. The diamond potential of these recently discovered kimberlites too is still to be determined.

Lamproite dykes of the Chelima and Zangamarajupalle areas have been known for a long time. They are the oldest (1400 Ma) (Chalapathi Rao, 1999) diamondiferous rocks discovered to date. Another 28 dykes have been recently reported by Rio Tinto (Radhakrishna, 2007). The cluster occupies an area of 160 km^2 and is referred to as •Krishna lamproite FieldŽ (Reddy et al, 2003). Exploration by Rio Tinto (Radhakrishna, 2007) has also revealed the presence of 8 additional kimberlite pipes, designated as the •Gooty cluster•. These are the first recorded kimberlites within the Cuddapah Basin.

Many of the recent sensational discoveries of diamondiferous kimberlite/lamproite intrusions in the EDC by the world pioneers in diamond exploration namely De Beers and Rio Tinto, are expected to set the trend for further discoveries. It is hoped that the commercial production of diamonds from many of the newly discovered intrusions will help India in regaining its position as one of the world•s premium diamond producers.

Mineralization in Mafic Dykes

As mentioned, no economic mineralization is known to be associated with the mafic dolerite-basalt-gabbro-picrite dykes (essentially unmetamorphosed) that occur in several different swarms. However, the mafic dyke material is in demand both nationally and internationally as an ornamental stone, under the label **•black granite•** and there are numerous quarries of this rock scattered throughout the Dharwar craton. Important mining areas are situated in the Chittor, Khammam, Prakasam and Warangal districts of Andhra Pradesh, in the EDC (Ramam, 1999) and in the Bangalore, Mysore, Kolar, Tumkur, Hassan and Uttara Kannada districts of the WDC (Radhakrishna, 1996).

CONCLUSIONS

Mafic-ultramafic magmatism is an integral part of the Dharwar craton development having taken place repeatedly at various stages during its more than 3.3. billion year history of evolution. While in the Sargur Group, comprising the oldest known greenstone belt(s) of the craton, the ultramafics dominate over the mafic units, in the Bababudan Group of the western block as well as in the Kolar type greenstone belts of the eastern block, the mafic volcanics constitute the bulk of the stratigraphic sequence and in the Shimoga-Chitradurga Groups, the mafic volcanics make up only a small proportion of the stratigraphic sequence.

The older pre-Palaeoproterozoic mafic magmatism is very predominantly volcanic with intrusive complexes being fewer. Contrastingly the post-Archaean mafic magmatism, which is widespread and taken place over a protracted period from 2.4 to 1.4 Ga has manifested overwhelmingly as dyke (and sill) intrusions. There were minor potassic ultramafic magmatism in the form of kimberlite/lamproite/diatreme intrusions during 1.4-0.8 Ga almost entirely in the eastern part of the craton. The craton as a whole is devoid of large batholithic intrusions of mafic-ultramafic magma.

Mafic-ultramafic magmatism associated with greenstone belts and supracrustal groups of Dharwar craton includes within it a range of mineral deposits. Lenses/layers/bands of *chromite* (this is commercially worked at several places) and *V-Ti magnetite* are the most important syngenetic mineral deposits associated with mafic-ultramafic complexes of both the Sargur and Shimoga Groups. While chromite is the typical early magmatic segregation in the dunite-peridotite units, the V-Ti magnetite is equally typical in the later formed pyroxenite with gabbro anorthosite units of the complexes.

No ore level *PGE* mineralization has yet been recorded in the mafic-ultramafic complexes of the Sargur Group, but, in the mafic-ultramafic complex comprising the Hegdale Gudda Formation, occupying the lowermost stratigraphic sections of the Shimoga Group, a commercially potential PGE deposit has been identified (Devaraju et al. 2007b; Alapieti et al. 2008). The PGE mineralization recorded is essentially localized along the chromite- bearing horizon and displays petrological-mineralogical features of early magmatic syngenetic formation.

Evidence of *Ni-Au-PGE* mineralization, which has been picked up as a sulphide zone in the metadunitic ultramafic body exposed within the Kuvempu University campus, warrants a thorough search for similar sulphidic mineralization in the ultramafic bodies elsewhere in the Shimoga belt.

The known *gold* deposits of Kolar, Ramagiri, Hutti, Gadag and also many of the old workings for gold scattered over the craton as well as *copper* in the Ingaladhal and Kalyadi areas are all located in the metabasic volcanics. A possible genetic link between the host metabasalt and Au/Cu mineralizations is suggested. The source of Au/Cu is thought to be in part, if not fully, the host metabasalt itself. Hydrothermal fluids emanating upon metamorphism of the metabasalt appear to have injected into the suitable dilatent zones of the host rock and also causing remobilization, scavenging and redeposition of Au/Cu in it.

It is hoped that a large number of kimberlite-lamproite intrusions discovered in the recent years in the districts of Anantapur, Mahboobnagar, Gulbarga, Raichur, Prakasam and Krishna in the EDC contain commercially exploitable concentrations of primary diamond and India will regain in the near future its position as one of the worlds leading producers of diamond.

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