PART I

CHAPTER I

GENERAL
1.1 Introduction

The very mention of the name ‘platinum’ is understood by the common educated public as an exquisite jewelry metal, more expensive and far less traded than gold.

Platinum-Group Elements (PGE), which include platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os), are the rarest of the precious metals in the earth’s crust. They have similar chemical properties and occur together in nature. The PGE belong to the transition elements group VIII in the periodic table, to which the ferrous metals, iron, nickel and cobalt also belong. Crustal abundance of Pt as well as Pd is about 5 ppb i.e., as scarce as gold (Au). The high resistance of the platinum-group metals to oxidation and corrosion qualifies them to be classified as ‘noble metals’ together with gold (Au) and silver (Ag), while their scarcity causes them to be called ‘precious metals’.

During the last about 20 years, industrial applications of PGMs have been assuming increasingly greater importance. In fact, the present day industrial uses of PGM’s are numerous and these account for most of their consumption.

1.1.1. Global Distribution – Spatial and Temporal

Primary, mafic-ultramafic related PGE deposits were discovered in Bushveld in 1924, 1938 after platinum was found as placer in 1786 in Columbia. Columbia remained the single global source till placer ores were found in the Urals in 1822. The recovery of platinum as a by-product of smelting the Sudbury Ni-Cu ores began in 1919. Currently, production from primary ores dominates the scene as Bushveld alone accounts for more than 50% of the world’s production and more than 80% of global resources. Major productive or potential source regions together containing > 99% of the known global resources are: (i) Bushveld, South Africa; (ii) the Great Dyke, Zimbabwe; (iii) Norilsk-Talnakh, USSR; (iv) Sudbury, Canada; (v) Still water, Montana; (vi) Jin Chuan, NW China; and (vii) Muni Muni, NW Australia.
1.1.2. Types and Modes of Occurrences of PGE deposits

Apart from the placers, PGE deposits are always associated with the nickel-copper sulphides in magmatic deposits. Naldrett (1989, 2004) has classified these deposits into two main categories: the PGE-dominated deposits and the Ni-Cu dominated deposits. The PGE-dominated group includes the Merensky-reef, UG2 Chromitite and the Platreef deposits of the Bushveld Complex (von Gruenewaldt, 1977; Cawthorn et al. 2002; Barnes and Maier, 2002), the deposits of Great dyke of Zimbabwe (Naldrett and Wilson, 1990; Wilson, 1996, 2001) and the Stillwater deposit of Canada (Campbell et al. 1983; Czamanske and Zientek, 1985). The Ni-Cu dominated deposits include the Sudbury deposit of Canada (Farrow and Watkinson, 1997; Naldrett et al. 1999; Lightfoot et al., 2001), the ore related to continental drifting – such as those in the Noril’sk-Talanakh area of Russia (Lightfoot and Naldrett, 1996; Komarova et al. 2002; Alapieti and Lahtinen, 2002), the Finnish deposits (Mutanen, 1997; Alapieti and Lahtinen, 1989), the Duluth complex of USA (Sims and Morey, 1972; Weiblen and Morey, 1980; Miller and Ripley, 1996), and the numerous deposits related to komatiites of ancient greenstone belts.

PGE ores are either Pt- dominant (Merensky; UG2) or Pd-dominant (J-M reef in Stillwater; Norilsk). PGE mineralization in ophiolites is widespread but often too sparsely disseminated to form workable deposits, these typically constitute the source-province for placer deposit, as in the ophiolite belts of the Western USA.

On the basis of settings the PGE deposits are classified into distinct groups; e.g. (i) intercontinental, anorogenic(?) layered complexes (Bushveld, Stillwater, Great Dyke, Muni Muni); (2a) intrusive phase of flood basalts related to rifted continental margins (Norilsk-Talanakh, Duluth); (2b) layered complexes in the rifted continental margins (Penikat in the Kemi-Koilismaa belt, N. Finland); (3) mafic intrusives of the ‘Alaskan’ type (Irvine, 1974) emplaced in the mobile belt during the late orogenic belts (the Cliffs deposit of the Unst ophiolites).

Within the layered complexes, the modes of occurrence are quite varied – from stratiform-stratabound to starta-transgressive bodies. In the Bushveld all the varities are represented (see Table 1.1).
1.1.3. Applications of PGM's

The platinum-group metals characteristically exhibit extraordinary physical and chemical properties that render them indispensable to modern technology and industry. PGMs find application all over the world and are used in a wide range of applications including medicines (e.g., cancer treatment, pacemakers, dental alloys), the automobile industry (e.g., catalytic converters), jewellery and the high technology sector (e.g., electric contacts, catalysts, production of glass fibers). Compared to Au and silver, PGMs are very late comers in man's life.

The fastest growing consumer market for PGMs is in the making of pollution control equipment. PGMs are the active 'pollution fighting' or the 'environmental' elements in the form of catalytic converters and catalytic incinerations. With the aggressive propagation of 'green movement', rigid laws are enacted to check effectively the environmental pollutions. Enactment of 'clean-air act' in early 80's in Europe has greatly increased the demand for PGMs. Therefore, PGM’s are currently receiving world-wide attention as an attractive exploration target.
One can visualize the importance assumed by PGMs as a whole and by the individual metals of the group for various applications by referring to their consumption patterns in 2006-07 given in the Table 1.2.

### 1.1.4 PGM's World Mine Production, Reserves and Reserve base

World mine production and reserves of the PGM’s adopted from USGS Mineral Commodity Summaries 2008 is given in the following Table 1.3

#### Table 1.2: Consumption of individual PGMs (1,000 Oz) for various applications during 2006-07 (adopted from Johnson Matthey 2008)

<table>
<thead>
<tr>
<th></th>
<th>Platinum</th>
<th>Palladium</th>
<th>Rhodium</th>
<th>Ruthenium</th>
<th>Iridium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autocatalyst:</td>
<td>3,905</td>
<td>4,225</td>
<td>4,015</td>
<td>4,450</td>
<td>863</td>
</tr>
<tr>
<td>gross recovery</td>
<td>-860</td>
<td>-890</td>
<td>-805</td>
<td>-1000</td>
<td>-171</td>
</tr>
<tr>
<td>Jewellery</td>
<td>1,640</td>
<td>1,585</td>
<td>995</td>
<td>740</td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td>1,830</td>
<td>1,940</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics</td>
<td></td>
<td></td>
<td>1,205</td>
<td>1,285</td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td>9</td>
<td>9</td>
<td>1272</td>
</tr>
<tr>
<td>Investment</td>
<td>40</td>
<td>170</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical</td>
<td>49</td>
<td>64</td>
<td>223</td>
<td>101</td>
<td>33</td>
</tr>
<tr>
<td>Electrochemical</td>
<td></td>
<td></td>
<td>137</td>
<td>119</td>
<td>34</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td>65</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Others *</td>
<td>1,195</td>
<td>1,360</td>
<td>23</td>
<td>23</td>
<td>54</td>
</tr>
<tr>
<td>Total</td>
<td>6,475</td>
<td>7,030</td>
<td>6,605</td>
<td>6,835</td>
<td>838</td>
</tr>
</tbody>
</table>

Osmium is used but quantity is not available

* Includes applications in the making of oxygen sensors, turbine engine blades, various biomedical items, plastics, silicones, spark plugs, etc.

#### Table 1.3: World mine Production, Reserves and Reserve base of PGMs (2007-08)

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>United States</td>
<td>3,860</td>
<td>3,700</td>
<td>12,800</td>
<td>12,400</td>
<td>900,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Canada</td>
<td>6,200</td>
<td>7,200</td>
<td>10,500</td>
<td>12,500</td>
<td>310,000</td>
<td>390,000</td>
</tr>
<tr>
<td>Colombia</td>
<td>1,400</td>
<td>1,700</td>
<td>NA</td>
<td>NA</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Russia</td>
<td>27,000</td>
<td>25,000</td>
<td>96,800</td>
<td>88,000</td>
<td>6,200,000</td>
<td>6,600,000</td>
</tr>
<tr>
<td>S. Africa</td>
<td>166,000</td>
<td>153,000</td>
<td>86,500</td>
<td>80,000</td>
<td>63,000,000</td>
<td>70,000,000</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>5,300</td>
<td>5,600</td>
<td>4,200</td>
<td>4,400</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Other countries</td>
<td>3,490</td>
<td>3,500</td>
<td>8,120</td>
<td>8,300</td>
<td>800,000</td>
<td>850,000</td>
</tr>
<tr>
<td>World total</td>
<td>213,000</td>
<td>200,000</td>
<td>219,000</td>
<td>206,000</td>
<td>71,000,000</td>
<td>80,000,000</td>
</tr>
</tbody>
</table>

* Estimated; NA – Not available; * included with other countries
**World Resources:** World resources of PGMs in mineral concentrations that can be mined economically are estimated to total more than 100 million kilograms. The largest reserves are in the Bushveld Complex, South Africa.

**Substitutes:** Some motor vehicle manufacturers have substituted palladium for the more expensive platinum in catalytic converters. Until recently, only platinum was used in diesel catalytic converters; however, new technologies allow as much as 25% palladium to be used. For most other end uses, one platinum-group metal can be substituted for other, with some losses in efficiency. In addition, electronic parts manufacturers are reducing the average palladium content of the conductive pastes used to form the electrodes of multilayer ceramic capacitors by substituting base metals or silver-palladium pastes that contain significantly less palladium.

**1.1.5. PGE mineralization: Indian Scenario**

PGE do not have the same status like gold and diamond in India. So far there is no record of history of mining or production of any PGMs primary products in India. The well documented, commercially promising potential PGE occurrences are known to exist at two places till date. One is the fine-grained mafic-ultramafite rock Hanumalapur segment, Karnataka (study area) of Western Dharwar Craton, about 60 km east of Shimoga (Devaraju et al., 1994, Devaraju et al 2007, Alapieti et al 2008) and the other is the in gabbro-breccia-hosted PGE deposit within the shear zone of the Nuasahi-Sukinda complex in the Boula area (Nanda et al. 1996; Mondal and Baidya, 1997; Mondal et al. 2001; Auge et al. 2002, 2003; Patra and Mukherjee 1996).

Mafic-ultramafic complexes of Usgao in Goa and Nuggihalli belt in Karnataka, Sitampundi, Rasipuram and Atlur in Salem district, Satyamangala group in Periyar, Coimbotore and Nilgiri districts, Chimalpad in Andhra Pradesh, Arunachalpradesh and Jammu-Kashmir are all being examined (By GSI & State DMGs) for discovering evidence of platinum mineralization, but, the results obtained so for have not indicated the existence of mineralized zones of possible commercial value. In recent years, GSI has taken up a drilling programme at Chettiampalaiyam-Tasamalaiyam sectors in Sittampundi layered mafic-ultramafic complex, Solavanur-Karappadi sector in Mettuppalaiyam ultramafic complex, Tamil Nadu, Hanumalapur segment of Channagiri mafic-ultramafic complex, Karnataka, but, the results are not available.
Recent exploration by Devaraju et al. (2008) for PGMs in the Holenarasipur schist belt has not yielded positive results.

In India there are no layered mafic complexes comparable in size to either Bushveld or Great Dyke, but we do have a large number of smaller mafic-ultramafic complexes distributed over many States of the country. Specially those mafic-ultramafic complexes of the country hosting Ni-Cu and chromite mineralization and chromitite-V-Ti-magnetite association, which are demonstrated to be ideal targets for associated PGE mineralization, need to be examined thoroughly on priority basis to make sure that we are not missing any of the important PGE mineralized zones in these ideal targets.

For identifying PGM deposits, in addition to geological information, a good setup of standardized analytical facilities are very essential to analyse the extremely low concentrations with high precision. SEM fitted with a (ED/WD) spectral analyzer and oscilloscope monitor is a minimum must to identify quantitatively the presence of platinum-group minerals, if any, in samples believed/suspected to have been collected from PGE mineralized zones. Facilities for Ni-sulphide fusion of sufficiently large quantities of samples and thoroughly standardized ICPMS/Emission Spectroscopic/INAA analytical facilities are also a must for quantitative analysis of PGE.

1.2 Aims and Objectives

The promising commercial potential of Hanumalapur prospect recognized by Devaraju et al. 2005; Alapieti et al. 2002 has motivated the author of the thesis to undertake detailed petrological and geochemical study of the Channagiri mafic-ultramafic complex as a whole and the Hanumalapur block in particular and to make an attempt to interpret the genesis of the PGE mineralization. Both Prof. T.C. Devaraju and late Prof. Alapieti thought that it was important and necessary to make such an attempt and as junior associate in their ‘Karnataka PGE Project’ they have encouraged me to carry out further detailed investigation by placing at my disposal all the outcrop and core samples collected by them.

The main objective of the present study is to examine thoroughly the material and data gathered by Prof. Devaraju and late Prof. Alapieti over a period of more than 14 years and to present a comprehensive account of the petrology, geochemistry and
petrogenesis of the Channagiri mafic-ultramafic complex in general and the PGE mineralized Hanumalapur segment of the complex in particular. The objectives of the present study are as follows:

1. Petrological and geochemical characterization of the Hegdale Gudda Formation in general, the Channagiri mafic-ultramafic complex as a whole and Hanumalapur segment in particular.

2. Petrological and geochemical logging of all the drill cores generated by the Karnataka State Department of Mines & Geology in support of the investigation of Devaraju and Alapieti.

3. Petrological and geochemical characterization of the PGE mineralization in the Hanumalapur segment.

4. 3-D reconstruction of the PGE mineralization in the Hanumalapur segment.

5. Interpretation of the petrogenesis of the Hanumalapur segment and the associated PGE mineralization.

1.3 Scope of the Work

There was a scope for undertaking the further examination of the large amount of outcrop and drill core data generated in the course of long years of investigation carried out jointly by Profs. T.C. Devaraju and T.T. Alapieti. A comprehensive synthesis of the great amount of petrological information and over 540 whole rock analyses especially drill core samples for major, selected trace and PGE data generated in the process of logging of the more than 1480m of core was very much desired. The author has made an attempt to accomplish the same.

1.4 Methods of Study

Both field and laboratory investigations have been carried out.

1.4.1 Field Investigations & Geological Mapping

Regional geological mapping of the Channagiri Mafic-ultramafic complex was done essentially on 1:50,000 scale using all the published geological maps, the Survey of India topographic sheets and geo-coded product data supplied in the form of FCC by NRSA, Hyderabad and SRTM topographic map. The geological map of the PGE mineralized 3.5km in long and ~ 300m wide Hanumalapur mafic-ultramafic segment has been updated incorporating space co-ordinate Garmin Map-72 GPS data and also...
based on the drill core petrological, geochemical study and geophysical (magnetic) data. In all 210 representative least altered outcrop samples, each weighing about 2 to 5 kgs, were collected from a wide range of major and minor lithologies of mafic-ultramafic complex and adjoining granitoids; the largest number was from the PGE mineralized Hanumalapur segment covering all the lithological variations of the segment.

1.4.2 Microscopic Study

Thin sections obtained for nearly all the outcrop samples covering all the lithological variations were examined determining petrographic and mineralogical characteristics using Leica DMLP polarizing microscope at the Department of Studies in Geology, Karnataka University, Dharwad. Modal analysis was performed at the same Department on more than 50 thin sections using James Swift point counter. In order to have a reasonably good statistics, over 1,000 counts were made on each sample. In addition, 242 drill core samples (JP-1 and 3) were prepared and studied at the Department of Geology, University of Oulu, Finland, utilizing their exceedingly good microscopic lab facilities.

1.4.3 Drill Core Study

In all 8 exploratory drill cores which were made available by Prof. Devaraju and late Prof. T.T. Alapieti, were thoroughly examined and logged. The boreholes were drilled at intervals varying from ~ 250m to 500m and all the holes was drilled at angles 58° to 60 due west. The borehole depths varied from 150 to 250m, altogether 1481m drilling was done covering ~ 2km strike length. The visual logging of the boreholes has been carried out systematically and the vertical cross sections are prepared with the aid of softwares.

Polished thin sections of drill core samples (from BH-1 and 3) were obtained covering all the lithological variations at the University of Oulu and were studied for gathering petrographic and mineralogical information.

Based on the visual logging particulars and also petrographic details of the drill core columns covering all the important lithological variations were distinguished and sampled systematically. Representative samples collected from the uniform looking columns with disseminated sulfides and chromitite/magnetite seams have been paid a special attention.
The cores were sliced with the help of cutting machine fitted with a diamond saw. The length of the core sample varied from 30 to 40 cm. About \( \frac{1}{4} \) to \( \frac{1}{2} \) portion of the core was crushed and the samples were prepared for whole rock and also PGE analyses. All together, 918 samples have been analysed for platinum, palladium and gold using Ni-sulfide fire assay. In addition 570 samples have been analysed for major, a large number of trace elements and selected REE.

1.4.4 Methods Chemical Analysis

**XRF Analyses:** In all, 44 outcrop and 543 drill core samples have been analysed for both major and a set of selected trace elements at the Institute to Electron Optics, University of Oulu, Finland employing SIEMENS (German) SRS 303AS XRF-analyzer, where the powder pellets was used for analysis. A small number of outcrop samples have been analysed for major and a few trace elements viz., Cr, Ni, Ba and S at the PPOD labs, AMSE, Geological Survey of India, Bangalore using Philips XRF machine.

**ICPMS Analyses:** A small set of 10 samples were analysed for all the 14 REE and 20 other trace elements viz, V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, Hf, Ta, Pb, Th, U and Sc at the Activation Labs, Canada. This was done a per what they call lithogeochemical package 4B2–STD using Lithium metaborate/tetraborate sample fusions. The fusion process ensures dissolution of minerals like sphene, monazite, chromite and REE in resistate phases. Analysis of fusion solutions has been demonstrated to provide research quality data.

**Ni-sulphide Fire assay:** All together 77 outcrop samples were analysed for PGE. Of those 28 samples have been analysed for all the six PGE, Au and Re. The remaining 49 outcrop samples and 926 drill core samples were analysed for only Pt, Pd and Au. The analyses were carried out at the Geological Survey of Finland, Rovaniemie Laboratory and Activation Lab, Canada. Both the labs are equipped for precise and reliable PGE analysis. For analysis Ni-sulphide and lead fire assay coupled with ICPMS and INAA techniques were employed. The detection limits for the methods adopted at those labs were as follows: Os 2.0, Ir 0.1, Ru 5.0, Rh 1.0, Pt 5.0, Pd 2.0 and Au 0.5 (values in ppb).
Fig 1.1: Topographic map of the study area, south of Channagiri derived from SRTM data, showing transport and drainage network.
1.5 Location and Accessibility

The area studied lies within the longitudes 75° 50'-76°05' E and the latitudes 13° 45'-13° 55' N. It occupies parts of the Survey of India toposheets 48 O/13 and 53 C/1. It is geographically located SE of Shimoga city and south of Channagiri town and occupies eastern margin of Shimoga, SW margin of Davanagere and northern margin of Chickmangalore districts (Fig. 1.1). Geologically the area comprises of southeastern portion of the main Shimoga schist belt and about 12 km eastern strip of gneissic terrain adjoining it (Fig. 1.2).

The study area can be readily reached by roads either from Shimoga/Bhadrawati side or from Harihar/Davanagere/Chitradurga side. The Hosdurga road and Shivani railway stations on Miraj-Bangalore broad gauge line lie on the eastern side of the area. An asphalt road connects Channagiri to several of the important villages in the study area like Hanumalapur, Nellihankalu, Tavarekere, Ubreni and Bukkambudi. All season metal roads and cart tracks serve the large number of other villages in the area (Fig. 1.1).

1.6 Topography, Drainage and Vegetation

The area studied lies in the environs of shadow zone of Malnad, comprising eastern border of Shimoga and western border of newly formed Davangere district. In the north and west it is a rugged hilly terrain (see Fig. 1.1), whereas the southern and eastern parts form sloping peneplain with a mean height of 780m and a rolling topography.

Relatively compact and chemically the most resistant rocks viz., granitoids, quartzite and magnetite stand up from the flat as low, smoothed ridges and mesa-like hills. The area on the whole has predominantly easterly slope. In the low-lying areas, the outcrops are scanty whereas in the hilly portions, the rocks are well exposed. Tavarekere-Bukkambudi tank is the largest of many tanks that dot the area almost all over.

The drainage pattern is dendritic, representing typical of the metamorphic terrain. The area has been heavily dissected by many streams (Fig. 1.1) and they are flowing mainly towards south to SE directions.
The hill ranges of Tavarekere, Masanikere and NW of Hanumalapur are covered with shrubs and thorny bushes. The slopes of Gaurapur and Ubrani hill ranges are covered by moderately thick jungle with bamboo trees, while the top of the ridges are covered by grasses. It is an extension of Joldhal Reserved Forest area.

1.7 Review of the Previous Works

The preliminary geological survey and broad geological mapping of the Channagiri area was carried out by Slater (1905, 1912). Afterwards, Jayaram (1915) carried out revision survey in the same area. Smeeth and Sampat Iyengar (1916) reported the occurrence of titaniferous iron ores from Ubrani. Many years later, MISL, Bhadravati carried out prospecting of V-Ti magnetites around Ubrani, Tavarekere and Myagathahalli by putting trenches/pits. Channappa and Subramanya (1973, 1979) did systematic prospecting and estimated reserves of V-Ti magnetite ore deposits constituting the Ubrani block and Gaurapur together at 1.7 mt. Ramiyengar and Chayapathi (1977), based on drill core data obtained for Masanikere V-Ti magnetite deposit, gave a comprehensive account of the stratigraphy and petrology of this deposit and also estimated the magnetite reserves. Besides, Ramiyengar et al. (1978), discussed the mineralogy and geochemistry of V-Ti magnetite deposit and Cu-mineralization associated with the gabbro-anorthosite complex of Masanikere. Vasudev and Srinivasan (1979) presented an overview of the available literature on geology, mineralogy and geochemistry of the magnetite deposits of Karnataka and based on morphology and structure they proposed a classification of these deposits as deformed, conformable and layered types.

Harinadha Babu et al. (1981) undertook revision survey and mapping and endorsed the cover-basement relation between Dharwar Supergroups and the gneissic complex. They regarded the mafic inclusions within the gneissic complex as a part of the Sargur Group. They classified the Dharwars in this part, in the ascending order, into Jhandimatti, Joldhal, Medur and Ranibennur Formations.

Chadwick et al. (1987, 1988) remapped a considerable portion of the Shimoga belt to the east of Bhadravati and gave an impressive synthesis of the structure, stratigraphy and geological evolution of the Late Archaean volcano-sedimentary rocks and their basement. They divided the Dharwar Supergroup of the area into seven Formations as

Naganna et al. (1976) have carried out the mineragraphic study of the Devanararasipura deposit.

Jayaraj et al. (1995, 1996) have discussed the widespread occurrences of hōgbomite in the V-Ti magnetite of the area and the unusual occurrence of chromiferous magnetite and the possible existence of a solid solution between chromite and magnetite in the Hanumalapur ultramafic complex.


Devaraju et al (2004) published an account of the geochemical, petrological and PGE distribution in the dismembered ultramafic lenses in Peninsular gneisses east of Channagri mafic-ultramafic complex. The study revealed that most part of this block consists of chromite-banded, dunite-peridotite-pyroxenite with occasional small pods of chromitite and fine grained Al-Fe-rich chlorite rock. However, mineralogical and geochemical data obtained for these lenses was not encouraging from the point of PGE mineralization.

Devaraju et al (2005) came up with an account of SEM-EDS based mineralogical study of outcrop samples of the PGE mineralized Hanumalapur segment and the study revealed the presence of more than 25 different PGMs. Among these sperrylite, stibiopalladinite, hollingworthite, keithconnite, mertieite II, laurite, ruarsite together with a suite of Pt and Pd alloys, constitute the more important carriers of PGE in the segment. Also, recognizing the close association of PGMs with chromite-bearing host
rocks, it is inferred that crystallization of chromite had the governing control over mineralization in the segment.

Devaraju et al. (2007a) 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). More than 200 Electron Probe analyses obtained by them show the existence of virtually unaltered and distinctly altered spinel. The former representing the whole range of Al-Fe chromite and the latter Cr-magnetite-magnetite. The chemical variations of Cr-spinels are attributed to distinct petrogenetic processes of ultramafic complexes. The 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.

Devaraju et al (2007b) presented an account on petrological mineralization and mineralization study based on the outcrop samples of the Channagiri mafic-ultramafic complex in general, and Hanumalapur segment in particular. They also gave a preliminary account of exploratory drill core investigation. Lithological zonation and layering of PGE mineralized Hanumalapur segment in the form of outer gabbroic, inner ultramafic zone and the interference zone of magnetite is highlighted with a 1:2000 scale map of the segment. This study also dealt with petrography of the all the lithological units, and has brought the light that the localization of commercially interesting PGE mineralization is mainly to the chromite bearing fine-grained ultramafite and eastern magnetite seam and postulated that the mineralization is chromite controlled and resembles well known UG2 of the Bushveld Complex and SJ reef of the Penikat. Based on detailed drill core log information existence of three reefs of 20, 30 and 35 cm thickness analyzing 3.7-5ppm Pt+Pd within 5m zone at depths of 97 to 102m of intersection is recognized.

Alapieti et al (2008) have given an account on exploration work carried out in the sulfide poor PGE mineralized Hanumalapur complex. They have presented a brief account of geological, geophysical, mineralogical, geochemical and preliminary beneficiation studies carried out by them. The authors have identified four distinct types of PGE mineralization in the segment. They are: (i) a silicate-hosted Pd type, (ii) a silicate-hosted Pt type, (iii) a base-metal sulphide hosted Pd type and (iv) an oxide-hosted PGE type. These authors have suggested that magma mixing and
resultant sulfide immiscibility during crystallization of ultramafic magmas possibly brought about PGE mineralization.

1.8 General Geology

1.8.1 Dharwar Craton

The area studied forms a part of western block of Dharwar Craton. The Archaean Dharwar craton lies between longitudes 72° 45'- 80° and latitudes (Fig. 1.2), covering an area of 4.5 lakh km². 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. The terminology Dharwar Craton was first proposed by Pichamuthu (1962) and summerised its geology under the same title (Pichamuthu, 1974; Pichamuthu and Srinivasan, 1983). It is bounded to the south by Pan-African Pandyan mobile belt (Ramakrishnan 1990, 1991); to the north by the by Purana (Middle to upper Proterozoic) sedimentary basins of Kaladgi, Bhima and Tertiary volcanic province of Deccan, to the NE by the by Palkal-Purana basin which is overlain by the Gondwana sediments of Goadavari graben; to the east by Proterozoic Eastern Ghat mobile belt and to the west by Arabian sea (Fig. 1.2).

The Craton is sub-divided into two tectonic blocks, Western and Eastern, after Swami Nath et al. (1976) on the basis of distinct changes in the lithology, volcano-sedimentary environments, magmatism and grade of metamorphism. The Western and the Eastern blocks were renamed respectively as the Western Dharwar Craton (WDC) and Eastern Dharwar Craton (EDC) by Rogers (1986). WDC and EDC are separated by Chitradurga shear zone (Fig. 1.2), it is situated along the eastern margin of the Chitradurga schist belt. It is now interpreted that the western block forms an older Archaean Peninsular gneissic nucleus, older than 3.0Ga and the eastern block consisting mainly of granitoids is a mobile belt made up largely of younger more potassium-rich granites and reactivated gneisses ranging in age from 2.5 to 2.6Ga (Jayananda et al. 2006) known as Dharwar Batholith (Chadwick et al. 2000). The Archaean gneissic complex of the WDC called ‘Karanataka Nucleus’ by Radhakrishna and Naqvi (1986), is dominated by the 3.4 to 3.0 Ga TTG Peninsular Gneisses (Beckinsale et al. 1983; Bhaskar Rao et al., 1992; Meen et al., 1992; Peucat et al., 1993) includes several supracrustal groups. 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, Canada and South Africa.

Fig. 1.2: Map of Dharwar Craton showing the broad geology of EDC and WDC (from Project Vasundhara, GSI, 1994)
1.8.2 Mafic-ultramafic complex of WDC

The area studied forms a part of Archaean WDC of Shimoga supracrustal belt and contains largely ~ 3 Ga old basement granitoids and Late Archaean supracrustals with mafic-ultramafic rocks. WDC has witnessed repeated mafic-ultramafic magmatism from 3.4 Ga to about 62 Ma. 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 (Devaraju et al. 2009)

The WDC is characterized by three major episodes of mafic magmatism (Ramakrishnan, 2009), namely

1. Mafic-ultramafic magmatism of Mesoarchaean (3.1 – 3.3 Ga) Sargur Group
2. Bimodal mafic-felsic magmatism of Neoarchaean (2.6-2.8 Ga) Dharwar Super Group
3. Proterozoic mafic dyke swarms (2.4, 2.0-2.2 and 1.6 Ga).

Each of these mafic magmatic cycles has significantly contributed to the changes in crustal configuration at different times in the evolutionary history of Dharwar Craton. There is no quantitative data available regarding the time span covered by these mafic-ultramafic complexes, but, considering their field relationships, petrography and geochemical information, it is believed that they are all genetically related and their emplacement took place in the early stages of basin formation and deposition of the supracrustal sequence.

The well known older ultramafic-mafic bodies in Peninsular gneisses of WDC constitute a part of Sargur belt, Holenarasipur Schist belt, Nuggihalli schist belt, Krishnarajpet belt, Hadanur belt, Melukote and Nagamangala, Kalyadi belt, Shivani-Antharaghatta belt, JC Pura and other Supracrustal belts.

The major mafic-ultramafic lenses/pods/complexes occurring in the Dharwar super group viz. Usgao, Mulemane, Kaiga, Ramanaguli,. Kumbarwada-Tevali, Ankola, Joida, Channagiri, Devanarasipur, Sakrebyle and Shankaraghatta form a girdle
parallel to the western and southern borders of the Shimoga schist belt and possibly define a late Archaean hot-spot zone. Many of the mafic-ultramafic bodies of the belt are well known hosts of V-Ti magnetite deposits. They are also known to host chromite deposits.

The mafic dyke intrusions occur throughout Dharwar craton and have emplaced over a protracted period from 2.4 Ga to about 1.6 Ga (Table 1.4) of which majority are of 2.0-2.2 Ga and 1.6 Ga. The dykes in the northern part of the Craton are essentially unmetamorphosed. Whereas, in the southern part of the craton we also have mafic dykes that have undergone amphibolite-granulite facies of metamorphism. The main types of mafic dykes are dolerite, quartz dolerite, olivine-dolerite and epidiorite with local gabbroic, pyroxenitic, lherzolitic and anorthositic variations. Geochemically most of the dykes show signatures of tholeiitic and sub-alkaline magmas of both continental and oceanic affinity.

1.8.3 Shimoga Basin

General geology

The Shimoga supracrustal belt is the largest of all the schist belts of Karnataka (Radhakrishna, 1984). It consists of volcano-sedimentary sequence of rocks. It extends from Tarikere valley to Goa in a north and northwesterly direction for a length of 250km, has a maximum width of 120 km (at Dharwar) occupies about 25,000 sq. km and is < 1 km to 8km thick.

The main rock formations of the belt belong to the Chitradurga Group. The Bababudan Group has limited extent and overlies the basement gneissic domes of Londa, Chandragutti, Kumbharwada, Shimoga, Honnali, Saulanga and the cluster of domes between Tarikere and Channagiri study area. A thick sequence of meta-greywackes occupies the northern section of the schist belt. The southern part of the belt, which generally comprises of an association of metabasalts and metasediments, occupies the interdomal gaps of Peninsular gneisses.

The belt is known to include several mafic-ultramafic bodies, which intrude both basement granitoids and the supracrustal sequence (Fig. 1.3a). These occur as pods, lenses, sills and small stock-like bodies and show conformable to sub-conformable relationship with the adjoining lithounits. Many of the bodies form dismembered/segmented arrays. Many of the mafic-ultramafic bodies of the belt are
well known hosts of V-Ti magnetite deposits. They are also known to host chromite deposits, but less commonly. Evidence of PGE mineralization is reported in two of these bodies viz., the Hanumalapur segment of Hegdale Gudda Formation (Devaraju et al 1994, 1994a, Alapieti et al 1994) (Fig. 1.3b) and the Shankaraghatta ultramafic body Ni-Au-PGE mineralization, 20 km SSE of Shimoga (Devaraju et al. 2004).

**Lithostratigraphy**

The generalized lithostratigraphy of the western Dharwar Craton is given in Table 1.4 (Devaraju et al. 2009). Available limited isotopic age data has indicated that the Shimoga supracrustal belt consists of 2.5 to 2.9Ga old late Archaean volcano-sedimentary stratigraphic sequence overlying 3 to 3.4 Ga old middle Archaean basement granitoids (Radhakrishna and Vaidyanadhan 1997). There is no isotopic age data available for any of the rock formations of the Hegdale Gudda Formation of the Channagiri-mafic ultramafic complex and the associated rocks of the study area. However, extending the information obtained for the adjoining Chikmagalur granodiorite and Bababudan and Chitradurga Supracrustals (Taylor et al. 1984), it is presumed that the basement granitoids are around 3.0 Ga old and the supracrustals are younger and the dyke intrusions are still younger. The Hegdale Gudda a formation is classified to occupy lower part of the supracrustal succession of the Shimoga belt (Chadwick et al., 1988) (Table 1.4). Contact between the supracrustals and the basement granitoids are broadly concordant. It is regarded here that the granitoids of the area are a part of the multiphase Peninsular Gneissic Complex.

**Structure**

The structure of the Shimoga belt (Fig. 1.4) is characterized by southwest verging folds in the Dharwar schists and by north dipping reverse faults forming the southern boundaries of basement domes like Tarikere, Honnali and Shimoga. The northern boundaries of these domes represent unconformities steepened by folding. Horizontal sinistral displacement is noticed in some shear zones. The basement gneisses on the other hand, are deformed in myriad brittle fracture as well as ductile, mylonitic shear zones. The major shear zone at the eastern margin of the belt, extending from Bababudan belt, as numerous iron formation bands within greywackes swerving into
Fig. 1.3: Geological map of Bababudan-Western Ghats and Shimoga belt (a) (from Radhakrishna and Vardyvaadhavan, 1997). Study area shown in blue colored oval. (b) Geological map of the area south of Channagiri (Chadwick et al., 1988).
<table>
<thead>
<tr>
<th>Felsic magmatism related rocks</th>
<th>Age (in Ga)</th>
<th>Mafic dyke intrusions &amp; Supracrustal Groups</th>
<th>Age (in Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neoproterozoic lamprophyre-diorite-monzonite-tungsite dyke intrusions</td>
<td>~0.8 7,8</td>
<td>U. Cretaceous – Early Tertiary</td>
<td>Mafic dykes related to Deccan volcanism</td>
</tr>
<tr>
<td>Chamundi granite</td>
<td>~0.8 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesoproterozoic</td>
<td></td>
<td>Younger mafic dykes</td>
<td>1.4 – 1.6 12</td>
</tr>
<tr>
<td>Palaeoproterozoic</td>
<td></td>
<td>Older mafic dykes</td>
<td>1.9 – 2.4 5,10,11,12</td>
</tr>
</tbody>
</table>

Table 1.4: Lithostratigraphic sequence in the Western Dharwar Craton (Devaraju et al. 2009)

| Closepet Granite and other potassic-granites | 2.5 – 2.6 8,6 | | |
| Channagiri Fm.: Phyllites with dolomitic lenses - quartzite - congl. | | | |
| Devaragudda Fm.: Phyllites interbedded with quartzite & dolomitic limestones - congl. | | | |
| Kurgudda Fm.: Phyllites with BIF, dolomitic limestone, quartzite interbands, polymict congl. | | | |
| Stilimaha Supracrustal Group | | | |
| Hiriyur Fm.: acid vol - mafic volcanics - pyro clast - cherts - polymict congl. | 2.46 – 2.52 6 |
| Ingaldhal Fm.: cherts - phyllite - acid vol - mafic. | 2.65 3 |
| Vanivilas Fm: Fe-Mn fm. - carbonates - phyllite - cherts - Taliya-Dodguni polymict congl. | | | |
| Chitrardurga Supracrustal Group | | | |
| Mullaligiri Fm: BIF interbedded with chlorite & graphitic schist | 2.72 8 |
| Santaveri Fm.: Acid vol. - pyro clast - cross bedded quartzite - mafic volcanics | 2.85 8 |
| Allampura Fm: Metaproxenite and gabbro - with interbedded quartzite | | | |
| Bababudan Supracrustal Group (Western Ghat belt, northern part of Holenarasipur belt) | | | |
| Kalaasapura Fm.: Amygdoidal basalts - interbedded with quartzite & phyllite | 2.91 8 |
| Hegdale Gudda Fm.: Ultramafic-mafic complexes with magnetite seams and minor phyllites & quartzite | | | |
| | | | |
| Peninsular Gneiss II (older charnockite) | 2.9 – 3.2 4,8 | | |
| Peninsular Gneiss Phase I | 3.3-3.4 7,3 | | |
| Sargur Group | Nuggihalli, Krishnaraj pet, Holenarasipur, Nagamangala, Javanahalli and Ghattihosahalli belts | | |
| - Ultramafic complex | - Fe-Mn formation - carbonates - m etapetites - amphibolites - pyroblolites. Cr-quartzite with local barite and chromite layers | > 3.3 – 3.4 4,8 |

it near Harapanahalli. Abundant carbonates seen in fractures attest to the role of CO₂ activity. These events denote two period of deformation. The evolution of Shimoga belt is governed by sinistral transgression in an ensialic-slip mobile zone (Chadwick, 1994).

Fig. 1.4: Map showing structures in a part of Shimoga belt (after Chadwick, 1994)

The structural characteristics of the Supracrustal sequence in the study area are as follows:

The overall synclinal fold structure identified in the cover rocks includes much of the Kur Gudda Formation (Fig. 2.2). The strongly marked fabrics in the cover rocks include bedding parallel-preferred orientation of phyllosilicates in all the lithologies. This is related to primary deposition and compaction phenomenon. Preferred linear and planar orientation of detrital grains and clasts are normal structural feature. Rotation of clasts and modification of grain shapes by pressure action has given rise to LS fabrics of cover rocks.
The fabrics of basement rocks include shear planes (S-fabric) of variable magnitude. The association of linear fabrics with the intense S-fabrics of basement domal blocks suggests variable displacement directions in each of the blocks. The LS fabrics in the basement rock were generated during post-depositional deformation of the cover. The systems of fractures and narrow shear zones common to most basement outcrops are presumed to be related to less ductile deformation of some areas of the basement. Prolific flushing of fluids including water and carbon dioxide through the basement and cover rocks during deformation is indicated by profound retrogression of both basement and cover rocks to assemblages rich in chlorite and carbonate. The centrally located Main Boundary Fault of the area has been identified on the basis of termination of Dharwar Supergroup comprising of Hegdale Gudda, Kur Gudda and Tuppyahalli Formations and to some extent by the presence of a well marked shear zone (Fig. 2.2)

**Metamorphism**

The Dharwar craton as a whole displays a progressive transition from low-grade in the north to high grade metamorphism in the south. The whole Archaean crust is affected by a major thermal event close to 2.5 Ga which is spatially associated with a major episode of juvenile continental accretion and reworking (Jayananda and Peucat, 1996 and Jayananda et al. 2000).

In the northern part of WDC supracrustal lithologies include mafic rocks and associated metasediments indicate the P-T conditions in the range of 3-4 kbar/400° c in the Bababudan area (Chadwick et al., 1981), which is agreement with low P-T estimates for the greenschist facies conditions further east of Chitradurga area (Raase et al., 1986). The lithounits of the Bababudan-shimoga schist belt bear evidence of mostly low-grade metamorphism in the range of green schist to low-amphibolite facies (Anantha Iyer, 1994).

The lithounits of Channagiri mafic-ultramafic complex viz. peridotite, gabbro and anorthosite have undergone penetrative hydrothermal and low-grade (green schist-low-amphibolite facies) metamorphism coupled with strong shearing. The original structures, textures and mineralogy of the lithounits of the complexes are completely altered and there are no relics of original dunite/peridotite/gabbro in the complex.