STUDIES ON THE
STRUCTURE, PETROLOGY AND CHROMITE DEPOSITS OF
PAUNI - BHIWAPUR AREA, MAHARASHTRA.

THESIS SUBMITTED BY

N. G. K. NAIR, *M. TECH.*

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DEPARTMENT OF GEOLOGY & GEOPHYSICS
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Petrology
Chromite Deposits

The thesis entitled "STUDIES ON THE STRUCTURE, PETROLOGY AND CHROMITE DEPOSITS OF PAUNI-BHIWAPUR AREA, MAHARASHTRA" presented by Shri N. G. K. Nair, M. Tech. embodies the results of investigations carried out by him from October, 1963 to July, 1968 as a full time research worker in this University. The work was done under my supervision and guidance. I certify that this work has not been presented for the award of any other degree or diploma.

K. K. SINGH, *M.Sc., Ph.D.*
Reader in Applied Geology
Department of Geology & Geophysics
University of Roorkee
Roorkee (U.P.), India

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ABSTRACT

The present work includes a scientific study of the structure, petrology and the chromite deposits of the Pauni-Bhiwapur area comprised largely of the Pre-Cambrian rocks of the Sakoli series. Interrelations of different rock units of the area, covering over 160 sq.km. and their stratigraphic sequence have been established on the basis of detailed geological and structural mapping. The lithology and general disposition of the various formations have been worked out. A brief discussion on the regional stratigraphy of the Sakoli rocks has been included with a view to facilitate correlation. Field data of different structural elements were used for the geometrical analysis of fold systems, with the help of selective and synoptic π and β diagrams. This, in turn, has made it possible to infer the tectonic history of the area.

Qualitative and quantitative petromineralogic studies of different rock units consisting of igneous, metamorphic and sedimentary types have been carried out and their petrography is discussed in detail. The data obtained from the mechanical analyses of sandstones of the younger sedimentaries as well as of their heavy mineral content have been used for the study of environmental conditions of deposition.

The genetic aspects of the various rock types, particularly the amphibolites, the granites and pegmatites and the iron ores have been deciphered from their field relations, mineral paragenesis and their grade of metamorphism. A brief review of the various ideas on the genesis of granites is presented.

The distribution, shape and size of the Pauni ultrabasics have been studied. The petrographic studies of various mineral assemblages

comprising the ultrabasics havebeen carried out. The different stages of hydrothermal changes suffered by these rocks have been discussed. A review on genesis of different types of ultrabasics is also given followed by a discussion on the origin of the Pauni ultrabasics.

The localisation of the chromite deposits, their structure,shape, size and types have been studied. An examination of several thin and polished sections, has revealed their texture, optical characters, and mineral associations. The major and trace-elements of 13 purified chromite samples of the area were determined by chemical and spectrographic analyses respectively. The interrelationship of various elements in the chromites and their variations have been established. A review of the chemistry of chromite is given in some detail. The genesis of the Pauni chromites has been discerned from their field features and megascopic and microscopic characters.

Mining methods applied for the exploitation of the chromite deposits have been examined. Various methods of prospecting and exploration for chromite deposits in general and their suitability in the present area have also been discussed. Further, a brief discussion on the beneficiation,production, reserves, grade, utilization and future prospects of the chromite deposits is given . Conclusions based on the above studies have been summarised in the last chapter.

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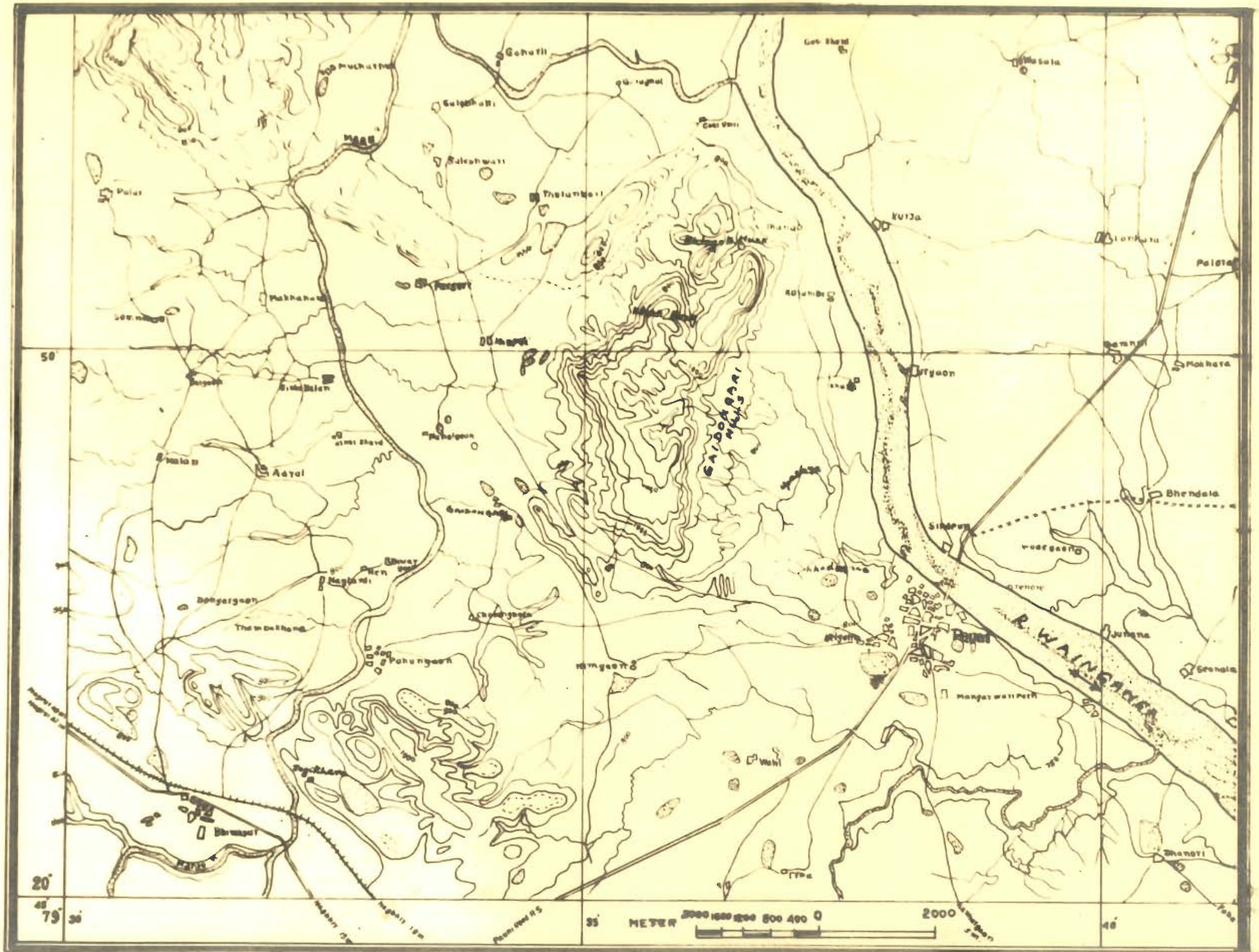
55 P/9



MAP No.1

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CHAPTER - I

INTRODUCTION

1.1. LOCATION OF THE AREA

The area under investigation covers over 160 sq.Km. around Pauni (20°47': 70°39') and Bhiwapur (20'49' : 79°32') towns in Bhandara and Nagpur districts of Maharashtra state. It falls under the Survey of India toposheet No.55 P/9 within latitude 20°31' to 20°42' and longitude 79°45' to 79°52'. About four-fifth of the area lies under Bhandara district which is demarcated from Nagpur district in the west by the Maru river. Pauni town is situated on the right bank of the Wainganga river. It is 83 Km. south-east of Nagpur and 42 Km. south west of Bhandara, and is connected with these places by metalled roads. Bhiwapur town is 15 Km. southwest of Pauni. The area is also connected by a narrow gauge railway line (Nagpur-Chandrapur-S.E.Rly.). Pauni Road (8 Km. southwest of Pauni) and Bhiwapur are the two railway stations (Map.1.)

1.2. PHYSIOGRAPHY AND DRAINAGE

In general the area represents a matured topography. A large part of the area is low lying plains with a mantle of alluvium or soil. The area south of Pauni forms an undulating topography (Map. 1.).

To the northwest of Pauni, the Gaidongari hills, elongated in NNE-SSW direction forms the most prominent topographical unit and extend in length for over 6.5 Km. with an average width of 2 Km. The maximum height attained by these hills is 400 m. from sea level, and about 130 m. from the plains. The eastern flank of the hills runs in an unusual straight alignment indicating the presence of a fault-f_1 (refer page 44). The rounded corners with a change in their elongation direction of these hills on the southern,western and the northern side are indicative of major folds(Map 1 & 2). These hills are composed mainly of meta-argillites, slates and conglomeratic slates. Generally the hills are residual in nature produced by differential weathering of hard and soft rocks. A separate elongated and discontinuous hill east of Gaidongari (20°48' : 79°34') and Mahalgaon (20°49':79°33') is formed of quartzites. The valley in between this hill and the major hills, and the adjoining lower grounds are composed of slaty shales and banded slaty shales and soft schists. A small elongated hill lying southeast of Thutanbori(20°51':79°34') extends in NE-SW direction, and the hill north of Parsori (20°50':79°33') extends in NW-SE direction. These hills are composed of comparatively softer rocks such as mica-chlorite schists.

North of Bhiwapur two hills trend along WNW-ESE for about 5 Km. In between these hills lies the valley of the Maru river. The average width is about 1.5 Km. and the maximum height attained is 360 m. from the sea level and about 100 m. from the plains. The alignment of the hill range is generally parallel to the strike of the rock units. The ridges and the higher elevations are occupied by hard quartz-phyllites, whereas the lower levels are formed of softer phyllites. There are several small hillocks representing as offsets and bifurcations of the main hills. The elongation of many of the hills exhibits parallelism with foliation of the rocks.

It would be evident later that the physiography of the present area is much governed by the structure in particular and lithology in general.

The Wainganga is an important perennial river of the area. It is a tributary of the river Godavari and flows towards southeast. It is a source of permanent water supply to the local population. In the west, Maru river, a tributary of Wainganga, flows towards north. It is a seasonal stream flowing only during rainy seasons. A small seasonal stream, Donrich, south of Pauni, flows from west to east. There are two seasonal nullahs(streams) traversing the plains north of Pauni; (i) Upashya nala* starting from the southern slopes of Gaidongari ranges, joins the Wainganga two Km. south of Khatsi(20°50':79°37'). Numerous streamlets join this nala from the eastern flank of Gaidongari hills (ii) Khadan (quarries) nala lying north of chromite quarries flows from west to east and joins the Wainganga about 1 Km.north of Pauni.

1.3. CLIMATE AND VEGETATION

Like other parts of central India, the area has a hot and humid climate with an average rainfall of 120 cm. The rainy months are July to September. The temperature during summer (May - June) ranges between 27° C and 42° C and lowest temperature during winter(December-January) goes down to 6°C.

* nala equivalent to nullah

The hills and their slopes are thickly forested, with wild animals. The important types of trees are Saja(Terminalia Tomontose), Dichamalis, Sal (Shorea robusta), Mahua (Bassia latifolia),Tenthu (Diospyros peregrina), Dhaura (Lagerstroemia) and Amla (Emblica officianalis).

1.4. PREVIOUS WORK

From the geological point of view the southern part of Bhandara district is one of the neglected Pre-Cambrian terrains of India. Although many workers have made contributions to the geological knowledge of the northern part of Bhandara presumably due to the known occurrences of manganese, kyanite and sillimanite deposits, very few attempted any detailed geological investigations in the southern region. It was only after the discovery of the occurrence of chromite in the Pauni area in the second half of the fifties, the southern Bhandara began to receive attention from the Geological Survey of India.

The earliest recorded work of this area is that of Bhattacharji,(in Fermor,1934). In the General report of the Geological Survey of India for 1933, the work of Bhattacharji is summarised in the following lines " This area lies partly in the Nagpur and partly in the Bhandara district, and is occupied by alluvium (of the Wainganga river), Vindhyans, Dharwarian rocks of both Sausar and Sakoli types and the gneissic complex. The Vindhyans form small exposures by the Wainganga in the neighbourhood of Pauni, and are composed of gently dipping sandstones, with an overlying conglomerates, and a coarse gritty basal sandstone resting on steeply dipping gneisses and schists. These rocks are deduced to be of Vindhyan age from the agreement of their strikes and general character, with the rocks mapped as Vindhyans by Mr. P.N.Dutta, a few miles to the south".

In 1956, Paithankar published a brief note on the occurrence of chromite near Pauni. He has mentioned the rock formations of Pauni to be composed of muscovite-chlorite gneiss, quartzites, phyllites, hornblende-schists, talc-schists, talc-chlorite-schists, chlorite-albite-zoisite schists, tremolite-chlorite schists and pegmatites. The same author in another brief paper (1960) 'on the petrography and origin of the chromite bearing rocks of Pauni', concludes thus, "Pauni chromite is associated with hornblende schist, tremolite-chlorite schist and related rocks which represent various stages of dynamothermal metamorphism of basic and ultrabasic igneous rocks. In the absence of any original igneous rocks, the origin of Pauni chromite is rather obscure. But the fractured chromite grains and the association of the ore with various deuteric minerals such as talc, tremolite,chlorite and serpentine weigh more in favour of the view of Fisher,(1929), Verner Jones, (1931), that Pauni chromite is mostly of late magmatic and hydrothermal class".

Sinha,(in Roy, 1962a) examined the chromite occurrences of Pauni. According to him the country rocks around Pauni is granite, intruded by pegmatite and also by a number of ultrabasic dykes, which contain chromite grains and bodies with conspicuous serpentinization in the mineralised zones. Sinha and Srivastava(in Roy,1962 b) carried out survey of the chromite deposits near Pauni. However, the text of the report is unpublished.

Sahasrabudhe, (in Roy 1962c) mapped an area of about 160 square Km. included in toposheet 55 P/9 in the Umrer and Bhandara Tehsils. Conglomerates, sandstones,quartzites,greywackes,phyllites shales. etc. of the Sakoli series (Archaeans) have been mapped for the first time as separate units. However, the geological map or the text of the investigations of Sahasrabudhe has not been published so far.

During the course of this investigation, the present worker has published part of his work on the following topics:

1. Geology and the associated chromite deposits of Pauni area, Bhandara district (Abstract-1966).
2. Hydrothermal alterations in the ultrabasics of Pauni area,Bhandara district (Abstract-1966)
3. On the occurrence of Vermiculites at Pauni, Bhandara district(1966)
4. Genesis of the chromite deposits of Pauni,Bhandara district (Abstract-1967).
5. Iron.ore deposits around Bhivapur,Nagpur-Bhandara districts, Maharashtra (Abstract-1967).
6. On the localisation and structure of the chromite deposits of Pauni area, Bhandara district (under publication-1968).

1.5. SCOPE OF THE WORK

The Pre-Cambrian rocks (Sakoli series) of Bhandara district present a complicated structural pattern. In the tectonic map of India, (fig. 9) three major structural trends meet in the Bhandara region, which is known as the 'Bhandara Triangle'. Krishnan (1960) has expressed the hope that detailed structural and stratigraphic work in the region would throw much light on the tectonic history of the Peninsular shield. In view of the above structural importance coupled with the occurrence of newly discovered chromite deposits, the present area called attention for detailed investigation. With these objectives in view Dr. K.K.Singh initiated the worker into the present investigations. As no systematic geological work has been done in the area previously it was hoped that the work undertaken would bring out valuable informations regarding structure, petrography as well as economic aspects of the chromite deposits and associated rocks.

Field investigations

A total period of over 8 months spread over three field seasons(1963-1966) was devoted for the field investigations. The area was visited by the present worker for the first time during December 1963 and January 1964. A reconnaissance survey of the chromite deposits and the geology around Pauni was carried out during this period. Detailed geological work extending for five months was done from December 1964 to April 1965. A month was devoted during May-June 1966, for the final field work, when the geological map was finalised and certain structures were confirmed.

The following works were carried out in the field:

1. Detailed geological and structural mapping of the area on 1: 10560 scale map.
2. Survey (Brunton Compass) and geological mapping of the quarries on 1:300 scale map.

3. Preparation of diagrammatic plans, sections and sketches of various important geological features.
4. Collection of systematic and representative samples of all types of rock units, especially of the ultrabasics and of the chromite ores.
5. Study of the working and methods of exploitation and collection of economic data of various quarries.

Laboratory investigations

All the laboratory investigations except the chemical analysis of chromite ore were carried out at the Department of Geology and Geophysics, Roorkee University. The chemical analysis was done at the Geochemical laboratories, Patna University.

The Laboratory investigations are enumerated below:

1. Preparation of Bibliography and perusal of uptodate literature on relevant subjects.
2. Petrographic studies: (a) Study of the physical characters of samples; (b) Study of rock and ore sections under the petrological microscope.
3. Ore-microscopic studies: (a) Study of polished sections of chromite and iron ores of the area under reflected light; (b) Determination of paragenesis of ore minerals.
4. Sedimentary petrographic studies of the sandstones, including mechanical and heavy mineral analyses.
5. Chemical analysis: 13 chromite samples were selected and analysed which included the following: (i) Separation of pure chromite from the ores (ii) Determination of major elements (iii) Determination of trace elements (iv) Calculation of mineral formulae

and norm of the chromites (v) Comparative study of the chromite ore with those of other ores in India.

6. Structural analysis (megafabric) of the Pre-Cambrian rocks with the help of selective and synoptic π pole and β pole diagrammes of various S planes in the different sectors and sub-areas, their interrelation and their critical comparison with the data from adjacent areas. Based on the above analysis discussion on the tectonic evolution of the area.
7. Classification of the chromite bodies and ores based on their structure, association, physical characters, and assay values.
8. Calculation of ore reserves with the help of the data available and from records of the quarries.

Discussions

Based on the findings of the above field and laboratory studies, this thesis was prepared which broadly covers the following aspects:

1 Geological set up and stratigraphic correlation of the country rocks and the intrusives.

2 Structure of the area.

3 Petrography of the various rocks.

4 Genesis and metamorphic history of the country rocks.

5 Occurrence, origin and mode of emplacement of the ultrabasic rocks. Their petrography and hydrothermal changes.

6. Occurrence, mineragraphy and genesis of the chromite deposits.

7. Geochemistry of the chromites.

8. Economic aspects of the chromite deposits. Its mining, exploitation and reserves.

GEOLOGICAL MAP, MAHARASHTRA PLATE No. III MAP No. 2

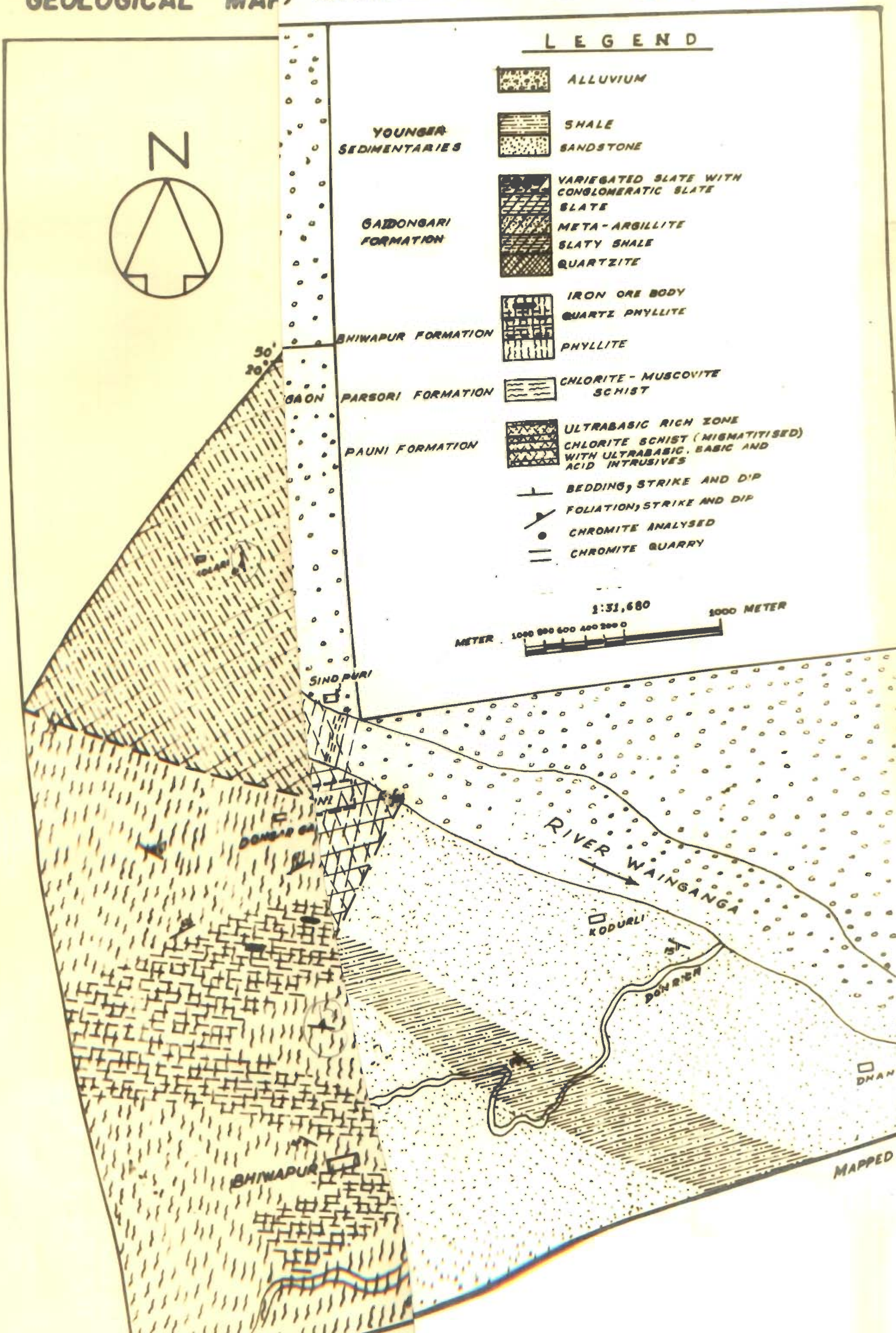


TABLE - 1

GEOLOGICAL SUCCESSION OF PAUNI BHIWAPUR AREA

	Alluvium	Recent
	Laterite	Pleistocene or later.
YOUNGER SEDIMENTARIES (> 3000 m)	Shales, sandstones and conglomerates	Gondwana?
	Erosional and tectonic unconformity	
	Metabasics	Sakoli Series / ARCHAEAN
GAIDONGARI FORMATION (>5000 m.)	Conglomeratic slates, variegated slates, slates, meta-argillites, slaty shales and quartzites	
	Tectonic unconformity	
BHIWAPUR FORMATION (> 3000 m.)	Phyllites, quartz-phyllites and associated iron ore bands	
	Tectonic unconformity	
PARSORI FORMATION (> 1000 m.)	Chloritoid-chlorite-muscovite schists	
	Tectonic unconformity	
	Granites and pegmatites	
	Metabasics (Amphibolites)	
PAUNI FORMATION (>5000 m.)	Altered ultrabasics containing chromite ore	
	Igneous unconformity	
	Chlorite schists and the associated grunerite-quartz-magnetite rocks	

An orderly sequence of the various rock formations of the area could not be properly established due to the structural complexity. However a tentative geological succession of the rock formations of the area is shown in Table-1.

In the following pages an account of the field characters of the various rock types of different formations and their interrelations has been given.

2.2. PAUNI FORMATION

2.2-1. CHLORITE SCHISTS

The chlorite schists occupying the lower grounds form the main country rocks around Pauni. At places few bands of quartz-grunerite-magnetite rocks are interlayered with the chlorite schists. The chlorite-schists were intruded later by ultrabasic, basic and acid bodies. The strike of foliation of these rocks varies from NW-SE to ENE-WSW with high dips (50°- 80°). In the southern part of Pauni the foliation dips towards north and in the northern part it is southerly dipping. A major synform fold has been deduced from the structural analysis (refer page 67 Pauni sector). The schists are generally very soft and weather easily, hence most of the schist bearing area is covered with soil. Good exposures of the chlorite schists are observed along the Upashya nullah and the Khadan nullah. Towards west and north-west, this Formation is separated from the Gaidongari Formation, by the Nimgaon-Korambi fault f1, running approximately NNE-SSW. Along this fault the quartzites, slaty shales, and meta-argillites of the Gaidongari Formation abut against the chlorite schists.

The chlorite-schists have been migmatitised to various degrees due to the injection of quartzo-felspathic materials. Hence their original composition and texture have been much obliterated. The altered products range from migmatites (lit-par -lit injected quartzo-felspathic material along the foliation planes of the schists)to gneisses. These rocks can be grouped under arterites or injection gneisses of Sederholm (1923). Pure chlorite schists unaffected by migmatitisation, are observed only at few places eg. at the base of the Younger Sedimentaries along the Wainganga river.

Quartz-grunerite-magnetite rocks

Few bands, consisting of quartz, grunerite and iron ore minerals in various proportions occur at some places, interlayered with the chlorite schists. Good outcrops are observed on the right bank and in the bed of the Wainganga near Itgaon (20°57':79°38')in between Khatsi and Itgaon, and to the east of Khatsi. The last mentioned is about 20 m. in width, striking in 40°-220°and dipping 65° towards southwest. An outcrop seen at Diwanghat near Pauni is 2 m. in width with a N-S strike. Another exposure observed in a tributary of Upashya nullah trends NW-SE. Here, a banded quartz-grunerite-magnetite body of about 5 m. thick is associated with a quartz-grunerite rock; the latter is flanked on the north by a 1.5 m. thick quartz vein. These rocks are comparatively harder and form elevated outcrops.

2.2-2 ULTRABASICS

The ultrabasic intrusives occur as parallel, discontinuous lenses in the chlorite schists of the Pauni Formation. The general trend of the intrusives is WSW-ENE. The width of the belt as exposed in the Wainganga river is for about 2 Km. Strikewise extension has been established over 2 Km. towards southwest, while the northeast extension is obscured by a thick cover of alluvium. The ultrabasics have been intruded by the later basic and acid rocks. The field features of the ultrabasics have been discussed in detail in Chapter VI.

2.2-3. AMPHIBOLITES

Swarms of amphibolites (metabasics) are exposed in the Pauni Formation. Good exposures of the amphibolites are observed along the right bank of the Wainganga river, along the Upashya nullah and the Khadan nullah (Map 1).

The amphibolites occur as sills of lenticular form or as discontinuous bands, broadly conforming with the trends of foliation of the country rocks. At places smaller bodies show an en echelon pattern. The amphi-bolites strike NE-SW around Upashya nullah, while along the bank of Wainganga river their strike varies from NNW-SSE to ESE-WNW.

Generally the individual bodies vary in width from 1 m. to 5 m. However few bodies have a width upto 20m. for example, the amphibolite exposed on the river bed near Korambi village (20°50':79°37'). Thin bands having a width of 15-20 cm. are not uncommon. Since the outcrops of the amphibolites are generally covered with soil and as these are mainly exposed along the bank of the Wainganga, in nullahs, and quarry cuttings, their lateral continuity could not be properly established. Nevertheless, from the nature of occurrence of smaller bodies, it has been concluded that they pinch out within short distances (Fig.6,8).

PLATE No. IV

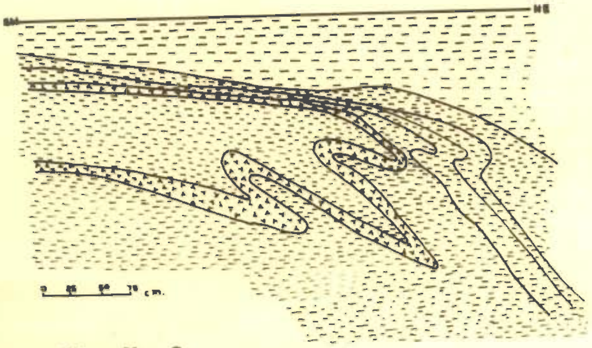
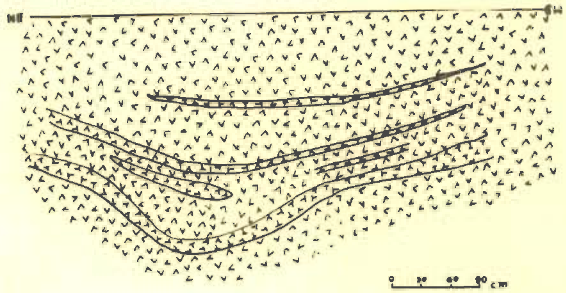


Fig. No. 2



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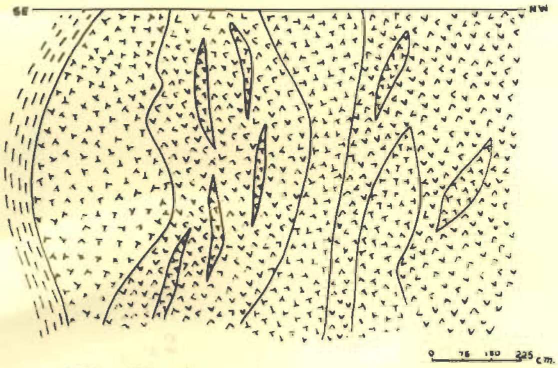

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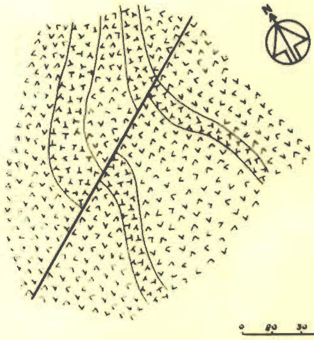

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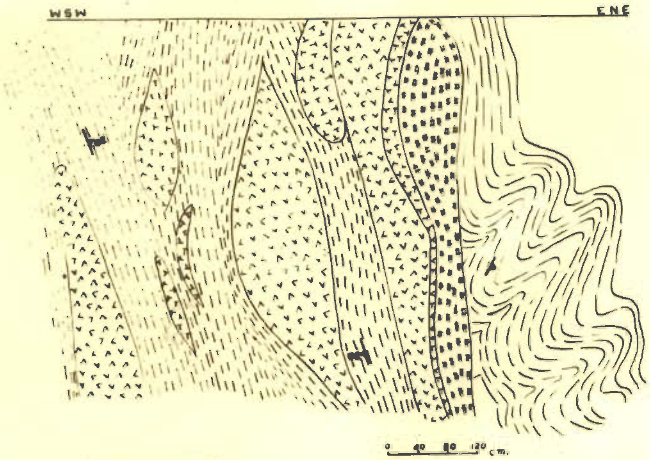

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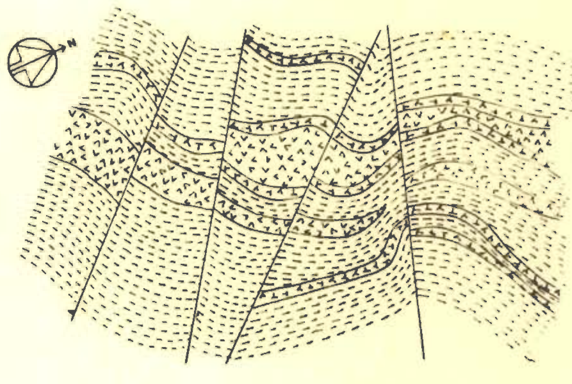

Fig. No. 7

INDEX

- GRANITE AND PEGMATITE
- AMPHIBOLITE
- ULTRA BASICS
- CHLORITE SCHIST

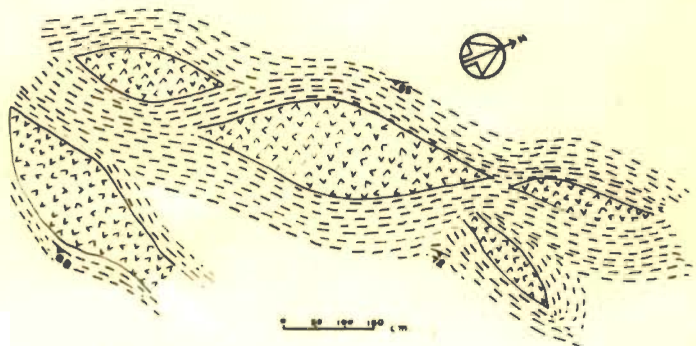

Fig. No. 8

PLATE No.IV

Fig.No.2	Section. Ptygmatic folds of quartz-felspathic veins in the country rocks. Location- near Diwan Ghat-Pauni.
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Fig.No.7	Closely spaced faults affecting the chlorite schists and intrusives. Location - Wainganga river bank, Itgaon.
Fig.No.8	Lenses of amphibolites showing en echlon arrangement. Location - Upashya nullah.

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Generally the individual bodies vary in width from 1 m. to 5 m. However few bodies have a width upto 20m. for example, the amphibolite exposed on the river bed near Korambi village (20°50':79°37'). Thin bands having a width of 15-20 cm. are not uncommon. Since the outcrops of the amphibolites are generally covered with soil and as these are mainly exposed along the bank of the Wainganga, in nullahs, and quarry cuttings, their lateral continuity could not be properly established. Nevertheless, from the nature of occurrence of smaller bodies, it has been concluded that they pinch out within short distances (Fig.6,8).

Contact effects

The contacts of the amphibolites with the migmatitised chlorite schists are rather sharp(fig. 8). However, narrow zones of hybrid rocks are a common feature. Gradational contacts have not been noticed in the area. The amphibolites are cut across by granite and pegmatite veins with sharp contacts (fig.4). The contacts of basic and ultrabasic rocks show actinolite rich zones. At places along these contacts, thin bands of crossfibre asbestos are observed.

At several places thin veins and bands of pegmatites are seen in the amphibolites along and across their cleavage planes (fig. 3,104) Further numerous minute veins of quartz criss-cross the amphibolites. Some of the amphibolites of Pauni area show partial migmatitisation, having lit-par -lit injections of quartzo-felspathic matter along their foliation planes.

Weathering

The amphibolites are weathered in some of the pits and nullah cuttings giving rise to light green to yellowish green clayey products. Locally ,few of the smaller bodies have been limonitized to various degrees giving a brownish yellow colour to the rock. Unaltered patches of green amphibolites are seen in these limonitized bodies.

Age

The field relations indicate that the amphibolites of Pauni Formation are younger in age to the ultrabasics but older to the acid rocks.

2.2-4. GRANITES,PEGMATITES AND RELATED ROCKS

Apart from the ultrabasic and basic intrusives, the Pauni Formation contains numerous lenticular bodies and sill like sheets of granites and pegmatites in the chlorite schists(fig.86). Like the ultrabasic and basic intrusives, the acid rocks also generally show concordant relationship with the foliations of the host rocks. Varietites of rock types ranging in character from very fine grained granites to coarse grained pegmatites and a few felspar rich bodies are exposed in the area. Some of the fine grained varieties show gneissose structure. Numerous exposures of the acid rocks are found along the Wainganga river bank near Pauni and along the Upashya and Khadan nullahs.

The lenticular acid bodies vary in width from 0.5 to 5 m.and in length from one metre to over 50 m. Small veins, bands and pockets of pegmatite bodies are also noted, showing both parallel and transgressive relation with the associated rocks. In some of the chromite quarries pegmatites have been observed cutting across chromite bodies(fig.66,70) Thin bands and veins of pegmatites are seen along the foliation,joint and fracture planes of some of the amphibolites. However, the majority of granites and pegmatites show structural kinship with the ultrabasics and the amphibolites. Some of the minor faults observed near Itgaon and in the quarry pits (GCS 3) have affected all the rock types (fig.57). Along the bank of Wainganga river some of the pegmatites forming discontinuous bands and lenses conform with the fold pattern of the host rocks (Map-5)

Thin quartz veins(1-25 cm.)traverse the pegmatites and granites along their joint planes and fractures.

<u>Contact effects</u>

The contacts of the pegmatites and granites with the older rocks are rather sharp,with thin zones of hybrid rocks(fig. 86). The contact of pegmatites and ultrabasics at several places shows irregular bands and veins consisting dominantly of tourmaline with subordinate amount of coarse grained quartz. Along the contacts with the amphibolites the acid rocks are of hybrid nature containing some green minerals.

Alterations

A large number of the granite and pegmatite bodies have been kaolinised to various degrees. The alteration appears to be localised along the weak planes and to a small depth, probably controlled by the meteoric water. At some places along the bank of the Wainganga the felspars in the pegmatites have been completely replaced by epidote, forming epidosites, with epidote and quartz as the only mineral constituents. Epidote veins traversing the pegmatites along weak planes have been noted at few places.

Age of the intrusives

As noted earlier, the granites and pegmatites cut across the ultrabasic and basic intrusives. It is quite evident that these acid bodies are younger in age to both ultrabasics and the amphibolites. Further, structural analysis of this part of the area (discussed later in page 69) has revealed that the pegmatites are of syntectonic origin.

2.3. PARSORI FORMATION

In the north of the area, the less metamorphosed Gaidongari Formation comes into juxtaposition with the more metamorphosed Parsori Formation. All along this boundary numerous quartz veins and reefs are observed. At several places the rocks near the contacts are sheared and accordingly the boundary represents a fault named as Pular-Parsori-Umri fault (f_2). The area under investigation covers only the southern part of this Formation. The Parsori Formation is represented in the area by chloritoid-chlorite-muscovite schists. The schists are mainly exposed in the Tutanbori-Parsori hill ranges, having a semi-circular pattern. The schists trend NE-SW between Tutanbori and Umri north of Khapri and when followed westwards they strike WNW-ESE. In the east the foliations show an east-west trend with an average dip of 50° towards north. Towards west the trend changes to WNW-ESE dipping 55° (average) towards north.

2.4 BHIWAPUR FORMATION

2.4-1. PHYLLITES

In the Bhiwapur Formation phyllites form two distinct horizons separated by quartz-phyllite beds. Good exposures of the phyllites are observed along Maru river, in the hills near Pahungaon,(20°47':79°33') the hills west of Dongargaon (20°47':79°32') and on the plains around Bhiwapur railway station. On the lower grounds the phyllites are often covered with a mantle of soil.

Foliation showing variable trends is fairly well developed in the phyllites. They generally strike between E-W and WNW-ESE. One of the horizons of the phyllite makes a U shaped outcrop in between two tanks northwest of Bhiwapur (Map 1 & 2). Here the foliation varies between ENE-WSW and NNW-SSE with an average dip of 60° towards north. Apart from the mesoscopic folds developed in the foliation planes, at several places (refer page 46) they also exhibit minor and micro folds(fig.52,53). Two to three sets of lineations represented by the puckering and micro-corrugation of the folia are common. The phyllites exposed in the hills near Dongargaon show well developed slip cleavages and lineations (fig.49).

2.4-2. QUARTZ-PHYLLITES

The quartz-phyllites of Bhiwapur Formation represent metamorphosed semipelites. These grade with the phyllites. Within the quartz-phyllites there are gradational sub-groups. Broadly these may be classified into three groups: pure (normal) quartz phyllites; garnet - quartz phyllites; and biotite-quartz phyllites. Due to gradations it is difficult to demarcate distinct boundaries for these rocks. The quartz phyllites exposed on the hills (1.5 Km. northwest of the Bhiwapur railway station) are hard and massive. In some exposures on the hill, the quartz-phyllites exhibit well developed lineation due to the elongation of uniformly distributed clusters of biotite (fig.54). The massive type occurs as intercalated bands or lenses within the lineated type. The lineation of the biotite clusters is very much pronounced in the hill north of Bhiwapur. At other places the biotite in the quartz-phyllites is observed as round or oval specks or spots.

The hard and massive garnet-quartz-phyllites show pink or pinkish brown garnets, with coarser quartz grains. The rock has more appearance like quartzites. Prominent horizons of this type occur in the Pahungaon hill ranges and the hillock north of Jogikhera (20°46' :79°33'). Some iron-ore bodies are associated with the garnet quartz phyllites. The quartz-phyllite outcrops trend between E-W and WNW-ESE. The foliations range in strike from N-W in the west to N-S and NNW-SSE towards the centre and east of the area with average dips of 65° towards north and east.

2.4-3. IRON ORE BODIES

Small occurrences of iron ore bodies are noticed in the Bhiwapur Formation, Outcrops and exposures of these bodies are found in the hill ranges near Pahungaon near Jogikhera and south of Tambakhana(20°47': 79° 79°32') near Dongargaon (Map 2). Old workings are seen in the hill near Pahungaon. Relicts of slags of iron ore are often found strewn near the pits.

Iron-ore bodies occur associated with the garnet-quartz-phyllites in detached outcrops as bands of 1-2.5 m. wide and 20 to 70 m.length. The trend of the ore bodies roughly conforms to the strike of foliation of the quartz-phyllites, which varies from WNW-ESE to NNW-SSE dipping 50° - 60° towards north. Across the strike these bodies show a sharp contact, but along their strike grade to ferruginous quartzites and finally into pure quartzites. These bodies are quite hard and compact and generally occupy the top of the ridges. Boulders and blocks of these rocks are scattered on the hill slopes.

2.5 GAIDONGARI FORMATION

2.5-1. QUARTZITES

Discontinuous hill ranges from Nimgaon (20°47':79°35') to Mahalgaon are formed of hard and compact quartzites. These quartzites are flanked on either side by slaty shales and banded slaty shales. Starting from the south near Nimgaon upto Mahalgaon the quartzites trend NNW-SSE, then veer about 90° with a strike along NE-SW and an average dip of 30° both towards east and west. Foliation is rather poorly developed in these rocks. The isolated hillock to the south of Khapri (20°50': 79°34') is formed of these quartzites. From this hillock about a kilometre to the northeast, the quartzite horizon pinches out bringing the flanking slaty shale and banded slaty shale horizons together. A major antiform fold whose axis runs parallel to the quartzites has been deciphered. Joints are well developed in the quartzites. At several places the quartzites show minor shearing and are traversed by numerous quartz veins.

2.5-2, SLATY SHALES AND BANDED SLATY SHALES

Rocks ranging in character from slaty shales to banded slaty shales form two distinct horizons in the south, southwest, and west of Gaidongari hill ranges. In the south the two horizons are separated by quartzites. However, near Khapri they merge together into a single unit. Near Nimgaon, the slaty shale horizons abut against the Pauni Formation as a result of the Nimgaon-Korambi fault, f_1(Map 2). Starting from south near Nimgaon, the slaty shale strikes NW-SE, then it gradually changes to N-S and finally to NE-SW towards Umri (20°52': 79°36') in the north (Map 3). The average dip of these rocks is 30° towards east. Good exposures of the slaty shales are observed in and around the Pauni-Khapri road, the southern slopes of the Gaidongari hills, and in the Maru river.

The quartzite-shale boundary runs roughly parallel to the Pauni-Khapri road. The slaty shales lying between the quartzites and the meta-argillites are banded in character,having well developed alternating layers of different shades. The slaty shales exposed on the western side of the quartzites along the Maru river are highly fissile and laminated. Banded nature though present is not much pronounced. The contact of these slaty shales and the Bhiwapur Formation is covered with thick soil. In the north, as mentioned earlier, the contact of Parsori Formation and the slaty shales of the Gaidongari Formation from north of Khapri to Umri, shows a disturbed tectonic discontinuity,with numerous quartz veins.

In the hillock west of Nimgaon, large number of quartz veins and reefs varying from few centimetre to about 2m. in thickness,traverse the shales, rendering them very hard and compact. Quartz veins traversing the shales are also observed in the exposures along the Maru river.

2.5-3. META-ARGILLITES

Meta-argillites form a major rock unit of the Gaidongari Formation. These are mainly exposed on the western slopes and on the upper reaches of the southern side of Gaidongari hill. On the eastern side of the hill, these rocks outcrop on lower reaches and towards north these are mainly found on lower grounds. The arcuate outcrop of the meta-argillites(Map 2) is due to cross folding (discussed in page 59). The eastern limb has been sliced by the Nimgaon-Korambi fault, f_1, bringing the meta-argillites in juxtaposition with the Pauni Formation. The faulted contact zone is mostly mantled by soil cover. The western limb of the meta-argillites lies between the slaty shales on the west and the slates on the east. Contact planes between the slaty shales and the meta-argillites are quite distinct, whereas the contact planes with the slates are gradational. Bands and lenses of siltstone and mud-stone occur within the argillites. The meta-argillites form U shaped outcrops,with a narrow nose north of Nimgaon, and a wide nose, east of Khapri. In the west of Gaidongari hills,it has a strike along both NNW-SSE and NNE-SSW while in the east the trend is between NNE and NE. The foliation has a ENE-WSW trend in the north with average dip of 50° towards north. In the south of the hills it trends both along NNW and NE with varying dips.

Meta greywacke - Along the western limb of the meta-argillites near, their contacts with the slaty shales, thin beds of meta-greywacke (upto 5 m. thick) have been observed. At times these beds pinch out along their strike and reappear after a short distance.

2.5-4. SLATES,VARIEGATED SLATES AND CONGLOMERATIC SLATES

The folded limbs of the meta-argillites enclose within it a heterogeneous rock assemblage forming an oval shaped outcrop(Map 2). This is mainly represented by slates,variegated slates and conglomeratic slates. The two limbs of the meta-argillites grade into slates towards the centre. The slates gradually pass into a centre zone of variegated (pebbly) slates. Apart from the angular to subrounded quartz fragments, elliptical and oval shaped fragments of slates and phyllites of different colours, give a variegated appearance to these rocks. The variegated slates enclose a thick horizon of conglomeratic slates around KhanHurk(20°50':79°55'), which are composed of pebbles,cobbles and boulders in a slaty groundmass. Some of the boulders are as big as 50 cm. in their diameter.

The Kulegote hill running north-south is comprised of the slates. East of Thana(20°51' : 79°36') and north of the Thana tank, on the eastern slopes of Kulegote hill, a thin lenticular bed (5 to 15 m.)of hematite quartzites trending WNW-ESE occurs within the slates. Near the contacts of the hematite-quartzites the slates are also ferruginous forming a 2-3m thick zone which finally merges with the normal slates. Near the hematite-quartzites, quartz veins trending east-west cut across the slates. Some of these veins contain platy crystals of hematite along the weak planes.

The slate outcrops follow almost the same trends as described earlier for meta-argillites. The variegated slates and conglomeratic slates together form an oval shaped outcrop in the top of the Gaidongari hill with U shaped edges (Map 2). The general trend of foliation is ENE -WSW with an average dip of 50° towards north.

2.5-5. METABASICS

Two occurrences of metabasics(amphibolites) have been observed in the Gaidongari Formation. In the Maru river bed about 250 m.north of Makhabardi(20°50':79°32') a sill like outcrop of amphibolite, 10 to 13 m. thick, is exposed in the slaty shales. A similar occurrence is noticed in a valley between the Parsori and Gaidongari hill ranges. High temperature contact effects are absent in the slaty shales adjacent to the amphibolites. The amphibolites of Gaidongari Formation were formed much later compared to the intrusives of Pauni Formation.

2.6. YOUNGER SEDIMENTARY FORMATION

Gently dipping sedimentary rocks forming a triangular outcrop occur to the south of Pauni on the right bank of the Wainganga river. This formation overlies unconformably the chlorite-schists of the Pauni Formation. The northern contact of the formation, outcrops about a kilometre south of the bridge across the Wainganga at Pauni. The southward extension of the sedimentaries although delimited by the southern boundary of the present area, coversthe Bedurli reserved forest and continuesbeyond Kanhgargaon (20°42':79°40') in Toposheet No.55 P/10. The lithological units constituting this Formation are conglomerates, sandstones,shales and their gradational types. Major part of this Formation is covered with soil and alluvium. Good outcrops and exposures of the sedimentary rocks are observed along the Donrich nullah,right bank of Wainganga river, and on the higher ground towards west and southwest of Dhanori (20°45':79°40').

The general strike of this Formation is along WNW-ESE on the eastern part and NNW-SSE towards west. They dip gently (8-20°) towards south. Local changes in the disposition of the rocks have been caused by minor flexures,bucklings and dislocations. The northern contact appears to be fault, f_4 running in the NNE-SSW direction, roughly parallel to the Korambi-Nimgaon fault, f_1. The sandstones show a change in strike with steep dips, near the faulted contact on the riverbank. A few NNE-SSW trending faults, mainly parallel to the northern boundary fault, have been observed affecting the various rock units,along the Donrich nullah. Many other local faults (strike between NNE-SSW and E-W) have affected the conglomerates, sandstones and shales(fig. 87).

The basal part of this Formation consists of few alternating thin horizons of granule conglomerates and pebble conglomerates. This is overlain by thick conformable horizons of sandstone(lower), shales, and sandstone (upper).

2.6-1. CONGLOMERATES

The conglomerates are well exposed about 2 Km. south of the Pauni bridge along the Wainganga river and about ½ Km. upstream of Donrich nullah from its confluence with Wainganga river. The phenoclasts vary from 2 to 10 cm. in diameter. Both grnule conglomerates and pebble-cobble conglomerates occur in the basal zone of the Sedimentary Formation (Fig.89). A granule conglomerate layer appears to be the base o sedimentaries, as it directly overlies the chlorite schists of the Pauni Formation as observed along the Wainganga river, near Kodurli (20°46':79°40'). Three horizons of cobble conglomerates of 3 m. average thickness with parting of granule conglomerates and sandy granule conglomerates have been noted in the area. Lateral variations among these have also been observed.

2.6-2. SANDSTONES

Sandstone beds form two distinct units (1) the lower sandstones and (2) the upper sandstones, separated by shale beds. They resemble in several aspects the Barakar Sandstones(Lower Gondwana) of the type areas. Locally, highly coherent and tough sandstones have developed. To the southeast of Dhanori, such rock types of the lower sandstones are used locally for building stones.

Shallow water features like current bedding, ripple marks,mud cracks etc. are preserved in the sandstones. Some of the joint and fracture planes of the sandstones are filled with secondary yellowish white calcareous matter.

2.6-3. SHALES

Shales are exposed in the Donrich nullah and its tributaries in the south (fig.88). They are very compact, and thinly laminated with closely spaced joints. At many places several thin lenses(10-15 cm. in length) of silt stones are inclosed in the shales.

The shale beds contain several intercalated thin bands of sandstones varying in thickness from 6 cm. to 25 cm. and spaced at rough intervals of 30 cm. They are tough and indurated having slickensided surfaces. Along few miniature faults occurring across the laminations of shales, the sandstone bands are slightly bent and displaced, showing minor drag effects.

2.7. REGIONAL STRATIGRAPHY AND CORRELATION

The Pauni-Bhiwapur area forms the south western part of the 'Sakoli synclinorium' (Sarkar, 1957 Fig.10). and consists mainly of rock formations belonging to the Sakoli Series of the Archaeans. The Sakoli Series has been named after the type area in Sakoli Tahsil in Bhandara district. This Series is exposed in a large triangular outcrop covering southern half of Bhandara district,south-eastern part of Nagpur district and northern part of Chanda district with a general strike of NE-SW(Fig.10,11).Due to the triangular pattern in the structural trends and the disposition of the outcrops, the area occupied by the Sakoli Series has been known as 'Bhandara Triangle' (Bhattacharya in Fermor 1934). Systematic geological mapping of the Sakoli belt was started by S.K.Chatterjee in 1928 and in the later years by D.S.Bhattacharya (in Pascoe 1929,1930;Fermor 1931,32,33,34). In the recent past Sinha (in Roy 1962a) and Sahasrabudhe(in Roy 1962c) have carried out geological mapping of the Pauni region.

According to Chatterjee(in Fermor 1931), the geological succession of the Sakolis as exposed in the centre of the Bhandara district is as follows:

TABLE - 2

GEOLOGIC SUCCESSION OF CENTRAL BHANDARA

SAKOLI SERIES	Quartz-dolerite Garnet-muscovite-granite, garnet tourmaline muscovite; granites and pegmatites
	Eruptive unconformity
	Crushed albite-microcline quartzite Phyllite and slate Heamatite and sericite quartzite Garnetiferous phyllites and chlorite-muscovite schists occasionally carrying chloritoid and graphite; jaspillite; epidote-chlorite schist; and felspathic chlorite hornblende schist.
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	SAUSAR SERIES

In the recent years the north-eastern part of the Bhandara Triangle has been investigated by Sarkar(1956,1957), Srivastava(1964) and Sengupta (1963,1965). The stratigraphic succession of this part as established by Srivastava (op.cit.) is given below.

TABLE - 2B

GEOLOGIC SEQUENCE IN NORTH EAST BHANDARA

		Alluvium
		UNCONFORMITY
		Quartz veins
		INTRUSIVE UNCONFORMITY
		Granite gneiss
		Amphibolites;garnet-amphibolite,meta-dolerites, and meta-diorites (Metamorphosed hypabyssal phases)
		INTRUSIVE UNCONFORMITY
SAKOLI SUCCESSION	Chandipahar Formation (1800 m.)	Graphite phyllite;chlorite phyllite; and chlorite-muscovite-quartz schist.
	Kharrapahar Formation (900 m.)	Chlorite phyllite; chlorite muscovite-quartz-schist; ferruginous phyllite ; and banded hematite-quartzite
	Rampur Formation (1500 m.)	Garnetiferous phyllite; chlorite-muscovite-quartz-schist muscovite-quartz; schist,chlorite-biotite-garnet-quartz schist, Hornblende schist (metabasic lava)
	Gangajhiri Formation (1500 m)	Tremolite-silliminite-biotite-staurolite-albite-quartz schist and tremolite-kyanite-biotite-staurolite-quartz schist with psammitic bands;muscovite-biotite-staurolite-quartz schists; muscovite-biotite schist;silicified graphite phyllite.

Base not seen (obliterated by granitisation)

The present area forms the southern most part of the 'Bhandara Triangle' (fig.9). The geological successiòn of the various rock formation of this area was not fully investigated earlier. The succession established by the the present worker is the first systematic attempt on the stratigraphy of the Sakoli Series of the southern Bhandara region (Table 1). It will be evident that the stratigraphic succession for the whole 'Bhandara Triangle' is yet to be established. Hence any attempt to correlate the rock units of the present area with that of the northern part, will be far from success. A complete picture of the Sakoli Series will emerge only after the detailed investigation of the central region.

Bhattacharji (op. cit) and Sahasrabudhe (op. cit) who worked in the southern part of Bhandara have attributed Vindhayn age to the Younger Sedimentaries whereas Dr. B.N.Sinha (personal communication) refers them to Gondwana age. On the basis of the field and laboratory investigations the present worker finds it difficult to correlate the younger sedimentaries with the Vindhyans. They show much similarity with the Lower Gondwana Formations. There are a few Lower Gondwana basins in the neighbourhood of the area (eg.Umrer-30 Km. eastwest, and Chimur 40 Km. southwest), having more or less similarity features. The petrography of the rock formation -conglomerates, sandstones and shales has much similarity with the lower Gondwanas. Hence the present worker tentatively correlates the Younger Sedimentaries with the Lower Gondwanas.

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CHAPTER - III

STRUCTURE

3.1. INTRODUCTION

Geometric analyses of the different structural elements especially the foliation planes, observed in the various rock formations, have helped considerably to unravel the complicated geologic and tectonic history of the area. As the structural and geological map prepared by the present worker is the only detailed map of this part of the Pre-Cambrians, it was found to be rather difficult to draw the structural interpretations on regional basis. Further as the area under investigation is rather small (about 160 sq.Kms.) and the major part of the lower ground (especially the Pauni block) is covered with soil and alluvium, some vital information regarding closures of some of the formations, style of folds and attitude of faults, fall short of perfection. This has restricted the worker into certain limitations in making some positive conclusions. Neverthless, it has been possible to reach at some plausible inferences on the tectonic history of the area which might be of some help to future studies on the structural interpretations of the adjoining areas.

3.2. METHODS AND PRINCIPLES OF STRUCTURAL STUDIES

Principles of Structural analysis - Structural analysis involves two philosophically distinct procedures. First is the study and description of a rock body in its present state - a study as free as possible from inference and extrapolation, except to the extent imposed by limitations and poor exposures in the field. Then comes genetic interpretation of the descriptive data, an attempt to reconstruct the structural evolution of the body in question. (Sander 1948;McIntyre 1951;Weiss 1954, 1958;Turner and Weiss,1963; Ramsay 1964 and 1967). Structural analysis of an area comprises mainly three phases of investigations in order of their decreasing certainty regarding the concepts on which they are based:

(a) Geometric analysis or study of structural geometry. It is mainly concerned with the direct observation of structures with certain amount of deductions depending upon the scale of investigations. The geometric data of a deformed rockmass collectively constitute a property analogous to the symmetry and structure of a crystal. Identical reproducible data should be obtained by different workers on the same body of rock.

(b) Kinematic analysis. It involves the reconstruction of the various movements suffered by the body during deformations like strain, rotations, translations etc., based on the data of geometric analysis. This can be made in two ways.

(i) The movement picture of the deformation is brought on the experimental assumption that the nature of the geometric order of the body reflects the geometric order of the differential displacements, rotations and strains that must be present during deformation of a real polycrystalline body. Here symmetric principles play a key role.

(ii) The present state of the deformed body is compared with an assumed parent state;and stages of kinematic development is deducted. However, it has got certain limitations as more than one interpretation may be made from the same observations and same assumptions regarding parent state. Hence the soundness of assumption is the most important factor.

(c) Dynamic Analysis. Here, stresses which affected the geologic body and the forces from within and without responsible for the stresses are reconstructed. Dynamic analysis of rock structures remain uncertain and speculative as it involves the physical state of rockmasses during deformations and the behaviour of the flow of the rocks in the solid state i.e. whether it is elastic or plastic. Interpretation of the same geometric data by different geologists even in the light of the same experimentally confirmed theories of flow and deformation may be widely different (Turner and Weiss-1963).

3.3. METHODS OF STUDY

For the structural analyses of the Pauni-Bhiwapur area, detailed geologic and structural mapping was carried out on a 1:10560 scale (Map 2 & 3)*. The maps prepared depict the lithologic boundaries and the orientation of planar structures like bedding planes(S_1) and axial plane cleavages (S_2). In the field all the axial plane cleavages representing different fold movements were plotted as S_2 planes as they are rarely preserved together on a mesoscopic scale. Data on the mesoscopic and macroscopic structures including the planar structures, various fold patterns, the nature of faults, joints and lineations have been collected for the whole area.

The area was grouped into three distinct tectonic blocks,which were further divided into thirteen sectors (I - XIII),mainly based on their structural homogeniety (Map 4)-

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*These maps have been reduced to smaller scale (1:31680) from the large scale field maps.

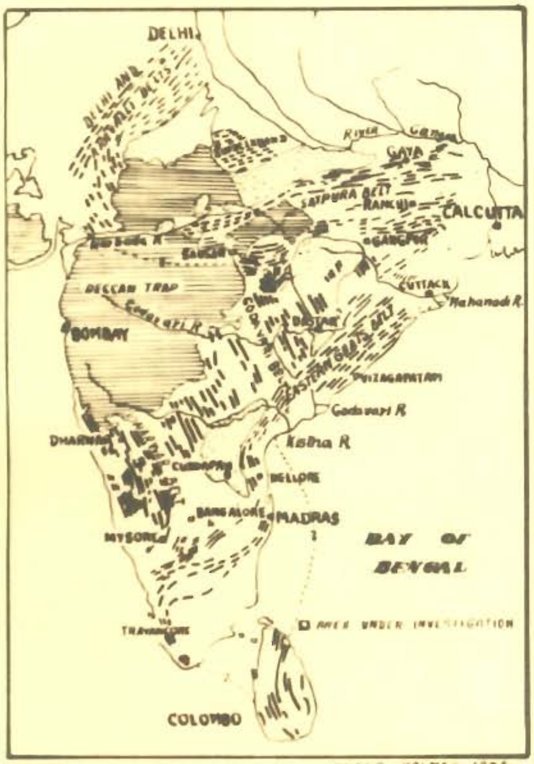
Structural data collected from the field were analysed for each of the sectors. The poles of the planar structures, mainly S_2 of the country rocks and the intrusive bodies, were plotted in the lower hemisphere of a Schmidt's equal area projection net and contoured on a Dimitrijevic net (π-pole diagrams).

Following the method used by Weiss (op. cit.) and Turner and Weiss(op. cit.) β poles of the three sectors(VI,IV,V) of the Bhiwapur block and three sectors(VII,VIII,X) of the Gaidongari block were plotted and contoured. These diagrams were prepared to ascertain whether their maxima coincide with the fold axes in the corresponding π - diagrams. No attempt was made to prepare the β diagrams of the sectors of the Pauni block because of its structural complexity. It has been proved that β diagrams are unreliable in areas of inhomogeneous folding where they give a false impression of structural geometry(Ramsay,1964). The synoptic diagrams of π S_2, β and B poles were prepared for each block from their selective diagrams. The above method of structural analysis when compared with the field diagrams, maps and sections have been of much help in establishing the structural geometry of rock formations in each sectors and blocks in particular and deriving the tectonic history of the whole area in general.

3.4. REGIONAL STRUCTURE

The Sakoli group of rocks are exposed in a large triangular outcrop covering the southeastern Nagpur district, southern half of Bhandara district, and northern part of Chanda district upto the vicinity of Wairagarh with a general NE-SW strike (Fig.9). It was

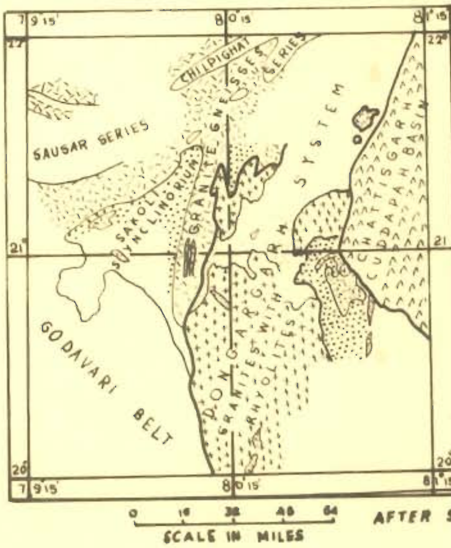
TECTONIC MAP OF PRE-CAMBRIAN OROGENIC BELT OF PENINSULAR INDIA



AFTER HOLMES 1955.

Fig.No.9

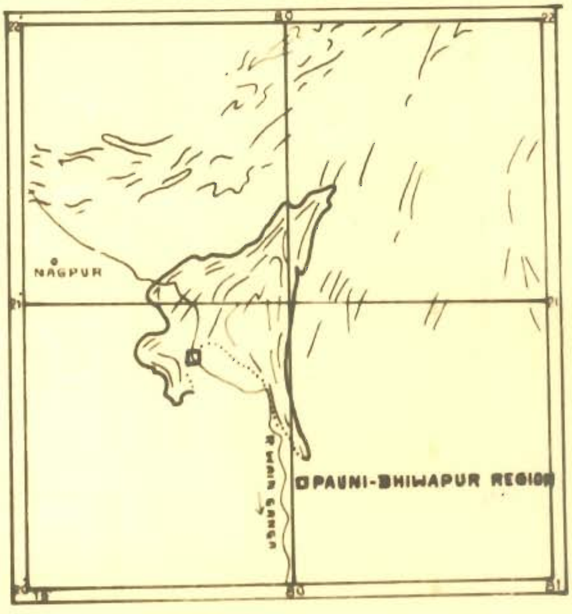
GEOLOGICAL MAP OF SAKOLI 'SYNCLINORIUM' AND ADJACENT FORMATIONS



AFTER SARKAR, 1957

Fig.No.10

TECTONIC MAP OF SAKOLI 'SYNCLINORIUM' AND ADJACENT FORMATIONS



AFTER G.S.I. 1963

Fig.No.11

thought earlier that the Sakolis belong to the higher horizons of the more metamorphosed Sausar Series and have been thrusted into the older rocks to the north(Pascoe,1951). Recent views are in support of two separate basins for the Sausars and the Sakolis.

Bhattacharji (in Heron,1936) has drawn attention to the Sakoli group of rocks showing a triangular arrangement in many aspects. On a regional scale, the Sakolis have a triangular outcrop pattern. Further, the alignment of the quartz veins, the foliations,and the intrusives are disposed in three general directions i.e.(1) N-S,(2) WNW-ESE and (3) ENE-WSW. The rocks of Bhandara have three cleavages or foliation directions roughly at 60° to each other. According to him these three directions are broadly parallel to the orogenic trends of the Eastern Ghats, the Godavari-Mahanadi,and the Satpuras respectively.

From various observations Bhattacharji concluded that the pressures which induced the orographic axes in the Eastern Ghats,the Satpuras and the Godavaris have affected the rocks in Bhandara even to their microscopic texture. Bhattacharji's observations are untenable in the light of the modern techniques in structural analysis and their interpretations. In an area, parallelism of the structural trends with the orogneic trends in the neighbouring regions need not indicate that both the trends have developed due to the same forces or they are of the same age.

In his Memoir on the structure and Tectonics of India,Krishnan (1961) describes the prevalence of Satpura trend (ENE-WSW) in the Nagpur-Bhandara region. According to him in the exposed patches of

Pre-Cambrian belt connecting Jabalpur-Nagpur-Bhandara-Chindwara-Balghat-Ranchi-Hazaribagh- Monghyr and Gangpur-Singhbhum- the general strike of foliation is that of the Satpura trend, though rocks of at least two different ages are involved. The strike varies in different places from NNE to ENE. It would appear therefore that two (or more)folding movements have been superimposed on each other, the trends being the same or slightly different. The Sakoli sub-belt is considered to be the southernmost part of the major Satpura belt(Holmes 1955). Both the workers have concluded that the Sakoli orogenic cycle may be correlated with the Satpura cycle.

According to Sarkar(1957,58) the major structure of the Sakoli group of rocks in the northern region is a synclinorium plunging at 75° due southwest. The sub-vertical flanks of the synclinorium widen out considerably towards southwest. From south to north the regional strike gradually changes from NNW to NNE and finally towards east, giving rise to an arcuate structural pattern, represented by the trend lines of the Sakoli orogenic cycle. According to Srivastava(1964),the northern nose of the synclinorium is exposed in the north-east of Bhandara and shows complicated folding,producing compressed synclines and anticlines. The incompetent core of the synclinorium showsdisharmoious cross folding near the nose.

From the detailed structural and stratigraphic study of Northern Bhandara, Drug and Balaghat districts, Sarkar (op. cit.) has drawn the conclusion that this region was affected by at least three periods of diastrophism and by crossfolds.These diastrophic periods have been designated as Sakoli orogenic cycle, Nandgaon orogenic cycle, and Khairagarh orogenic cycle. The Sakoli orogeny was accompanied and followed by regional metamorphism and (first) granitisation. In the NE part of Bhandara district, towards SE of Gondia the orogenic trend lines vary between NNW and E and towards east and northeast of Deoria and southwest of Gondia they vary between NNE and ESE where the Sakolis mainly occur as basement inliers. The Nandgaon orogenic cycle varies between N and NNE. The fold axis of Khairagarh orogenic cycle is between NNE and NE.

Sarkar further concludes that, broadly, simultaneous cross-folding took place with each of the three orogenic cycles as accommodation structures in a limited space and also to some extent due to control by the grain basement. Cross-folding continued even after the close of the last orogenic episode (Khairagarh orogeny) developing locally new sets of cleavages.

As the northwest strike of the Godavari belt has considerably controlled the folding of the northeast trending Sakoli synclinorium giving rise to cross-folds and a triangular area of Sakoli group of rocks, it is evident that the Godavari orogenic cycle is earlier than the Sakoli cycle. In other words the Godavari cycle is earlier to the Satpura cycle. On the basis of the geochronological studies of some rock samples of the Pre-Cambrian of Penninsular India, Sarkar et.al.(1964,1967) consider the Sakolis(1935 m.y.) and Nandgaon(1200 m.y.) orogenies to be earlier to the Aravali-Satpura orogenies (864-993 m.y.). Further, the Khairagarh orogeny (600 m.y.) is taken to be later to the Delhi orogeny(734-844 m.y.). The above conclusions reached by Sarkar et.al. are very much debatable in view of the unreliability of the geochronological data provided by few rock samples of the Pre-Cambrians.

Recent work by Sengupta(1965) on the northestern Bhandara shows that the Sakoli group of rocks passed through two successive stages of folding. The first phase F_1 involved isoclinal folding on the bedding S_1 and the development of mineral foliation S_2 (axial plane type). Later folding F_2 involving small scale warping of both S_1 and S_2 develpped strain slip cleavages S_3. S_2 with an average strike of N 30° is usually cut across by S_3 striking between N 50° and N 70°.

The above account on the regional structure of the Sakoli group of rocks is largely based on the structural data obtained from the north and northeast part of the Sakoli synclinorium. As the area under investigation is over 100 Kms. south of the above areas, and falls in the south-western part of the Sakoli synclinorium, separated by a large unmapped region, it is rather difficult to correlate the same. Based on the detailed structural analysis(refer pp.49-68) it has been concluded that this region of the Sakoli group of rocks, has suffered at least three fold movements named as F_1, F_2 and F_3 producing complex fold patterns. The Pauni block of the present area shows imprints of the three episodes of folding where as the Bhiwapur and Gaidongari blocks were affected by the later two deformations only. Although the general trend of F_1(NE-SW) could be correlated with the regional trend of Sakoli synclinorium, the other two fold trends F_2(NNW-SSE) and F_3(ENE-WSW) in the Bhiwapur and Gaidongari blocks(lithologically equivalent to the

Sakolis) are rather difficult to compare with those of the Nandgaon and Khairagarh orogenies of Sarkar. For the present, the three fold movements are considered as three stages of deformations suffered by the Sakoli Series in the present area. It is quite possible that F_2 and F_3 fold movements represent successive phases of the same orogeny; while the F_1 representsan earlier orogeny.

3.5. STRUCTURAL ELEMENTS

3.5-1. PLANAR STRUCTURES

Three main types of planar structures referred to as 'S' planes are recognizable in the rock formations of Pauni-Bhiwapur area. These planar structures have been designated as S_1(bedding planes)and S_2 (foliation-schistosity and axial plane cleavages) and S_3(slip cleavage planes). During the course of the structural study emphasis has been given on the orientation of S_2planes. Several sets of joint planes exposed in the different rock formations also form planar structures, but these have not been systematically analysed.

1. Bedding planes (S_1) - The primary bedding and compositional layers in the country rocks form the bedding planes(S_1). Wherever alternating deposition of argillaceous and arenaceous sediments have taken place with marked differences bedding is quite pronounced. The different rock boundaries and their general outcrop pattern in the map indicate the general trend and attitude of S_1. These are the most dominant structural features in the Younger Sedimentary Formation south of Pauni described earlier (page 24).

In the Bhiwapur block, the contacts of the two lithological units, phyllites and quartz-phyllite layers, and compositional variations in the quartz-phyllites (presence or absence of garnet or biotite) suggest the trend of S_1. The dominant trend of the bedding is along WNW-ESE with an average dip of 20° - 30° towards both north and south. In the Gaidongari block, the lithological boundaries of quartzites and slaty shales give conspicuous S_1. The thin bands represented by colour variation in the slaty shales also provide excellent bedding planes. The boundaries of the meta-argillites and slates are gradational. The two prominent strike directions of S_1 in this block are NNW-SSE, and NE-SW with an average dip of 25° towards north and south. In the Pauni block S_1 is not discernible, as the country rocks are dominantly of a single lithologic unit-chlorite-quartz-schist, except for the sporadic occurrences of grunerite-quartz-magnetite layers.

2. Foliations S_2 (Axial plane cleavages and schistosity) - S_2 is represented by the foliations in schists, amphibolites, phyllites, meta-argillites and the cleavages in slates and slaty shales. These are the most dominant well developed planar structure in the area and are more easily recognizable than the bedding planes. However, these are less common in quartzites. Wherever folds on S_1 planes are visible in the incompetent rocks the S_2 planes are parallel to the axial plane of folds and hence these have been designated as 'axial plane cleavages'. Folding of the S_2 planes is discernbile on macroscopic, mesoscopic and microscopic scales in the phyllites of Bhiwapur Formation suggesting refolding. Apart from the intersection of the

S_1 and S_2 at the closures, the intersections are also observed along the limbs of the folds at several places in Bhiwapur and Gaidongari. The S_2 planes exhibit varying trends and fanning within small areas particularly in the Pauni block. Such a behaviour of the S_2 suggests cross-folding of the formations and development of axial plane cleavages along with the folds of different deformational episodes. The wide variation in the trend of S_2 of the Pauni block is due to the three fold movements suffered by the block.

In the Bhiwapur block two major trends of ~~th~~ foliations are prevalent (i) E-W to ENE-WSW with an average dip of 60° towards north and (ii) NNW-SSE to N-S with an average dip of 60° towards north. In the Gaidongari block two major trends of foliation have been noted (i) ENE-WSW with an average dip of 50° towards north and (ii) NNW-SSE dipping 50° towards east. In the Pauni block, the foliations generally show variations between NNE-SSW and E-W with average dip of 60° towards both south and north. However, the most predominating trend is along NE-SW. In several localities of this block the S_2 is highly variable locally in strike and dip (Map 3) indicating a complex deformational history. These are further modified by the various stages of igneous intrusions.

3. <u>Slip cleavages</u> (S_3) - Sharp refolding of S_2 on a minor scale (microfolds) tends to produce shear fractures which have been designated by several names e.g. 'slip cleavage ' 'false cleavage', 'strain slip cleavage' and 'herring bone structure' (Bagdley, 1961). It first appears as discontinuous planar zones of crenulate mica layers which define the foliation S_2. With intense folding the crenulate zones become long lenticular slices of tightly folded and appressed mica

layers bounded by surfaces along which a perceptible amount of slip has occurred. Similar features have been called microlithons by de Sitter(1956). The sharp flexuring of the earlier foliation tends to rotate the platy minerals of the phyllites and schists towards parallelism with the new fractures. Turner and Weiss(1963) describe these slip cleavages as follows:" The surfaces of slip are not discrete fractures but rather laminar domains of intense strain. These domains may become foci of syntectonic or post tectonic recrystallization of mica, so that ultimately the strain slip structures evolve into 'foliation' schistosity". Bagdley(op.cit.) opines that slip surfaces are discrete fractures.

In the Bhiwapur Formation the phyllites at many places exhibit incipient S_3 planes developed by the above process. Megascopically these slip surfaces are not very much perceptible. Under the microscope the development of S_3 plane with a definite sign of slip movement along them can be observed (fig.131). However, recrystallization of chlorite or mica has not taken place along these planes. These slip cleavages appear to be parallel to the axial planes of the microfolds. Some concentration of iron oxide is observed along these planes.

Slip cleavages of a different origin have been noticed in the phyllites adjoining the Dongargaon-Pahungaon fault f_3, and in the chloritoid-chlorite-muscovite schists in the proximity of the Parsori-Umri fault, f_2. They have developed on the megascopic scale and are definite planes of slip. These are of restricted occurrence in the shear zones, and they cut across the S_2 planes at acute angles. All the field evidences indicate that the slip cleavages are related to the major fault movements.

3.5-2. JOINTS AND SHEAR PLANES

Several sets of joints and shear planes have been noted in the various rock units of the area. Detailed information of the joints has been collected from the Pauni block where proper opportunities were available to study them in three dimensions in the chromite quarries and along the Wainganga river. In the Pauni block several sets of joints and shear planes are observed in the granites,pegmatites, ultrabasics and the chromite bodies. Since the area has been affected by at least three stages of deformations, complex sets of joints and shear planes have developed in the region. Generally at a particular place four to five sets of joints are observed. In relation to the trend of a lithological unit these can be grouped as follows: (a) strike joints (b) dip joints (c) bedding joints and (c) oblique joints. The orientation diagrams prepared for the separate rock units, show several maxima with a circular girdle (fig.12-16)Generally the joints in the ultrabasics and chromite bodies appear to be shear joints as they exhibit slickensided surface. Many of these shear surfaces are curviplanar,probably caused by rotational movements.

Average joint set patterns were calculated for some of the rock types from their respective orientation diagrams and have been summarised in Table 3.

In the Gaidongari and Bhiwapur blocks, four to five sets of joints in the competent horizons are noticed.However, detailed work

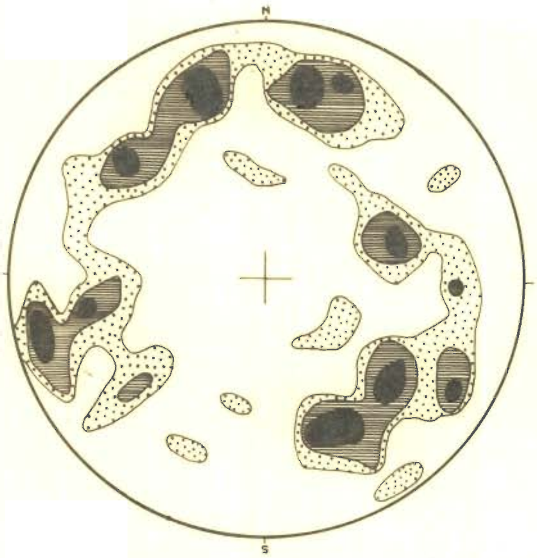


Fig.No.12

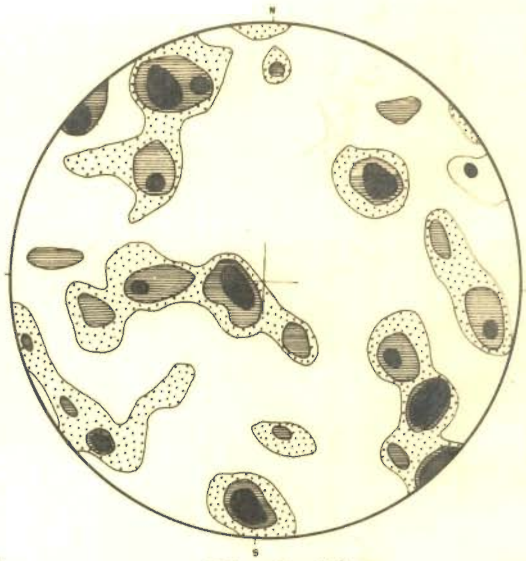


Fig.No.13

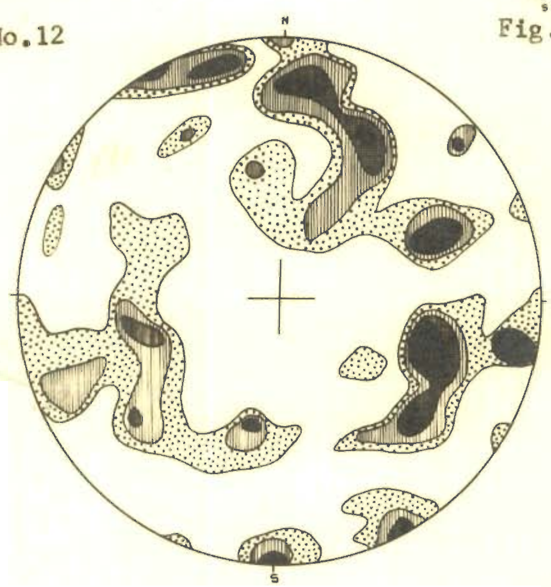


Fig.No.14

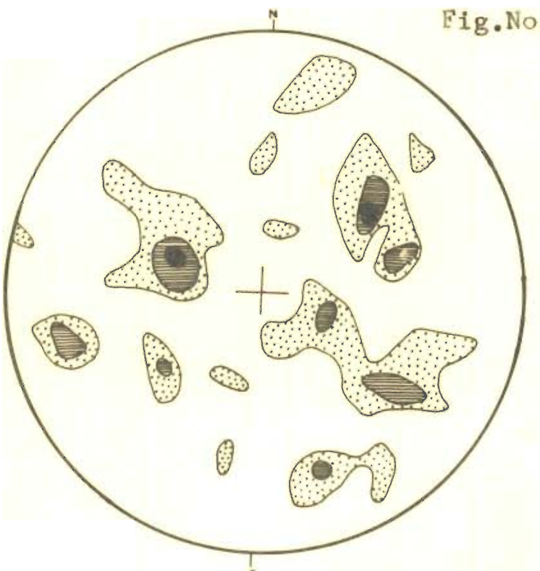


Fig. No.15

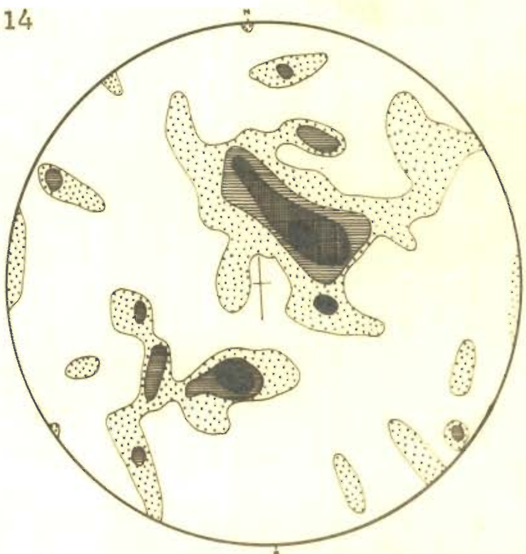


Fig.No.16

TABLE-3

CHARACTERISTICS OF ORIENTATION DIAGRAMS OF JOINT PLANES

Fig.No.	Rock type	No. of poles	Contour values (percentage)	Maxima plunge	Bearing	Strike and dip of average joint planes corresponding to Maxima		
						Strike	Amount of Dip	Dip direction
13	Chromitite	87	0.5-1.5-2.5-3.5-5.5	37	52	140-320	42	230
				20	126	34-214	41	304
				10	180	92-272	80	2
				80	228	134-314	10	44
				4	310	38-218	86	128
				16	330	60-240	74	134
12	Ultrabasics	82	0.5-12-2.4-3.6-4.8	30	308	38-218	60	128
				26	338	70-250	64	160
				26	10	100-280	65	190
				39	130	40-220	50	310
				38	155	64-244	52	334
14	Granites and Pegmatites	96	0.5-1-2-3-5	32	70	162-342	50	252
				37	110	16-196	54	286
				9	103	8-188	84	278
				30	132	40-220	60	310
				31	29	120-300	60	210
				20	11	98-278	70	188
				3	332	60-240	88	150
				46	254	160-340	52	70
16	Quartz phyllites (Bhiwapur)	67	0.5-1.5-3-4.5-6	60	197	110-290	30	20
				70	41	130-310	10	220
15	Quartzite and Meta-argillite (Gaidongari)	47	0.2-4-6	60	52	140-320	40	230
				61	285	16-196	28	106

on the joints of these block could not be done. The joint patterns of quartz phyllites of Bhiwapur block and of quartzites and meta-argillite of southern part of the Gaidongari block have been summarised in Table 3.

3.5-3. FAULTS

The Pauni-Bhiwapur area has been affected by four major faults which form the boundaries of the five different stratigraphic units viz. the Pauni Formation, the Parsori Formation, the Bhiwapur Formation, the Gaidongari Formation and the Younger Sedimentaries.

The Korambi-Nimgaon fault f_1 trends NNE-SSW direction and separates the Pauni Formation from the Gaidongari and Bhiwapur Formations. The following are important field evidences to indicate this fault;

(i) truncation of the lithological units of the Gaidongari Formation,

(ii) brecciation of the slaty shales and the quartzites of the Gaidongari Formation,

(iii) sudden changes in the metamorphism and lithology of the two Formations and

(iv) occurrence of quartz veins along the faulted boundary.

The Parsori-Urri fault f_2 is of semi-circular pattern forming the boundary between the Parsori Formation and the Gaidongari Formation. When followed from the east it has NE-SW trend, and gently curves towards WNW-ESE in the west. There are quite good evidences for this fault such as:

(i) truncation of the Gaidongari Formation against the Parsori Formation;

(ii) difference in the grade of metamorphism-the low grade Gaidongari Formation in contact with the high grade Parsori Formation,

(iii) all along the boundary prolific occurrence of quartz veins, which have been reported to be mineralised by copper sulphides (Sahasrabudhe, in Roy 1962 a) towards west of the area near Pular.

The Pahungaon-Dongargaon fault f_3, trending WNW-ESE is an inferred fault, which forms the tectonic boundary between the Bhiwapur Formation and the Gaidongari Formation. This has been deciphered on the basis of the sudden change in the grade of metamorphism and the structural fabric in the two stratigraphic units. The general trend of the phyllites of the Bhiwapur Formation is WNW-ESE and that of the slaty shales of the Gaidongari Formation on the other side of the fault is generally NNW-SSE direction.

The Pauni fault f_4, forms a boundary fault between the Pauni Formation and the Younger Sedimentaries. There are strong evidences to indicate this fault, along the Wainganga river. The gently dipping Sedimentaries have a high dip along the contact. Further, the strike of the sediments truncate along the faulted boundary.

Nature of the displacement and net slips of the major faults could not be determined due to lack of key horizons on either side of the faults in the area under investigation.

Several minor faults are noticed in the Pauni Formation near the Wainganga river bank. These faults have affected all the later igneous rocks of the area. A fault in the quarry (GCS) trends in the NNE-SSW direction with high dips towards east (fig. 90). The displacement is about a metre. The rock exposures on the river bank near Itgaon show several closely spaced faults of small dimensions traversing the country rocks and the associated intrusives like amphibolites and pegmatites. Their trends vary within E-W to NW-SE in a radiating pattern (fig.70). Most of these faults appear to be parallel to the axial traces of minor folds. The strike-slip of these faults varies from a few centimetre to above 40 cm.

In the quartz phyllites of the Bhiwapur Formation about one and a half kilometre NW of the railway station few closely spaced faults were observed . These generally trend in E-W to NW-SE direction. The faults have also displaced some of the quartz veins.

3.6. LINEATIONS

Except for the Bhiwapur Formation linear structures (on mesoscopic scale) are not common in the area. In the Bhiwapur Formation the following types of lineations, mostly developed on the S_2 planes of phyllites, are observed.

1. Puckers - Puckers and microcorrugations varying in their wave length from 1 to 2 mm. on the foliations of the phyllites are often observed. Two sets of puckers with different plunges are common, while in certain horizons a third set is noted. They are all due to flexural slip folding on a small scale on the foliation surfaces. The orientation of the spindles of chlorite with quartz and magnetite inclusions and certain elongated quartz grains is probably governed by these puckers (under the microscope). The average trends of the puckers are as follows: (i) NW to NNW with plunges between 40 to 70°; (ii) NE to WNE with plunges 30 - 80°; (iii) SSW to SW with plunges 40 - 70°.

2. Axes of microfolds - These represent the axes of minor folds observable in hand specimens. They are well developed in the phyllites and poorly developed in the quartz-phyllites. The average trend of micro-fold axes noted at many places is between NE and ENE.

3. Mineral lineations - In certain layers of the quartz-phyllites lineations marked by streaks consisting clusters of biotite on the foliations,are well preserved. Thin rods of quartz also exhibit lineations in some horizons of the quartz-phyllites parallel to their foliation.

All the types of lineations mentioned above are designated as b-lineations as they are parallel to the major fold axes.

In the Pauni area the shear planes in the ultrabasic and chromite bodies show slickensided surfaces. This is considered as a-lineation as it is not related to any fold axis.

3.7. FOLDS

From the orientation of bedding planes(S_1) and the foliation planes (S_2) and from the nature of the outcrop patterns (Maps 1 and 2) it is clear that the rock formations of the area have been subjected to several stages of deformations giving rise to complex fold patterns. The folds vary from macroscopic,mesoscopic to microscopic dimensions. The macroscopic folds as revealed from the lithological and structural maps are exposed in the U-shaped and V-shaped closures formed by the S surfaces.

Based on the geometric analysis of the S planes(described later) in the different rock formations and amply supported by the outcrop

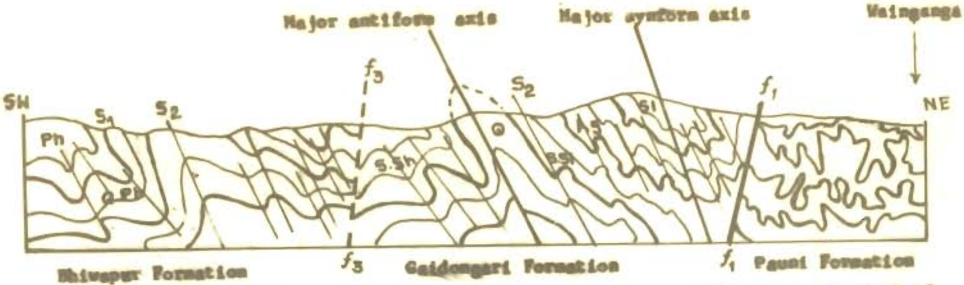


Fig. No.160 Generalised section in NE -SW direction(from north of Bhiwapur to south of Korambi) across the Bhiwapur, the Gaidongari and the Pauni Formation. (Ph. = Phyllites. Q.Ph. = Quartz Phyllites. Q = Quartzite. S.Sh. Slaty Shale. Ag. =Argillites. Sl. = Slate)

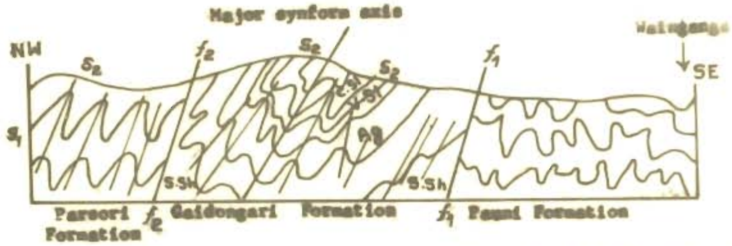


Fig.No.161 Generalised section in NW SE direction(Thutamberi to Khatsi) across the Parsori, the Gaidongari and the Pauni Formations (S.Sl. = Slaty Shale. Ag = Argillites. Sl. =Slates. V.Sl. Variegated slates. C.Sl.=Conglomeratic slates).

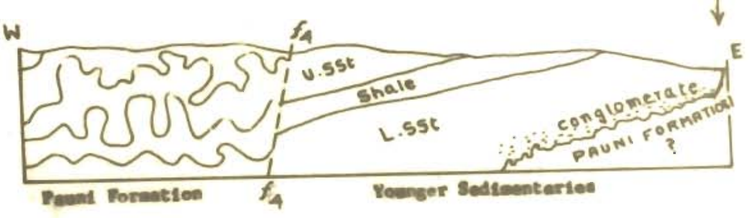


Fig. No.162 Generalised section in E.W. direction across the Pauni Formation and the Younger Sedimentaries.

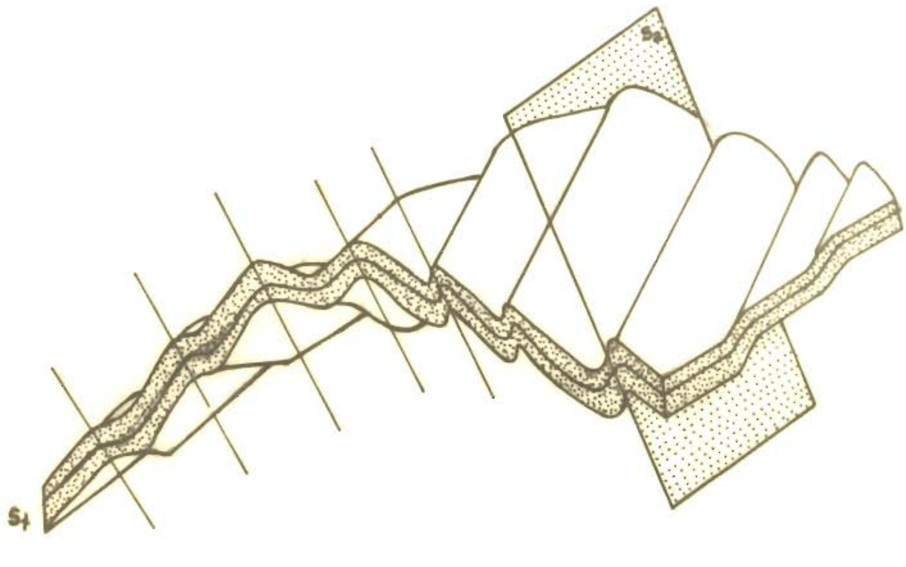


Fig. No.163 Idealised diagram showing superimposed folding in the Gaidongari and the Bhiwapur Formations. (Cf. Turner and Weiss,1963)

(NOT TO SCALE)

patterns it has been concluded that the area has been folded in three stages. The first stage fold F_1, trending NE-SW, has been superimposed by cross folds F_2, trending NW-SE, and F_3 between ENE-WSW and E-W. The cumulative effect of the folds have been resulted in non-plane non-cylindrical folds on regional scale and polyclinal and reclined folds on local scale (Map.5).

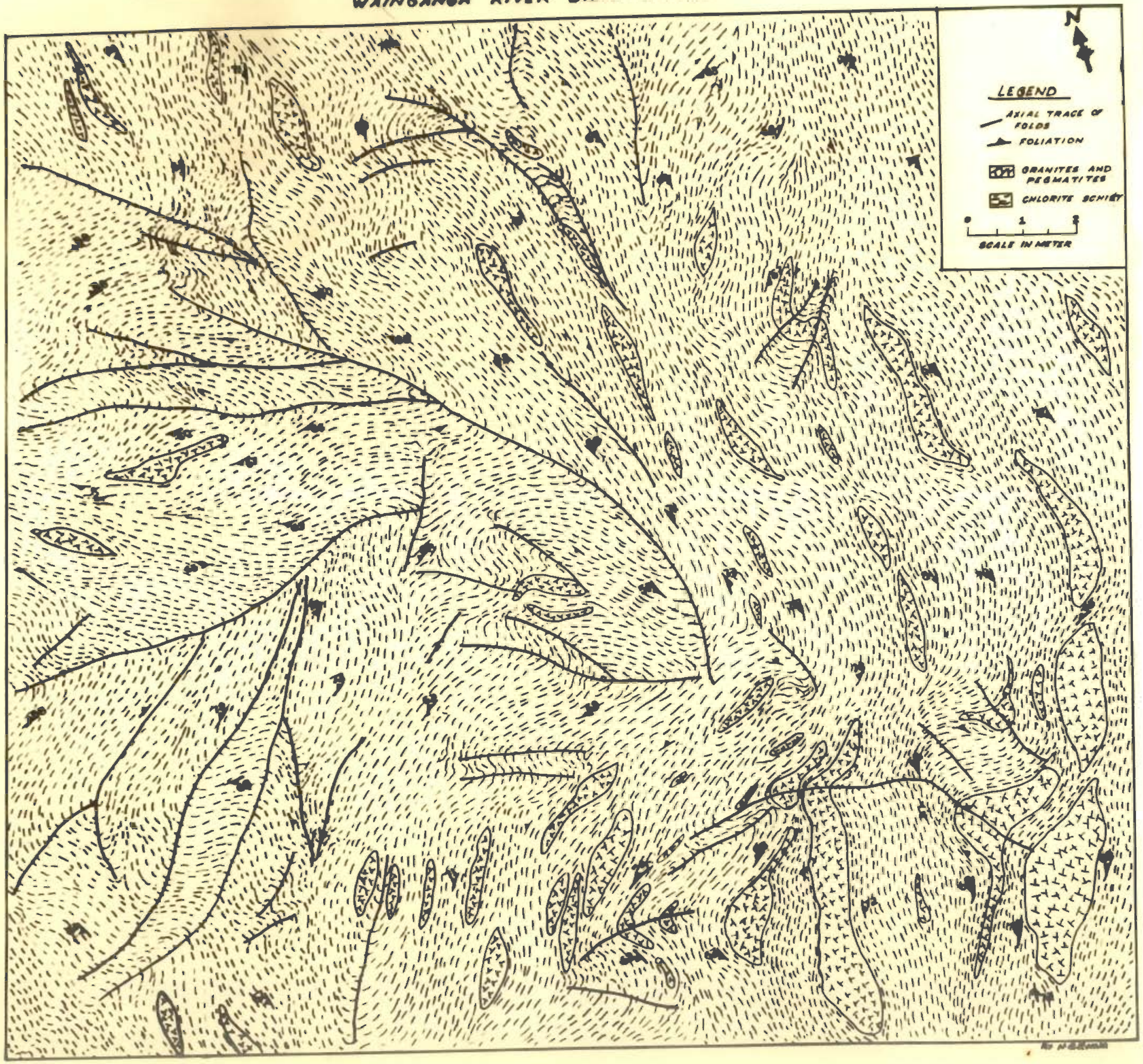
In the Bhiwapur block four major axial traces related to fold F_2 have been traced (Map 4). They are curvilinear due to the crossing of F_3 folds. In the south of the block the axial traces trend NNW-SSE while in the north they veer towards WNW-ESE. The axial traces of F_3 have an average trend of ENE-WSW. Though parallel they are discontinuous. Due to lack of sufficient data, it was not possible to give a genetic nomenclature to the F_2 and F_3 folds of this block.

Several minor folds of both mesoscopic and microscopic dimension have been developed in the phyllites of the Bhiwapur Formation; their axial traces being generally parallel to that of F_3. The phyllites show well developed kink or chevron folds at some places(fig. 51).

In the Gaidongari block a synform and an antiform of F_2 system have been inferred (map 4). The axis of the antiform passes through Nimgaon-Mahalgaon. A parallel axis of the synform passes through the middle of the Gaidongari hill ranges. Starting from the south, their axial traces trend NNW to N, which in the north gradually veers towards east due to the superimposition of the later fold F_3.

The youngest fold F_3 is represented by a major synform having an axial trace along ENE-WSW roughly passing through Thana in the

POLYCLINAL FOLDS AND PEGMATITE BODIES IN THE CHLORITE - SCHISTS
WAINGANGA RIVER BANK - PAUNI



MAP No.5

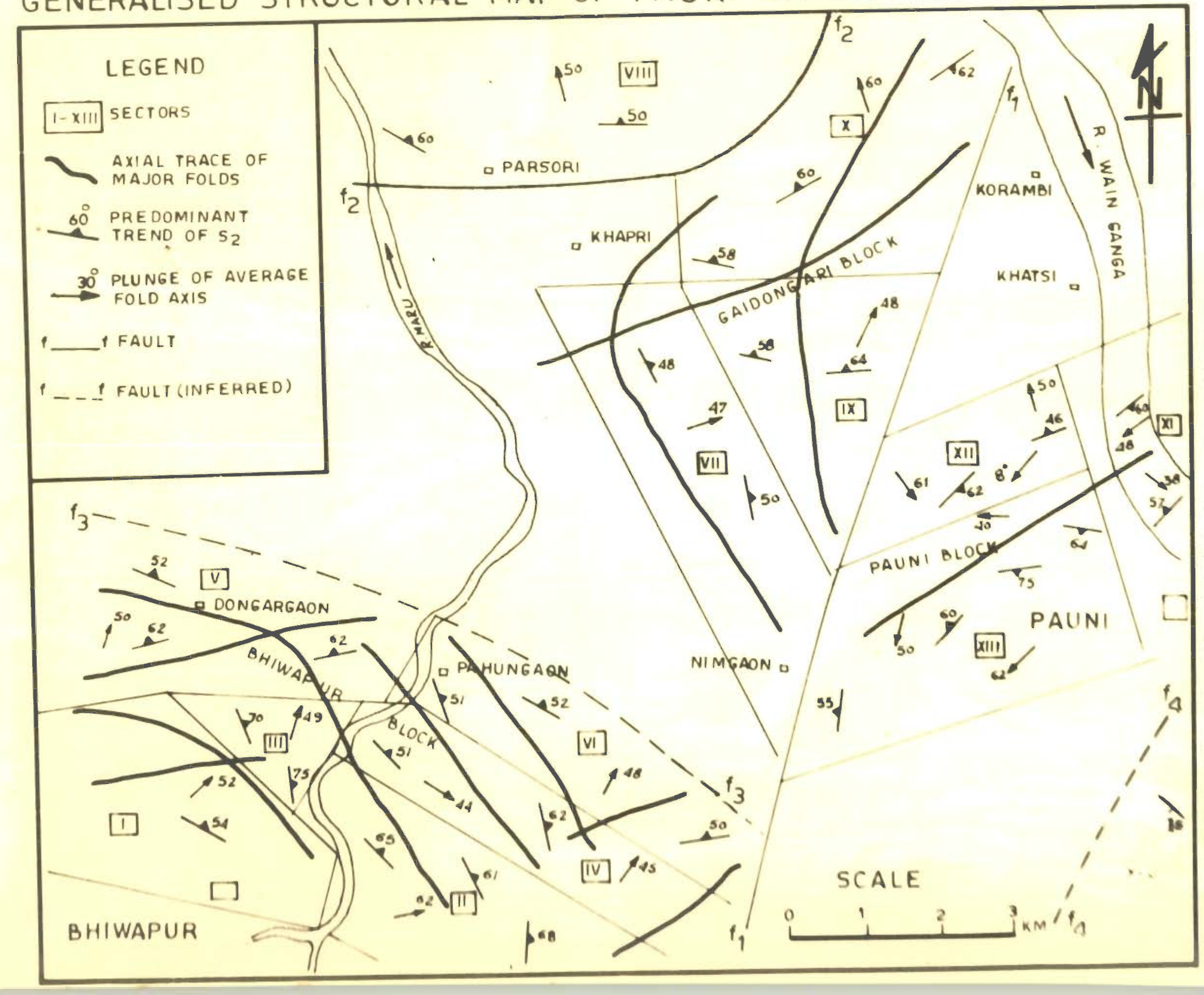
PLATE No.IX

northeast and Mahalgaon towards west. As a result of the cross folding of two synforms of F_2 and F_3 in the Gaidongari Formation, a 'depression' has formed where the younger variegated slates and associated conglomeratic slates are lithologically bounded from all the sides by the older slates and meta-argillites. Similarly south of Khapri, where the F_3 synform crosses the F_2 antiform a 'col' or 'saddle' structure of the quartzites has developed (Map 2). Folds on mesoscopic and microscopic scale have not been observed in this block.

As mentioned elsewhere, in the Pauni block due to the absence of key horizons and the obliteration of the earlier structure and lithology by igneous activities and hydrothermal alterations, it has not been possible to properly decipher the fold patterns. However, a major synform has been recognized in the area with its axial trace in the NE-SW direction. This is sub-parallel to the alignment of the chromite belt. This axis represents the first generation of folds F_1 in the area. Due to the superimposition of the later two stages of cross-folding it has been quite difficult to unroll the folds of the first stage.

Several minor folds seen along the river bank have axial traces along WNW-ESE to NNW-SSE parallel to the axis of the major fold F_2 (Map 5). In the quarry No.1 the mesoscopic folds observed in the country rocks have axial traces roughly between NE-SW and ENE-WSW, with their plunge towards north or northwest which show parallelism with the major folds F_1. In the same quarry few folded chromite bands (fig.61) have axial trace in the NNW-SSE direction, parallel to F_2 folds. A third set of minor folds has axial traces in the NNE-SSW direction.

GENERALISED STRUCTURAL MAP OF PAUNI BHIWAPUR REGION



MAP No. 4

PLATE No. X

3.8. STRUCTURAL ANALYSIS

For the convenience of structural analysis, the three structural blocks (Pauni, Bhiwapur and Gaidongari) have been treated separately. These three block combined were divided into 13 sectors; the Bhiwapur block into 6 sectors, the Gaidongari block into 4 sectors, and the Pauni block into 3 sectors. As the Pauni Formation suffered severe deformations, and was subjected to successive igneous intrusions, their original structure and lithology have been much obliterated. The outcrops and exposures of the Pauni Formation are mainly confined to three linear tracts covering the nullahs, river bank and the quarry pits (Map 2,4). This restricted occurrence of the outcrops, the complexity of the folds on mesoscopic scale and the absence of any key horizon in the lithology, made it difficult to make systematic structural study in the Pauni block. Consequently 13 πS_2 pole diagrams were prepared along with the π-S_2 synoptic diagrams of the three structural blocks. In addition 6 βS_2 pole diagrams of the Gaidongari and the Bhiwapur blocks were prepared. The characteristics of all these diagrams are summarised in the tables (4,5 & 6). The following pages give an account of some of the salient structural features of the different sectors, followed by the synoptic features of the three blocks.

3.8-1. BHIWAPUR BLOCK

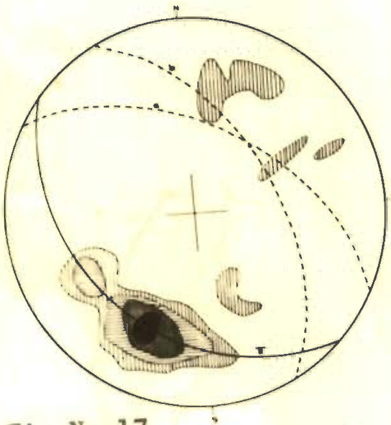
Sector -I - Sector I covers the small semi-circular hills north of Bhiwapur railway station and the adjoining plains. Both phyllites

PLATE No.XI

BHIWAPUR BLOCK

Orientation diagrams(contoured)

For details of S_2 diagrams see Table 4



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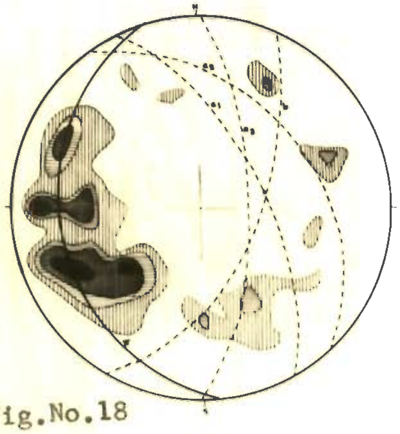

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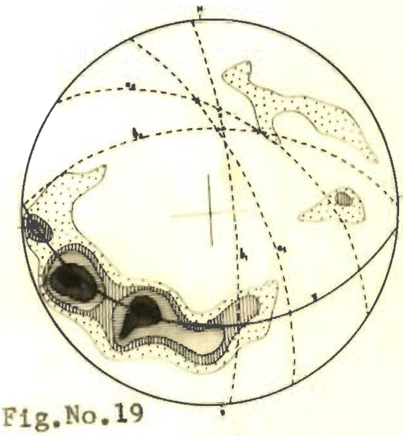

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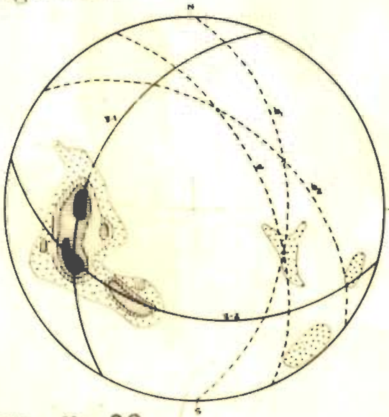

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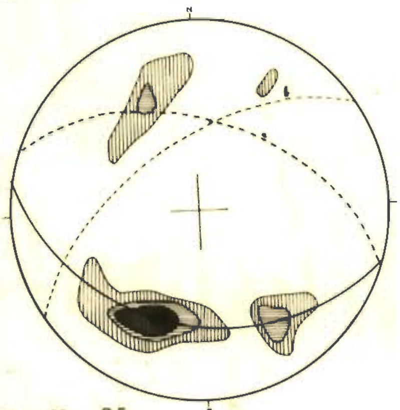

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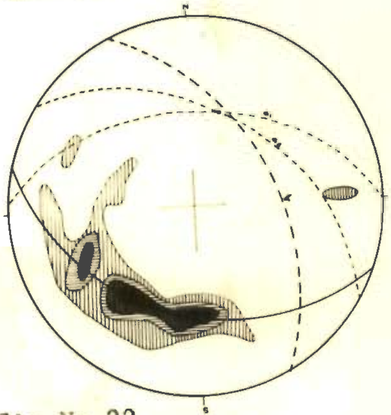

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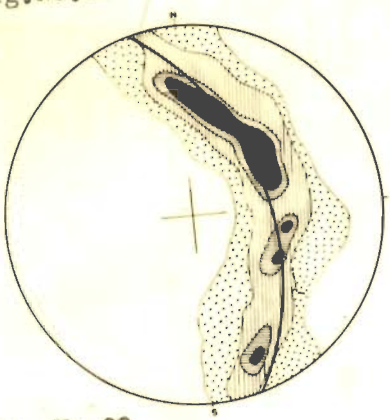

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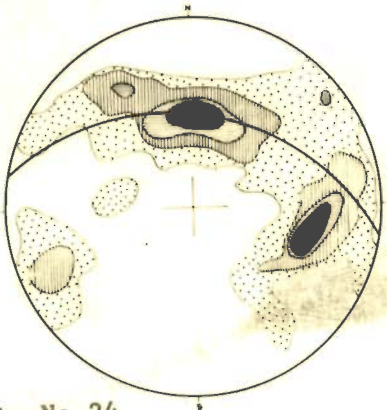

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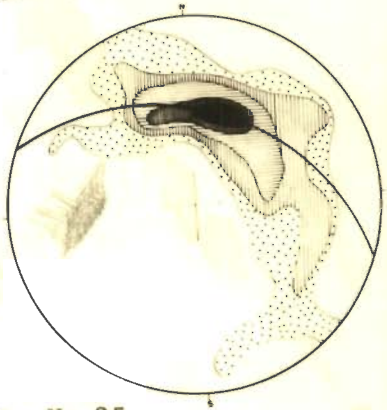

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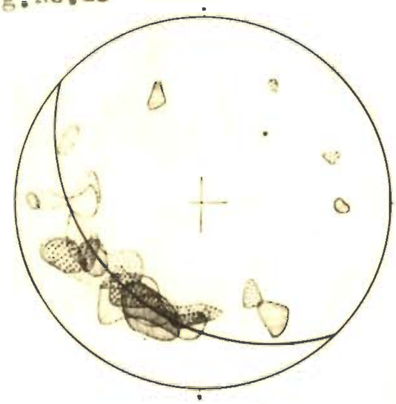


Fig.No.26

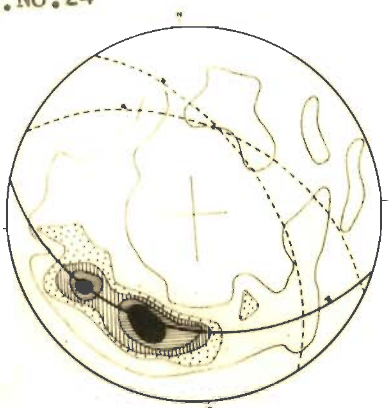


Fig.No.27

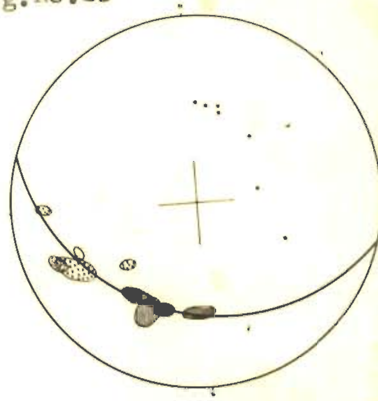


Fig.No.28

and quartz-phyllites are exposed in this sector;their gradational contact forms a V-shaped closure with its apex pointing towards WNW indicating a major plunging antiform fold. The primary bedding S_1 is not well preserved. However, the S_1 noted at few places varies between N 290° to N 330° with an average dip of 30°. The foliation planes S_2, show two general trends, N 335° and N 300° with an average dip of 60° towards north. These are related to F_2 folds with certain amount of rotation caused by later F_3 folds. Towards southwestern and northern corners of the sector, the foliations trend N 65°E which appears to be related to the axial planes of F_3 folds. The S_2 planes generally cut across the lithological boundaries near the closures; at other places they are either sub-parallel or cut at acute angles. It is quite apparent from the foliation patterns that the F_2 folds overturned towards south and was cross folded by F_3.

In the π-S_2 diagram(fig. 17)a well developed maximum (20%). falls in the southwest quadrant. This maximum along with a sub-maximum to its north in the same quadrant forms an incomplete girdle.Two great circles S_2a and S_2b corresponding to the maximum and sub-maximum represent average axial planes of the F_2 folds. The elongated maximum and sub-maximum, the incomplete girdle and the map pattern clearly indicate regional rotation of F_2 folds. The intersection point β of the great circles S_2a and S_2b coincides with pole B of the π - circle. B plunges 52° due N 44° representing the orientation of the cross-folds. Overall the fold axis is perpendicular to the average axial planes in this sector.

<u>Sector-II</u>. Sector II is situated to the east of Maru river and south of sector IV. It is mostly formed of phyllites with a small outcrop of quartz phyllites in the southeastern corner. The primary bedding planes S_1 are not well preserved. The general gradational contact of the rock units generally trends inNNW to NW on the northern part, while in the southern part it forms a broad closure whose apex points towards north.

The foliation planes S_2 show variable trends in this sector. They generally trend N 330° in the northwest, but when traced towards southwest they show clockwise rotation towards N 300°, N 25°, and N 65° in the southeastern corner. The S_2 planes vary in dip from 45° to 80° towards north, east-north-east, east and northwest. A few southerly dips are also observed. Although the general trend of the foliations is related to F_2 folds but due to superimposition of later fold F_3, these have suffered rotation of about 180°.

In the π-S_2 digram (fig.18) an elongated well developed maximum and two small maxima occur in the southwestern quadrant. A conspicuous sub-maximum has developed in the north-western quadrant. They together form an incomplete wide girdle. The inclined great circles S_2a_1, S_2a_2, S_2a_3, S_2b_1, S_2b_2, corresponding to the maxima and submaxima represent the average axial planes of F_2 and F_3 folds and their limiting positions in this sector.

The β obtained from the intersections of the great circles of S_2 and the corresponding β-diggram having several maxima and sub-maxima with an inclined girdle indicate divergently plunging fold axis. The wide distribution of maxima and submaxima are partly due to complexity of folding and partly due to irregular distribution of structural data observed in this sector. The complexity of fold pattern is x due to superimposition of the cross folds F_3 on the earlier F_2 folds.

Sector -III. Sector III represents a triangular area south of sector V and west of the Maru river. This sector consists of the quartz-phyllites, the iron ore bands and the phyllites. Primary bedding planes S_1 are not well preserved. The trend of the lithological units in the rocks has been regarded as S_1 which varies between E-W to ESE-WNW. In the major part of the sector the average strike of foliation (S_2) varies between N 20°W to N 50°W. At certain localities in the centre of the sector a N-S trend is also present. In the southern end of the sector an E-W trend of foliation is observed locally. The S_2 planes show a variable dip of 50° to 80° mainly towards north. It is quite evident from the general map pattern that the S_2 planes cut across the quartz-phyllite boundaries with acute angles.Further the S_2 planes in the northern and central part of the sector also show cross-cutting relations.This may be due to the superimposition of oblique cross folds F_2 and F_3.

In the πS_2 diagram (fig. 19)two pronounced maxima and submaxima in the southwestern quadrant form a girdle. Three great circles (S_2a_1,S_2a_2, S_2b_1) corresponding to the two maxima and a sub-maxima represent average axial planes of F_2 while the S_2b_2 represents the average axial plane of F_3. The incomplete girdle and elongated maxima suggest regional rotation of the F_2 folds overturning towards south. The pole of the π circle B falls in the centre of a triangle formed by the intersection of the various great circles. Its plunge, 49° due N 11°, represents the average plunge of the cross-folds in this sector with limiting positions between N 300° - N 45°.

Sector -IV. Sector IV represents the area south of sector VI and east of the Maru river. It is largely comprised of quartz-phyllites. The primary bedding S_1 is not well preserved as in the earlier sectors, and the general trend of the outcrop pattern and the gradational contacts have been considered as S_1. These generally strike in NNW-ESE direction. The prevalent foliation trend S_2 lies between N 310° to N 360°, with 40° -60° dips towards east. The S_2 cuts across the S_1 at an acute angle at several places. When traced from west to east the S_2 changes from NW-SE, NNW-SSE, and finally to ENE-WSW, in an anti-clockwise direction. The predominant foliation trend has been influenced by the axial trace of F_2 folds, trending NNW-SSE with some fanning and rotational influence of F_3 folds.

The πS diagram (fig. 20) shows a maximum in the southwest quadrant flanked by two elongated sub-maxima on either side, with a tendency to form two incomplete girdles. Consequently the two inclined π circles (π_1 and π_2) passing through the maximum suggest regional rotation of the F_2 folds which appear to be overturned towards west. Three great circles S_2a, S_2b and S_2b_2 corresponding to the maximum and submaxima represent the average axial planes of the F_2 folds in this sector and the limiting positions of their rotation. The poles B_1 and B_2 of the incomplete girdles(π_1 and π_2 circles)coincide with the intersection points S_2a with S_2b_1(β_1) and with S_2b_2 (β_2) respectively. Thus the axes of the folds plunge divergently in 44° due 110° and 45° due N 180°. This is further apparent from the corresponding β diagram(fig. 23)showing a girdle with two pronounced maxima and several submaxima.

Sector V. Sector V consists of the phyllites exposed near Dongargaon forming small hill ranges. The Maru river forms the eastern boundary of the sector. As primary bedding planes are not observable in the phyllites, the general trend of the formation may be taken as S_1, which strikes E-W (±10°). In the northern half of the sector, the the foliation plane S_2 strikes N 290° with an average dip of 50° towards north. In the southern part, the S_2 planes strike between N 65° and N 90° dipping 50° - 60° both towards south and north. The two trends form a V shaped closure. An axis of F_3 fold trending in N 290° with bend pointing towards east passes through Dongargaon hill. Another trace of F_3 fold trending N 100° occupy the centre of the sector. Minor folds, microfolds and slip cleavages(fig. 50-53)developed on the S_2 planes are observed at several places in the sector.

The πS_2 pole diagram (fig. 21)shows one pronounced maximum in in the south-western quadrant with a sub-maximum in the south-eastern quadrant forming an incomplete girdle (π-circle). Two great circles (refFrred to as S_{2a} and S_{2b} in fig. 21) corresponding to the maximum and submaximum represent the average axial planes of F_2 folds on the northern and F_3 folds on the southern part of this sector. The elongated maximum and the incomplete girdle suggest regional rotation of F_2 folds due to cross-folding by superimposed F_3 folds. The fold axis B (pole of πcircle) plunges 50° due N 19°E. B does not exactly coin= cide with β, the intersection point of S_2a and S_2b_1. From the disposition of the maximum and sub-maximum and B it is evident that overall the fold axis is perpendicular to the average axial plane which is overturned towards south.

<u>Sector VI</u>. Sector VI represents the area south of the fault f_3 And east of the Maru river with the hills forming the northern parts extending from Pahungaon towards southeast. The phyllites form the only lithological unit in this sector. As in the previous sector, the bedding planes S_1 are not noticeable. The general trend of the formations is WNW-ESE. The foliation planes strike N 20°W in the northwest, but when traced towards southeast, these show anticlockwise rotation towards N 80°E. The S_2 planes have an average dip of 50° towards north. Two major axes of F_3 folds trending N 80° have been deciphered towards the southeastern part of the sector.

The π-S_2diagram (fig.22) shows two pronounced maxima(17%).

These maxima along with a submaximum in the same southwestern quadrant form an incomplete girdle. Two great circles S_2a_2 and S_2b corresponding to one of the maxima and submaxima represent the average axial traces of the F_2 folds on the northwest part of the sector. The great circle S_2a_1 corresponding to the other maximum, represents the average axial plane mainly observed in the southeastern part of the sector. The elongated maxima and submaxima, and the incomplete girdle suggest regional rotation of the F_2 folds due to the superimposing F_3 folds. In general the folds are overturned towards south.

The intersection point of the great circles β, coincides with B (F_3) which plunges 48° due N 18°E. It represents the overall orientation of the F_3 axis of the large scale flexure on F_2 fold axial plane. Here again, as in the V^th sector, the average strike of the axial plane is nearly perpendicular to the trend of the F_3 fold axis.

Synoptic character of Bhiwapur block

The synoptic π-S_2 diagrams(fig. 27)of the whole area shows a strong maximum (10%) and a sub-maximum (8-10%) in the southwestern quadrant with an incomplete wide gridle. The inclined great circle (S_2b) corresponding to the maximum gives the orientation of the average axial planes(N 120° -N 300° dipping 52° towards north)of fold $F_2 \wedge F_3$. The inclined great circle (S_2b) corresponding to the submaximum represents subsidiary average position of the axial plane of the F_2 fold (N152°-N 332° dipping 58° towards north) in certain sectors. The pole of the π-circle represents the fold axis B.

The intersection point β of S_2a and S_2b nearly coincides with B, thus suggesting that the average B axis or axis of cross folds(F_2 F_3) plunges about 50° due N 16°. For the purpose of comparative study maxima and sub-maxima of π S_2diagrams of all the six sectors were drawn separately on projection diagrams(fig.26,28)From the corresponding πcircle passing through the maxima B was determined, which plunges 50° due N 18°. This almost tallies with the B derived in the synoptic diagram. The B derived from the corresponding sub-maxima π circle plunges 49° due N 41°. The average axis of the cross-folds is perpendicular to the axial plane of the folds.

From a systematic comparison of selective and synoptic diagrams, the tectonic maps and the structures of the adjacent Gaidongari and Pauni blocks, the following conclusions are drawn: (1) TheBhiwapur block was affected by two stages of folding F_2 and F_3. (2) F_2 folds are dominating in this block. Their axial planes vary between N 300° N 335° dipping 52° towards north. The fold axes plunge divergently between N 40°-N-120°. The folds are generally overturned towards south. The rotation and complexity of the F_2folds are due to the superimposition of the later F_3 folds. The average F_3 axial trace as obtained by connecting the F_3 fold hinges generally trend N 70°-N 280°, with their axial planes dipping 52° towards north. (3) Lack of parallelism of S_1 and S_2trends and regional considerations suggest that the resultant of the two folds is geometrically of non-plane non-cylindrical type. The discordant relation between the axial plane and the fold axes suggests that largely the folds are reclined types on the local scale . (4) The orientation of F_3 fold axis has been controlled by the pre-existing form surface of F_2 folds. These F_3 axes cannot be unrolled to horizontal for structural analysis because they were developed on altready inclined form surface and so were initially tilted(Cf Weiss,1954). (5) The imprint of the F_2 fold is well preserved in the relatively competent quartz-phyllites whereas in the incompetent phyllites the influence of the younger fold F_3 is prevalent. Lapham and McKague (1964) have reported a similar occurrence from the Glenarm series, Haines Brook area, Pennsylvania. Here, the more competent and brittle, impure quartzites have preserved the S_1-S_2 orientations whereas, S_3 dominates in the less competent, less homogeneous mica schist. It can be noted from the map 4 that the major axial traces of F_2 folds show a rotation towards the F_3 trends.

3.8-2. GAIDONGARI BLOCK

Sector VII. Sector VII covers the area on the western side of the Gaidongari hills(Map 1,4) from Nimgaon to about 1/2 Km. south of Khapri. Slaty shales, quartzites and argillites are the main rock types exposed in this sector. In the northern end of the sector the quartzite horizon forms a U-shaped closure approximately pointing towards west indicating a plunging fold. It abruptly pinches out towards north and south of the closure. Primary bedding S_1 is observed in the quartzites and banded slaty shales. It generally strikes in N 20°E to N 20° W dipping both towards east and west. The foliation or cleavage planes S_2 observed both in the quartzites and slaty shales trend between

PLATE No.XII

GAIDONGARI BLOCK

Orientation diagrams (contoured)

Fig.29 S_2 poles of Sector VII

Fig.30 S_2 poles (709) - Sector VII

Fig.31 S_2 poles - Sector VIII

Fig.32 S_2 poles (616) - Sector VIII

Fig.33 S_2 poles - Sector X

Fig.34 S_2 poles - Sector IX

Fig.35 S_2 poles (951) - Sector IX

Fig.36 Synoptic diagram - S_2 poles of Gaidongari block

Fig.37 Synoptic diagram of the submaxima (S_2) - Gaidongari block

Fig.38 Synoptic diagram of the maxima - Gaidongari block

For details of S_2 diagrams refer Table 5

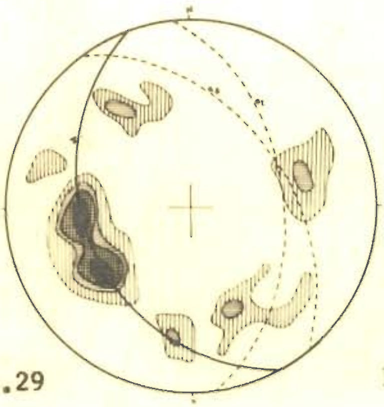
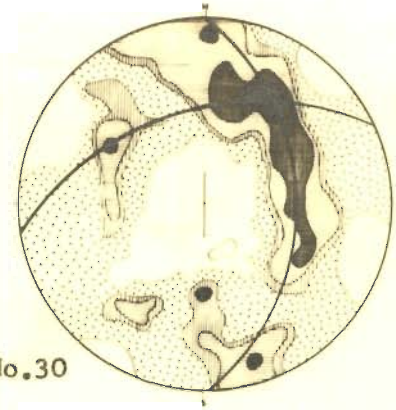


Fig.No.29



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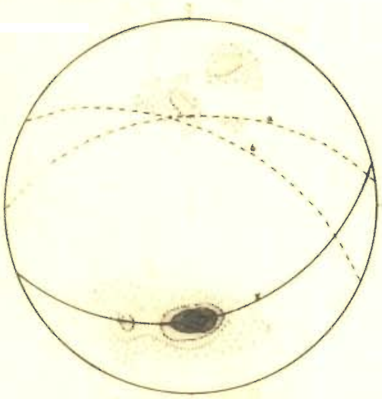

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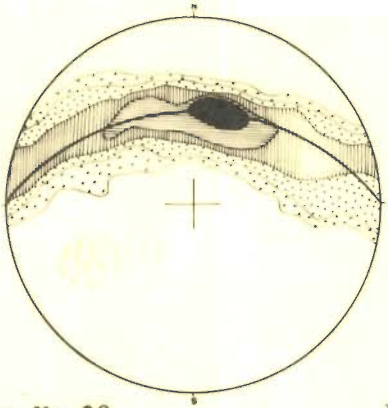

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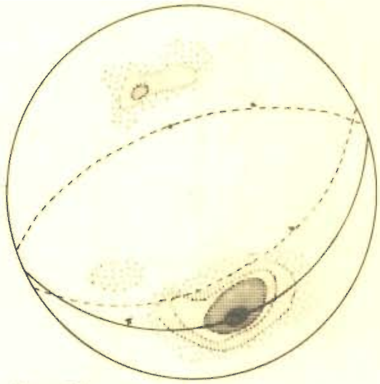

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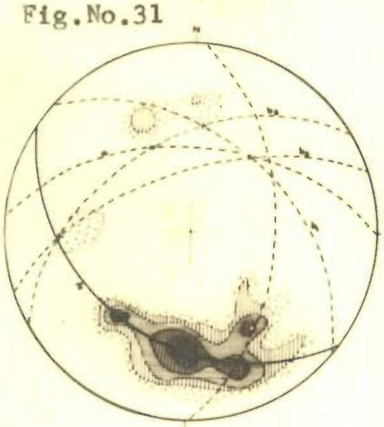

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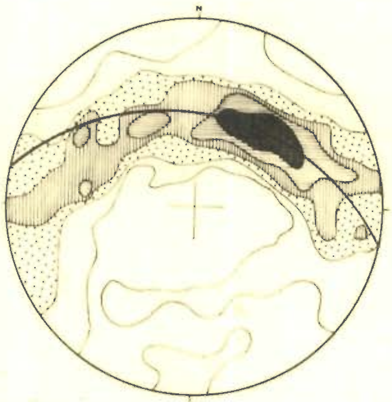

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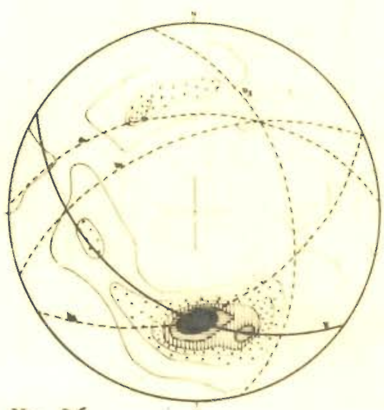

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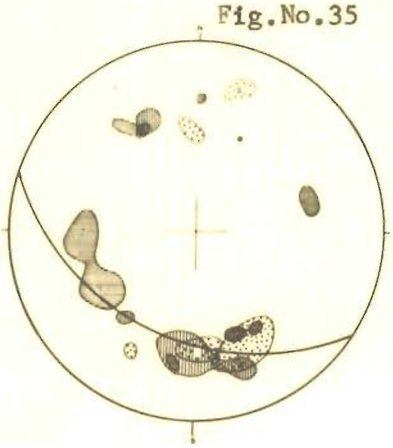

Fig.No.37

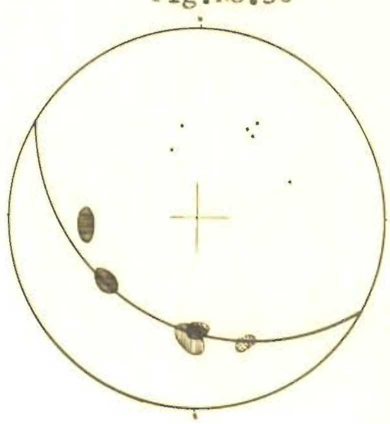

Fig.No.38

PLATE No.XII

GAIDONGARI BLOCK

Orientation diagrams (contoured)

Fig.29	S_2 poles of Sector VII
Fig.30	S_2 poles (709) - Sector VII
Fig.31	S_2 poles - Sector VIII
Fig.32	S_2 poles (616) - Sector VIII
Fig.33	S_2 poles - Sector X
Fig.34	S_2 poles - Sector IX
Fig.35	S_2 poles (951) - Sector IX
Fig.36	Synoptic diagram - S_2 poles of Gaidongari block
Fig.37	Synoptic diagram of the submaxima (S_2) - Gaidongari block
Fig.38	Synoptic diagram of the maxima - Gaidongari block

For details of S_2 diagrams refer Table 5 on the local scale . (4) The orientation of F_3 fold axis has been controlled by the pre-existing form surface of F_2 folds. These F_3 axes cannot be unrolled to horizontal for structural analysis because they were developed on altready inclined form surface and so were initially tilted(Cf Weiss,1954). (5) The imprint of the F_2 fold is well preserved in the relatively competent quartz-phyllites whereas in the incompetent phyllites the influence of the younger fold F_3 is prevalent. Lapham and McKague (1964) have reported a similar occurrence from the Glenarm series, Haines Brook area,Pennsylvania. Here, the more competent and brittle,impure quartzites have preserved the S_1-S_2 orientations whereas, S_3 dominates in the less competent,less homogeneous mica schist. It can be noted from the map 4 that the major axial traces of F_2 folds show a rotation towards the F_3 trends.

3.8-2. GAIDONGARI BLOCK

Sector VII. Sector VII covers the area on the western side of the Gaidongari hills(Map 1,4) from Nimgaon to about 1/2 Km. south of Khapri. Slaty shales,quartzites and argillites are the main rock types exposed in this sector. In the northern end of the sector the quartzite horizon forms a U-shaped closure approximately pointing towards west indicating a plunging fold. It abruptly pinches out towards north and south of the closure. Primary bedding S_1 is observed in the quartzites and banded slaty shales. It generally strikes in N 20°E to N 20° W dipping both towards east and west. The foliation or cleavage planes S_2 observed both in the quartzites and slaty shales trend between

N 355° to N 325° ,with an average dip of 50° towards east. The latter trend is more conspicuous towards the eastern part of the sector. Near the closure of the quartzites S_2 cuts across S_1. The nature of outcrop pattern and the general trend of S_1 and S_2 confirm an antiform of F_2 fold system. The axis passes through the quartzite in N 340°, taking a turn towards northeast near the closure. An axis of F_3 (synform)cross-folds trending east-west crosses the closure. The crossing of the antiform of F_2 by the synform of F_3 has produced a 'col' or saddle structure (Map 2)

π -S_2 diagram presents two pronounced elongated maxima(16%) in the southwestern quadrant forming an incipient girdle (π-circle). The corresponding great circle S_2a_1 represents the average axial planes of F_2 folds overtunred towards west,while S_2a_2 gives the average axial plane due to regional rotation and cross folds F_3 which are overturned towards south. The intersection point β of the two great circles(S_2a_1 and S_2a_2) coincides with the fold axis $B(F_2)$. B has a plunge of 47° due of 47° due N 68° (Fig.29).

Sector VIII This sector covers the area north of the fault f_2 which separates the Gaidongari Formation from the Parsori Formation. Chlorite muscovite schists are the chief rock types exposed in the sector. Though these schists form a separate lithological and stratigraphic unit from the Gaidongari Formation but due to their structural kinship with the latter,they have been grouped within the Gaidongari block for structural analysis. The primary bedding planes(S_1) in the schists are quite rare; the general trend of the formations has been considered as S_1. It varies from NE-SW in the east to WNW-ESE in the west. In the eastern part of the sector the foliation planes S_2 show a general trend in E-W with an average dip of 50° towards north. A few southerly dips are also noted. But when traced towards west the S_2 gradually shows a clockwise rotation towards N 300°. The S_2 planes cut across the S_1 towards east, but they become sub-parallel in the west.

The π-S_2 diagram (fig. 31) shows a pronounced maximum in the south and a sub-maximum towards the southwestern quadrant. They together form an incipient girdle (π-S_2). The elongated maximum and the incomplete girdle indicate regional rotation of earlier folds F_2 due to cross-folding F_3. The intersection point β of the great circle S_2a and S_2b representing average S_2 planes corresponding to the maximum (30%) and sub-maximum (12.5%), coincides with the fold axis $B(F_3)$ The fold axis plunges 50° due N 348°. The folds are generally overturned towards south. The overall trend of fold is nearly perpendicular to the average strike of axial planes.

<u>Sector IX.</u> Sector IX covers the southern part of the Gaidongari hill in between Sector VII and fault f_1. Major part of the sector consists of meta-argillites and slates. In the north variegated slates are exposed. These units form a U-shaped closure with its hinge pointing towards south, suggesting a plunging fold. The primary bedding S_1 is observed at few places in the meta-argillites and slates and shows variable trends with low dips. Generally two trends, one a NNW and

the other NNE to NE, parallel to the limbs of the closure are common. The nature of outcrop pattern confirms a synform of F_2 fold in this sector with its axial trace trending roughly N-S. The predominant foliation planes S_2 trend roughly along E-W with an average dip of 55° towards north; subordinate trends are observed in the ENE-WSW with dips of 50° - 65° towards north -S_2 cuts across S_1 at various angles. In general the S_2 follows the trends of F_3 folds in this sector.

In the π -S_2 diagram (33) a pronounced maximum (17%) occurs in the southern sector. The maximum along with two sub-maxima(10-13%) forms an imperfect girdle(π-circle). The great circle S_2a corresponding to the maximum represents the average axial plane of the F_3 crossfolds. The great circle S_2b, corresponding to the maximum gives the average axial plane of F_2 folds after regional rotation due to cross folding. Other great circles $S_2b_2$and S_2 $b_3$represent the intermediate positions. The intersection point of the great circles S_2a,S_2b and S_2b_3 coincide with the fold axis BF_3. B has a plunge of 48° due N 34°. This is further corroborated by the corresponding β diagram(fig.34)
with a pronounced maximum.

<u>Sector X.</u> Sector X includes the northern half of the Gaidongari hills. The sector comprises of slaty shales,meta-argillites,slates,variegated slates and conglomeratic slates. The variegated slates and conglomeratic slates form an oval shaped closure,part of which lies in sector IX. The S_1 planes with variable trends are often observed in the

slates and phyllites. These generally vary from N 55° to N 110° with both northerly and southerly dips at low angles. In this sector the closure of the beds is due to the intersection of two major synform fold axes of F_2 and F_3 forming a 'depression' (map 2,4). The axial trace of F_2 synform trends in NNE-SSW direction. The change of the trend from N-S (as observed in sector IX) to NNE-SSW is due to the effect of the F_3 cross folds. The axial trace of younger fold F_3 (synform) trends in ENE-WSW direction. The most common strike of the foliation planes S_2 in the sector is ENE-WSW with an average dip of 60° towards north. In the northern part of the sector the foliations dip largely towards South. Throughout this sector S_2 planes intersect the S_1 planes at various angles.

The π-S_2 diagram (fig.33) contains a well developed maximum (22%) in the southeastern quadrant forming a wide incipient girdle. A sub-maximum is developed in the northwestern quadrant. The S_2a and S_2b great circles corresponding to the maximum and submaximum represent the average positions of axial planes of the F_3 folds. The average fold axis B (as obtained from the pole of the π circle) has a plunge of 60° due N 339°. The pronounced maximum and the submaximum in the opposite quadrants, the elongation of the maximum and submaximum and wide incipient girdle give the limiting positions of the cross-folds F_3 developed on F_2.

SYNOPTIC CHARACTERISTICS OF THE GAIDONGARI BLOCK

The synoptic π -S_2 diagram (fig. 36)of the Gaidongari block shows a well formed maximum (15%) towards south. Two sub-maxima(10% and 4%) are developed in the southeastern and southwestern quadrants respectively. A third sub-maximum (6%) is noticed in the northwest quadrant. In general the π-diagram has a tendency to form a cleft girdle. The inclined great circle(S_2a) corresponding to the maximum gives the orientation of the average axial plane of fold F_3 trending E-W and dipping 40° due N. The inclined great circles S_2b,and S_2b_2 corresponding to the submaxima represent subsidiary mean position of axial planes of the F_3 fold. The great circle S_2b_3 corresponds to the sub-maximum representing the average axial plane of F_2 folds in some sectors of the area. The pole B of the πcircle represents the average fold axis of F_3. The intersection point β of the great circles S_2a, S_2b_1 and S_2b_3 coincides with B suggesting that the average B axis of the cross folds plunges about 42° due N 33°.

The fold axis B derived from the circle formed by the maxima of the four sectors combined (fig.38) has a plunge of 46° due N 30°. Similarly; the fold axis B from the submaxima of all the sectors(fig.37) gives a plunge of 46° due N 24°. The characteristics of the various diagrams have been mentioned in the Table.5.

The following conclusions are drawn from a systematic comparison of selective and synoptic diagrams and the tectonic map of the Gaidongari block.

(1) The Gaidongari block has been affected by two stages of folding termed F_2 and F_3 folds.- the same fold movements which have affected the Bhiwapur block. (2) F_3 folds were superimposed on the earlier formed F_2 folds. The F_3 folds are more pronounced towards north and northeast of the area while F_2 is more conspicuous towards south and southwest. The average axial plane of F_3 varies between N 60° to 90° dipping 50° to 60° towards north indicating that in general the folds are overturned towards south. The F_3 fold axis generally plunges 50° to 60° between N 35° to N 340°. The average axial plane of F_2 varies between N 320° to N 300° dipping almost 80° towards north. There is general lack of parallelism of S_1 and S_2 and they intersect at acute angles. (3) Two major fold axes, an antiform and a synform of F_2 folds, and a major synformal axis of F_3 fold superimposed on the F_2 folds have been established in this block. In the northeastern part of the blocks a well developed 'depression' is noted. A 'cole or saddle' is observed towards NE of the block due to intersection of antiform of F_2 and the synform of F_3 folds. (4) At places the orientation of the F_3 fold axis has been partly controlled by the pre-existing form surfaces of F_2 folds. (5) The forces responsible for the F_3 folds were stronger in the Gaidongari Formation in the north and their effects gradually decreased towards south. (6) The resultant fold structure of the two folds is geometrically non-plane non-cylindrical type.

3.8-3. PAUNI BLOCK

Sector XI. Sector XI covers a linear tract along the right bank

PLATE No.XIII

PAUNI BLOCK

Orientation diagrams (contoured)

Fig.No.39 $-S_2$ poles - Sector XI

Fig.No.40 $-S_2$ poles - Sector XII

Fig.No.41 $-S_2$ poles - Sector XIII

Fig.No.42 Synoptic diagram S S_2 poles of Pauni block

Fig.No.43 Synoptic diagram of submaxima ($-S_2$) of the three sectors in Pauni block

Fig.No.44 Synoptic diagram of maxima ($-S_2$) of the 13 sectors of Pauni Bhiwapur area

See Table 6 for other details

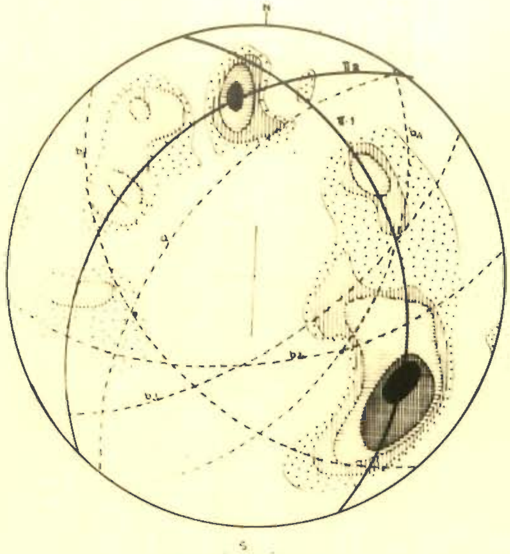

Fig.No.39

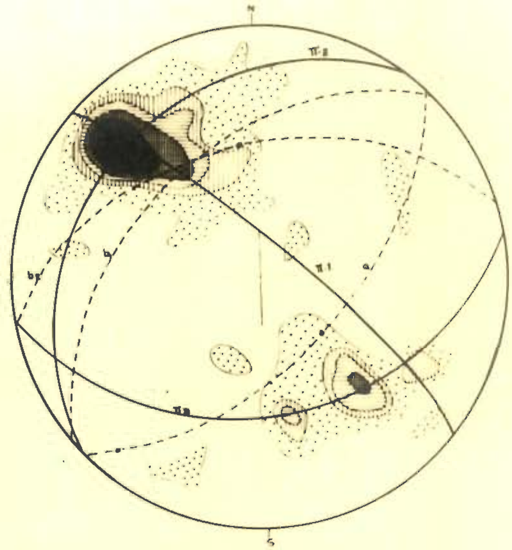

Fig.No.40

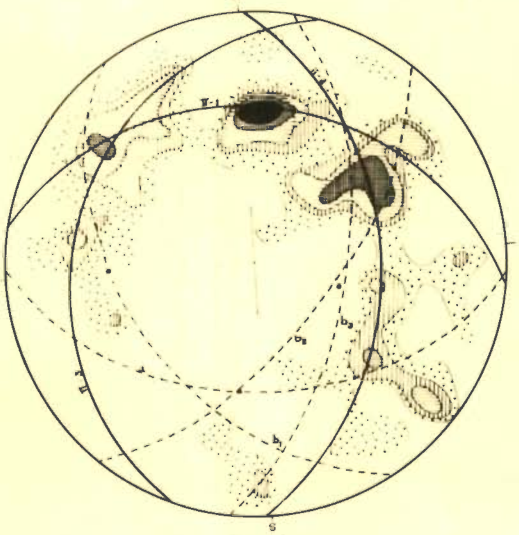

Fig.No.41

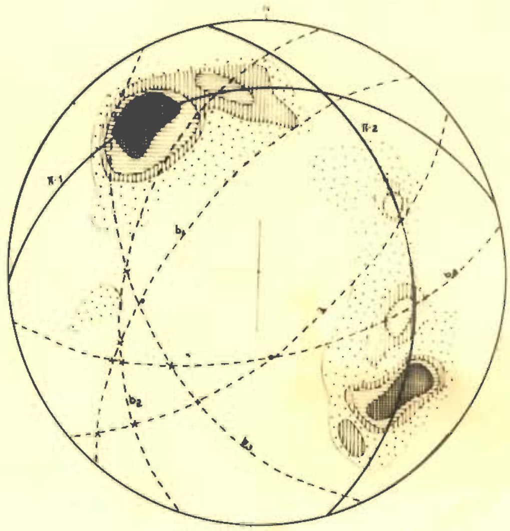

Fig.No.42

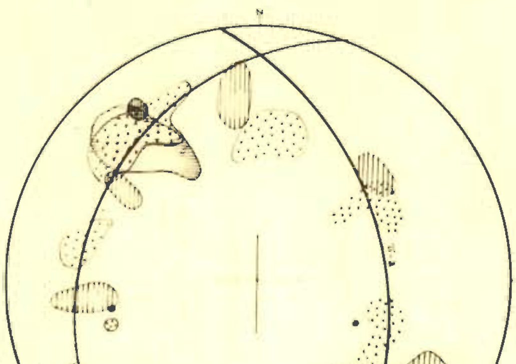

Fig.No.43

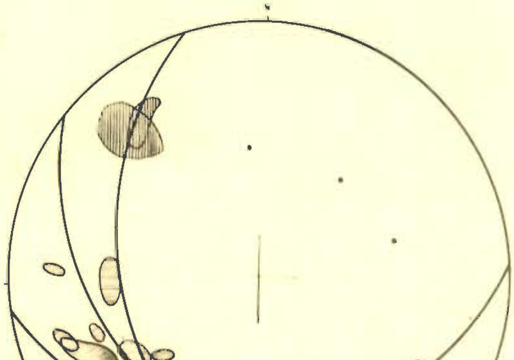

Fig.No.44

of the Wainganga river, including part of its bed(map 4)extending from the confluence of Upashya nullah in the north to just south of Pauni town. In this sector numerous exposures of granites, pegmatites, amphibolites and ultrabasic bodies are associated with the chlorite schists. Primary bedding planes (S_1) could not be deciphered in this sector. The foliations(S_2) are well developed in the chlorite schists, less common in the ultrabasics and amphibolites and rarely observed in the granites. In the northern part the general trend of the foliations varies from NNE-SSW to ENE-WSW with an average dip of 65° towards north. At many places foliation trends vary towards NW-SE and N-S directions with high dips towards northeast and east. Locally several other trends of foliation are observed. This diversity of foliation which is also noted in other sectors of this block, is partly due to the three stages of deformation(referred to as F_1, F_2 and F_3) and partly effected by the different stages of igneous intrusions. This has produced complex type of folds. The detailed plan(Map 5) of an outcrop of the sector shows the complexity of the fold styles (polyclinal and disharmonious types) with diverse trends in fold axes and axial planes. Based on the attitude of the foliation i.e. their convergent trends and opposite dips a major synform with axial trend ENE-WSW has been predicted.

The π-S_2 diagram(fig. 39)includes a maximum(10%) in the southeastern quadrant. This,together with several submaxima shows an incomplete cleft girdle suggesting a complex fold pattern in this sector. For convenience of interpretation two π-circles(π_1 and π_2) passing through the maxima and submaxima have been draw . The poles of these circles π_1 and π_2 ,B_1,B_2 have plunges 49° in N 248° and 38°in N 129° respectively. The intersection points (β) of the great circles S_2a and S_2b_1,S_2b_2, S_2b_3, S_2b_4 and S_2b_5 corresponding to the maximum and submaxima show divergent plunges(amounts ranges from 0 to 50°). The details of the π and B are summarised in the Table6.

Sector XII. Sector XII comprises a linear tract along the Upashya nullah extending for about 3 Km. from the Wainganga river to the foot of Gaidongari hills. The chief rock type is the chlorite-quartz schists with numerous bodies of amphibolites,granites and pegmatites. A few ultrabasic bodies are also observed in this sector. As in the Sector XI foliations S_2 are well developed in the schists and less common in other rock units. The predominant trend of foliation is in NE-SW direction with an average dip of 60° (varying between 30° to 80°) towards south,although northerly dips are not uncommon. Variation in trends of the foliation between N 30° to N 80° is observed at many points.

The π-S_2 diagram(fig. 40)shows a pronounced wide maximum(12%) in the NW quadrant and a well developed sub-maximum(10%) in the SE quadrant. The elongation of the maxima and submaxima forms an incomplete girdle (π1-circle), with their spreading along two inclined incipient girdles(π2and π3circles). The nature of the maxima and submaxima confirms the presence of at least two system of folds

(F_1 and F_3) intersecting each other. The corresponding great circles S_2a, S_2b_1, S_2b_2, represent the mean position of axial planes of the folds. The variations are partly due to rotation of the fold axis by cross-folds and partly due to emplacement of igneous intrusives as in the Sector XI.

Sector XIII. Sector XIII represents a rectangular area south of sector XII covering most of the chromite quarries. In this sector the chief rock types include the ultrabasics with the associated chromite deposits, the amphibolites, the granites and pegmatites,and the chlorite schists. The alignment of the three isolated quarries trends ENE-WSW which probably represents the axial trace of a major synform fold(map 4). Several small scale simple and complex folds are observed in the chromite quarries. The predominant trend of foliation is E-W with an average dip of 50° due south. There is wide range of variation in the trends and dip of the foliation in this sector.

The corresponding π-S_2 diagram (fig. 41)shows a maximum(7%) with several submaxima forming a cleft girdle indicating the complexity in the fold pattern. Based on the elongation of the maximum and a sub-maximuma, three πcircles $\pi 1$ $\pi 2$ and $\pi 3$ have been drawn. B_1, B_2 and B_3 corresponding to these circles have plunges 50° in N 192°, 40° in N 272° and 62° in N 110° respectively. The intersection points of the great circles, S_2a, S_2b_1,S_2b_2, S_2b_3 ,corresponding to the maximum and submaxima show divergent plunges. This further confirms the complexity of fold styles in this sector,which is as mentioned earlier mainly due to the three stages of deformation F_1, F_2 and F_3 and partly due to various stages of igneous activities. The details of diagrams are summarised in Table 6 .

Synoptic character of the Pauni block

The synoptic π-S_2 diagram(fig. 42) of the Pauni block shows an elongated maximum(6%) in the northeast quadrant. There are several sub-maxima (4% and 3%) with a tendency to form a cleft girdle. The inclined great circle S_2a and S_2b_1 dipping 66° in N 136° and dipping 64° in N 308° respectively corresponding to the maximum and one of the submaxima represent the orientation of average axial plane of the earliest folds F_1. The great circles S_2b_2 and S_2b_3 corresponding to the other sub-maxima probably represent the average position of the axial planes of F_2 folds.

The inclined great circle S_2b_4 (dipping 62° in N 166) corresponding to the submaximum represents the average axial plane position of the superimposed F_3 fold.

The pole B_1 of the π-1 circle represents the fold axis F_3. The intersection point β of the great circles S_2a and S_2b_1 coincides with B_1, suggesting that the average axis of the cross-folds plunges 61° due N 171°. The pole $B_2(F_3)$ of the π-2 circle has a plunge of 50° due N 53°.

From the two π- circles formed by the submaxima of the three sectors combined, two fold axes were determined for comparison with the earlier findings. The former has a plunge of 40° due N 261° and the latter plunges 60° due N 113° (for details refer Table 6 and fig.43)

From a comparative study of selective and synoptic diagrams and the tectonic map of the Pauni block, the following conclusions have been drawn: (1) The Pauni formations were affected by three stages of folding F_1, F_2 and F_3 folds. (2) The imprint of F_1 fold (N 30-50°) is dominant in this block, while the effects of the younger folds F_2 and F_3, especially of the former, are less conspicuous. (3) There is great diversity in the trends and dip of the foliations S_2 and the corresponding fold axes, which are mainly controlled and conditioned by the various stages of folding and igneous intrusions. This has produced complex styles of folds of non-plane non-cylindrical, disharmonic and polyclinal types (Map 5). (4) The ultrabasics are associated with the first phase of F_1 fold movement. In the Pauni region, the ultrabasic intrusives have been mainly controlled by the axis of a major synform having a trend between NE-SW to ENE-WSW. (5) The acid intrusives (granites and pegmatites) were emplaced during the last stage of the F_1 fold movements and the basic intrusives followed in between the ultrabasic and the acid igneous activity in this block.

3.9. TECTONIC HISTORY

On the basis of the detailed field investigations of the different structural elements, their interrelationships and their geometric analysis with the help of selective and synoptic π-S_2 and β diagrams of the different sectors, the following conclusions regarding the tectonic evolution of the area have been drawn:

1. Development of the Pauni basin(may be part of a geosyncline) with deposition of the rocks of the Pauni Formation,mainly ferruginous clays and occasionally fine sands.

2. Development of the first stage fold movement (F_1) generally trending NE-SW by stress couples probably acting along NW-SE. Due to lack of any prominent competent layers,rarity of primary bedding planes S_1, complexity of deformation produced by later fold movements (F_2 and F_3),and modification and mobilisation of the S_2 planes due to igneous activities, it was not possible to unroll the F_1 folds to their horizontal position, and to decipher their kinematic history

3. During the early phase of the F_1 movements, emplacement of ultrabasics (including chromite bodies) took place as linear parallel lenses, mostly concordant along the weak zones of the country rocks following the predominant trend between NE-SW to ENE-WSW. In the later phase of the same fold movements acidic intrusions (granites and pegmatites) and permeation of the country rocks by quartzofelspathic solution (migmatitisation) took place along the weak zones of the country rocks. In between these two phases basic rocks (now represented by amphibolites) were intruded mostly as concordant bodies.

4. Formation of independent basins of Bhiwapur and Gaidongari regions and deposition of mainly pelitic to semi-pelitic sediments with occasional layers and lenses of psammitic and ferruginous sediments. Most probably another basin (Parsori) was formed with similar deposition north of Gaidongari with its southern fringe lying within the area studied.

5. Development of F_2 folds along N-S to NNW-SSE by stress couples probably acting in directions between N-W and ENE-WSW. These fold movements were more intensive in the Bhiwapur region and gradually decreased towards north and northeast. This stage of folding gave rise to a major antiform and a synform in the Gaidongari region and a series of alternating synforms and antiforms in the Bhiwapur region. These folds are generally overturned towards south and south-west. Their average axial planes dip 50°-60° towards north and north-east with their axes plunging at 40° to 60° towards east.

6. Development of F_3 folds superimposed on the earlier folds with their trends generally lying in between E-W to ENE-WSW by vertical stress couples acting in the north-south directions. This fold movement was more active in the Gaidongari region, than in the Bhiwapur region. The cumulative effect of different fold movements caused the formation of complex folds in Pauni, Bhiwapur and Gaidongari areas. The deformation F_3 caused the formation of a major synform (Khapri-Thana synform) in the Gaidongari region and a series of en echelon folds in the Bhiwapur area, generally plunging towards north. The crossing of the Khapri-Thana synform (F_3) with the Gaidongari synform (F_2) gave rise to a 'depression'. A 'col' or 'saddle structure' has developed near Khapri where the F_3 synform crosses the antiform. Folds like non-plane non-cylindrical, polyclinal and disharmonious types are not uncommon
The axial planes of earlier folds have considerably been deflected and rotated from their original disposition due to the later F_3 folds.

7. The orientation of the F_3 folds was controlled and conditioned by the pre-existing orientation of S_2 planes, relative competency of the rocks, and partly by the nature and direction of the stresses.

8. In the later phase F_3 deformations gave rise to three major faults (f_1,f_2 and f_3) forming the tectonic boundaries of the Pauni, the Parsori, the Gaidongari and the Bhiwapur Formations.

9. Though the general trends of F_2 and F_3 are nearly normal to each other, their variable intensity within a small region suggests that these movements might represent successive phases of a single orogenic cycle. Detailed structural analysis of the adjoining areas, particularly towards west and north, may corroborate the above conclusions. Further, such a study would help in correlating the tectonic history of the present area with that of the 'Sakoli Synclinorium' in the north as established by Sarkar (1957).

10. Finally, at a much later period(probably during Gondwanas) development of a small basin in the southeastern region of Pauni took place, with the deposition of sands, grits, pebbles and mud and silt. Their gentle deformation (uplifting, tilting and some dislocation), with the concurrent development of a major fault (f_4) on the northern borders was the last episode of tectonic history of the present area.

CHAPTER - IV

PETROGRAPHY

This chapter deals in some detail the petrography of various rock types of different formations met in the area. The description of the rocks has been followed in the order from the oldest formation i.e.Pauni Formation to the youngest,i.e. the Younger Sedimentaries. Their field description and major classification have been dealt in Chapter II. Here the megascopic and microscopic characters of the individual rock units have been discussed,the latter includes the texture,structure,mineralogy,and their modal analyses wherever possible. The petromineralogical characters of various rock types of the area have been summarised in Table 7.

4.1. PAUNI FORMATION

4.1-1. CHLORITE-SCHISTS(LARGELY MIGMATITISED)

Megascopic Characters. The chlorite schists which are largely migmatitised present a striped appearence having dull olive green to brownish green layers of flaky chlorites and minor amounts of biotite, alternating with continuous or discontinuous layers of white quartzo-felspathic material. The schistose character is well preserved in most of the specimens. Generally these rocks are soft due to weathering and the layers are easily separable. The felspathic material is altered in most of the samples. Some specimens show a gneissic character with alternating bands of lighter and darker shades.These gneissose rocks are harder than the schistose variety. The pure chlorite schists are quite rare and a few samples collected at the base of the Younger Sedimentaries,are dark green in colour,well foliated and soft. These are largely comprised of the flaky green chlorites with quartz grains along the planes of foliation.

Microscopic features

Mineralogy and texture. Thin sections of the chlorite schists under the microscope show well developed schistose textures. In migmatitised schists, the schistosity is obliterated due to quartzo-felspathic veins and in such rocks gneissose texture predominates. The mineral constituents are chlorite, quartz, felspars and biotite. The schists next to amphibolite bodies contain hornblende and in some sections of the schists (particularly near quartz-grunerite-magnetite rocks) grunerite is also observed. Secondary minerals like calcite and prehnite form thin veins. Sericite is a common alteration product of felspars. Minute grains and particles of iron ores are often noted as inclusions in chlorite. Quartz and felspars together form lenticles within layers of chlorite and they also form veinlets generally parallel to foliations. These minerals appear to be of extraneous origin.

Chlorite. It occurs either as flakes moulded around quartz and felspar grains or as clusters of flakes. It is pale green to yellowish green in colour and weakly pleochroic with absorption: X=pale green; Y = pale green; Z = pale yellowish green. It has parallel extinction and low order polarisation colours.

Felspars. This is a common constituent in the migmatitised schists. Both soda and potash felspars are found. As most of the grains are largely altered it is difficult to make out the amounts of potash felspars and plagioclase. The plagioclase is of oligoclase composition($An_{16}Ab_{74}$).

In potash felspars orthoclase predominates over microcline. The felspar grains show granulation and strain effects. Generally the felspars (particularly the plagioclase) are highly sericitised but twinning is still preserved in many sections. Some of the grains are clouded due to kaolinisation.

Quartz. Quartz occurs as aggregates of smaller grains and as bigger individual grains. The latter shows cataclastic effects like granulation and cracks and is often associated with felspar. Undulose extinction is quite common. Smaller grains occur either as inclusions in chlorite or in the interstitial spaces of chlorite flakes.

Biotite. It is found in some sections as small flakes. It is light brown with strong pleochroism from light to dark shades. Some of the flakes show alteration to chlorite.

Hornblende. A few elongated prismatic grains of green hornblende are observed in some sections. It is strongly pleochroic from light yellowish green to green. Extinction varies upto 18° ($C \wedge Z$).

Grunerite. It occurs in elongated prismatic crystals arranged in a linear direction parallel to the foliation planes of chlorite. It is neutral to light greenish yellow, faintly pleochroic. Extinction varies upto 15° ($C \wedge Z$). It is generally altered to chlorite and limonite.

Veins. Thin veins cutting across these rocks contain either calcite or prehnite or both in combination. Calcite occurs as colourless sub-hedral grains showing parting and high order polarisation colours. Prehnite occurs as aggregates of small laths and needles showing one direction cleavages and parallel extinction. It has variable birefringence in different grains with abnormal interference colours.

4.1-2. QUARTZ-GRUNERITE-MAGNETITE ROCKS

Megascopic characters. The magnetite bearing rocks are formed of alternate parallel bands of quartz,ore-minerals and altered(limonitised) grunerite. (Fig.103) The width of the bands varies from 1 mm. to 15 mm. Quartz bands are of white,dark grey or greenish grey colours while limonitised grunerite bands give yellowish brown or brownish yellow colour. In some rocks of this group,different shades of grey quartz form layers. Iron ore minerals are disseminated in them in linear pattern without forming any definite bands. Brown amphiboles form thin layers.In massive variety iron ores and grunerite are found in the interstices of quartz grains. The quartz rich variety is green,greenish grey,dark grey or greyish black in colour. Green or yellowish brown amphiboles(grunerite) is found in the interstitial spaces of quartz or sometimes as thin layers.Ore minerals are not observed in the hand specimens. Grunerite rich rocks are yellowish brown or brownish yellow in colour and appear to contain some amount of limonite apart from iron ore minerals(magnetite and hematite).

Microscopic features. Following mineral assemblages have been recognised from microscopic studies: (1) Quartz-magnetite-grunerite banded rocks. (2) Quartz-grunerite rock-massive type.(3) Grunerite-magnetite rock with minor amount of quartz.

All these rock types contain various amount of limonite as a secondary product. The texture is generally granulose,and in the banded type coarse banding is often observed.

(1) Quartz-magnetite-grunerite rock.

Quartz: Quartz grains vary in size from 0.1 mm. to 1 mm. and form a mass of interlocking grains. Few of the grains are clouded by concentration of iron oxide dust. In some sections randomly oriented thin needles of rutile are present as inclusion in quartz.The grain boundaries and cracks of quartz are coated with yellow to yellowish brown semi transluscent films of iron oxide.

Grunerite: In most rocks grunerite bands have been limonitised.Unaltered types exhibit typical characteristics of the amphibole. It is neutral to pale green or pale yellowish green in colour and is feebly pleochroic in coloured variety. It occurs as clusters of small prismatic grains which show parallel or sub-parallel,linear orientation (fig. 129).Both simple and multiple twinning are observed in the prismatic sections, the latter being more common.The twin lamellae are closely spaced. Extinction angle varies between 10° - 15° ($C \wedge Z$). In several sections, grunerite is replaced by fine quartz and limonite along the cleavages, fractures and grain boundaries.

Iron ore minerals: They occur as elongated plates,lenticles,streaks and anhedral grains of various dimensions. In some sections the long dimensions of the ores are oriented parallel or sub-parallel to each other. Many of these grains show rugged borders. Some of them contain small inclusions of quartz.

In polished sections under reflected light,magnetite,hematite and goethite are observed.Magnetite is the only primary ore mineral present. It has largely been altered to or replaced by hematite as a result of martitisation.Goethite is a supergene mineral replacing the earlier ores and the silicates.

Magnetite:It is found as a relict mineral in patches,which are enveloped by hematite.Magnetite grains with various degree of alteration are present. Small idiomorphic grains as octahedra and dodecahedra showing replacement by hematite along the cleavages and peripheries of the grains are seen.It is pinkish grey in colour,shows low reflection and is isotropic.

Hematite: It occurs as xenomorphic linear grains and elongated plates with rugged borders. Octahedral cleavages of the original magnetite are retained by many grains. Several pseudomorphs of hematite(martite) are seen as small idiomorphic grains. Some of the bigger hematite grains form a fine mass containing some well developed rectangular plates of the same mineral,along the relict crystallographic directions(of magnetite).It is bright white in colour,shows high reflectivity and anisotropism.

Goethite: It occurs as vein fillings and as irregular patches.It has partially replaced some magnetite and hematite and completely replaced some grunerite(fig.128). It is white with a grey tint,and weakly anisotropic.It apppears to have formed much later during oxidation of the rock.

On the basis of the above features, the paragenesis of the iron ore minerals can be summarised as below:

Time

Magnetite

Hematite
(Martite)
Goethite

(2) Quartz grunerite rock. In this rock grunerite occurs as aggregates of short prisms and tabular grains in random orientation or in irregular bands.Clusters of grunerite contain quartz in their interstitial spaces. Bigger grains contain inclusions of quartz. Irregular grains of iron ore occur in the interstitial spaces of grunerite.

(3) Grunerite rich rocks. In this variety grunerite forms more than 85 to 90% of the rock.Long and short prisms and tabular grains of various sizes form aggregates in random orientation.Platy types show inclusions of quartz.Quartz grains upto 0.5 mm. in diameter occupy the interstitial spaces of grunerite aggregates.Iron-ore(magnetite-hematite) is present mostly as xenomorphic grains.

4.1-3. AMPHIBOLITES

Megascopic characters. The amphibolites are of greenish black,dark green,dull green and light green colours with white specks. Both foliated and non-foliated types with intermediate varieties occur in the area. Foliated variety forms the dominant group. In this type green amphiboles are either platy having parallel arrangement and closely spaced foliations,or show linear orientation with broad foliations. The latter also shows linear arrangement of light coloured minerals as specks,streaks and lenticles. One group of the foliated rocks is of striped or banded nature due to alternate segregation of light coloured and dark coloured minerals.

The non-foliated type is mostly fine to medium grained with felsic material interlocked with mafic minerals without any preferred orientation. Some specimens are medium to coarse grained,dark green coloured with randomly oriented constituents.This variety is very hard and massive. Felsic minerals are either absent or present in very minor amount.

Microscopic characters

Classification: Based on the mineralogical composition and modal analyses(Table 8-11)the amphibolites of Pauni area have been classified into the following four groups:

(1) Normal amphibolites (2) Quartz free amphibolites (3) Plagioclase amphibolites (4) Hornblendites.

The predominant group among these is the normal amphibolites in which hornblende percentage varies from 45 to 70% and that of plagioclase from 25-40%. Quartz is invariably present in this group(1 -5%). Chlorite is present in varying amounts depending on the degree of alterations suffered by the hornblende.Ilmenite,sphene,epidote and apatite form the minor constituents(Table 8). The second group is quartz free amphibolites in which hornblende is 60 - 85% and plagioclase 10 - 40%. Ilmenite,sphene epidote etc. form the minor constituents(Table 9). Plagioclase amphibolites form the third group which are represented in the field by striped,banded or gneissose varieties.In these the amount of plagioclase exceeds that of hornblende. Plagioclase is generally over 50% of the total composition while hornblende varies from 30-40%.Quartz is present in small amounts (Table. 10). The last group is represented by hornblendites which are rather of restricted occurrence in the area found in the quarries of Modern Plastics Ltd. Claim. In these hornblende exeeds 90% (Table 11).

It was found that the recent classification of amphibolites by Cannon(1963) could not be applied to the rocks of the area under

TABLE - 8

Modal analysis of normal amphibolites

Sp.No.	grain size in m.m.	Hornbl-ende	Andesine	Quartz	Chlo-rite	Sphe-ne	Ilmeni-te	Epit dote	Apa-tite	Total %
1/158	1-2	62.35	28.45	4.9	2.2		2.10			100
1/104	0.2-0.5	59.50	24.9	3.2	6.4	3.6	3.46			100
1/891	1-2	61.50	36.00	2.5	-	-	-			100
1/174	0.5-1	50.70	32.60	4.22	8.57	-	3.97			100
1/807	0.3-0.8	53.47	35.60	5.26	2.26	-	-	2.96		100
NL158	1-2	46.96	37.42	1.82	13.35	-	-		0.42	99.97
1/579	0.30	69.50	26.21	1.7			2.59			100
1/851	0.5-15	65.00	31.10	1.30	-	2.50				99.90

Location of the specimens: 1/158 Khadan nullah. 1/104 Korambi
1/891 River bank near the electric tower (Pauni). 1/174 Waingange river bed near Sindouri. NL 158 Upashya nullah. 1/807 Khatsi.1/579 Khadan nullah
1/851 Quarry -Modern Plastics claim.

TABLE -9

Modal analysis of quartz-free amphibolites

Sp.No,	grain size in mm.	Hornblende	Andesine	Chlorite	Ilmenite	Sphene	Total
1/802	1-2	84.03	14.35	-	1.65	-	100.03
1/114	0.1 -0.3	59.45	33.95	3.5	3.1	-	100.00
1/814	0.65--2	84.45	10.82	2.57	2.16+	-	100.00
1/113	1-2.5	32.68	40.00	23.54	-	2.52	98.74
1/826	0.5-1	68.00	30.07	-	-	1.93	100.00
1/816	0.20	65.32	29.36	2.17	3.15++	-	100.00

\+ including apatite
++ including sphene

Location: 1/802 Pauni-Nimgaon Road. 1/114 Khadan nullah behind quarry 2(SCS)
1/814 River bank,south of Pauni bridge. 1/113 Upashya nullah
1/826 Pit 2 Quarry 2 (SCS). 1/816 Pit 3 .Quarry (GCS)

TABLE -10

Modal analysis of plagioclase amphibolites.

Sp.No.	Grain in size in m.m.	Hornblende	Andesine	Chlorite	Quartz	Ilmenite	Sphene	Total
1/1220	1-2.8	33.46	56.78	2.06	2.06	3.06	2.06	99.48
1/565	2.00	45.07	52.63	-	0.68	1.62	-	100
1/413	1-2	42.85	45.15	7.63	-	4.37	-	100
1/751	0.2-1	31.5	54.17	11.58	1.35	1.35	-	100.05
1/154	0.5-1	39.5	52.69	5.9	1.00	0.8	-	99.87

Location: 1/1220 Pauni-Korambi road, north of Quarry (GCS)
1/565 Khadan nullah. 1/413 Maru river (Gaidongari Formation). 1/751 Quarry 1 Pit No.6; 1/154 Wainganga river bed south of Khatsi.

TABLE -11

Modal analysis of hornblendites

Sp.No.	Grain size in mm.	Hornblende	Chloritised hornblende	Chlorite	Sphene	Ilmenite	Quartz	Andesine	Total
1/102	0.5-1.5	63.64	23.59	9.32	3.45	-	-	-	100
1/125	1-2	67.15	23.80+	-	-	3.5	4.65	0.9	100
1/62	0.5-2	79.25	19.44+	-	-	0.8	0.72	-	100.21

+ including chlorites

1/102 Khadan nullah adjacent to Quarry (GCS). 1/125 River bank north of quarry (G.C.S.). 1/62 Pit 3, Quarry (G.C.S.)

investigation. The present worker feels that Cannon's classification is inadequate to cover the amphibolites of different localities,having varying mineral assemblages. Cannon envisages the normal amphibolites to have an approximately equal amount of plagioclase and quartz,and further proposes that the difference between quartz and plagioclase should not exceed 10%. From the Tables (8-10)it could be seen that in the amphibolites under discussion, the amount of quartz and plagioclase,is never equal and further their difference varies between 25 to 35%.

Microscopic features

(1) Normal amphibolites

Texture: The normal amphibolites exhibit nematoblastic texture. Prismatic grains of hornblende of various length are arranged in parallel or subparallel orientations. Smaller grains are randomly oriented and criss-cross each other. In certain sections a sort of interlocking chain texture has formed where the layers formed by linearly oriented minerals are connected together by shorter grains disposed obliquely and the interstitial portion is occupied by plagioclase quartz and other minerals.In certain sections porphyroblasts of hornblende(tabular habit) show sieve structure.

Mineralogy: Normal amphibolites are mainly composed of hornblende, plagioclase (andesine),quartz and chlorite,with sphene,ilmenite,apatite and epidote as accessories (Table. 8).

Hornblende: It forms the most abundant constituent(45 - 70%) and occurs in various forms and sizes as mentioned in the texture. The grains are mostly prismatic and tabular,subhedral to anhedral(Fig 158).The grain size varies from 0.3 to 2.0 mm. It exhibits different shades of green colour and is strongly pleochroic with the absorption. X = green, pale yellow and greenish yellow; Y = pale green, greenish yellow and yellowish green; Z =dark green and green(Z >Y >X). Rarely some of the prismatic sections show simple twinning with the twin plane parallel to the cleavages. Extinction angle varies from 10° to 20° in prismatic sections,and is symmetrical in basal sections. The hornblende grains show inclusions of quartz,plagioclase and sphene. Some grains exhibit pleochroic haloes. These are probably due to inclusions of allanite. Partial or complete chloritization has taken place in some of the grains. Fractures are common across the cleavages. Brown or red staining is seen in the weak planes due to iron oxide.

Andesine ($Ab_{62}An_{38}$): This is the next mineral in abundance (25 - 37%). Andesine occurs as subhedral to anhedral grains and laths (0.5 to 2 mm.),generally in the interstitial spaces of hornblende.In some sections hornblende projects into andesine. The characteristic polysynthetic twinning has been obscured in many sections due to alterations. Sericitisation to various degrees is observed in several grains, while saussuritization has taken place in a much lesser degree with small flakes and grains of chlorite,pistacite and zoisite as alteration products. Inclusions of quartz,apatite,and sphene,are quite common in the plagioclase.

Quartz: It does not exceed more than 6% in these rocks,and generally occurs as small anhedral grains in the interstitial spaces or hornblende. Small grains of quartz occur as inclusions in the hornblende. Both sharp and undulatory extinctions are noted.

Quartz of secondary origin is also observed along with other secondary minerals like chlorite, sericite and epidote. It also occurs as vein mineral along with epidote.

Chlorite: Small flakes and fibrous aggregates of chlorite present in the amphibolites, are formed due to the alteration of hornblende. It is ripidolite variety having green or yellowish green colour. It is distinctly pleochroic with absorption as X = green or yellowish green, Y = green or yellowish green and Z colourless, yellow. (X=Y> Z). It has straight extinction and exhibits low order polarisation colours.

Small pale green flakes and radiating fibrous aggregates of chlorite occur in veins associated with epidote group of minerals. It is penninite variety of chlorite. It is pleochroic. X = pale green, Y = pale green, Z = pale green to pale yellow green (X = Y > Z). It shows straight extinction and anomalous blue polarisation colours.

Ilmenite. It occurs as anhedral and skeletal grains showing pale pink or greyish white with a pink tint under reflected light in polished sections. It is anisotropic. Some grains show lamellar twinning. Basal sections are isotropic. Some of the ilmenite grains contain thin parallel streaks of hematite as exsolution intergrowths. Sphene forms rims around some of the grains.

Sphene. It occurs as disseminations and aggregates of granules in the interstitial spaces of hornblende and plagioclase and also as inclusions in them. As noted earlier, it forms rims around ilmenite grains It is brown or greyish brown in colour and is pleochroic. Relief is well marked. Polarisation colours are masked by its body colour.

Epidote. It generally occurs in veins, in which pistacite is the dominant constituent with subordinate amount of zoisite, chlorite and quartz. In some sections, pistacite also occurs as disseminated grains and granules in the plagioclase. It is lemon yellow in colour and exhibits high order polarisation colours.

Apatite. Small prismatic and elliptical grains of apatite form inclusions in other minerals. It shows high relief and first order polarisation colours in prismatic sections.

Prehnite. Few white to greyish white (4 to 8 mm. in width) veins observed in some of the amphibolites consists predominantly of prehnite. It occurs as aggregates of small laths and radiating needles. Cleavages are well developed in one direction and the laths show parallel extinction. Lamellar twinning is observed in some laths. It shows high relief and variable birefringence (upto 2nd order) in different grains.

(2) Quartz-free amphibolites

Texture. The amphibolites of this group show both granoblastic and nematoblastic textures. In the former short and stumpy prisms of hornblende criss-cross each other, with the interstitial space occupied by plagioclase. Few long prisms and tabular grains show porphyroblastic texture. Many of the hornblende crystals are interlocked at right angles to each other. Nematoblastic texture is not well developed in these rocks. Here, though the individual prisms lack preferred orientation, their clusters and aggregates show a definite tendency for parallel alignment.

Mineralogy. These amphibolites are composed of hornblende, andesine, chlorite, ilmenite sphene, apatite, and epidote (Table 9). As these minerals have been described in detail in the first group, only their certain important characteristics are mentioned below.

Hornblende. Generally the hornblende occurs as short and stumpy prisms (0.2 to 0.5 mm.). Porphyroblasts of big tabular grains (1.5 to 2.5mm) are common and are riddled with quartz inclusions (sieve structure). Many hornblende grains show rugged and corroded borders against plagioclase.

Andesine ($Ab_{66}An_{34}$). Andesine occurs mainly as anhedral and rarely as subhedral grains occupying the interstitial spaces of hornblende. Sericitisation is often noted along the twin planes. Sausuritization is observed in few sections with chlorite, epidote and calcite as alteration products. In some sections plagioclase is clouded due to secondary alterations.

Chlorite (Ripidolite). It is pale green to yellowish green in colour and occurs as pseudomorphs after hornblende. Few flakes and fibrous aggregates are also present.

Among the accessories, ilmenite, occurs as anhedral grains with ragged borders (0.2 to 0.4 mm.) and as as skeletal crystals. Sphene occurs as granules and clusters of granules disseminated in the groundmass and forming rims around ilmenite grains. Apatite is observed as elongated and round grains projecting into hornblende. Veins consisting of epidote minerals (pistacite and zoisite) and quartz cut across the other constituent minerals.

(3) Plagioclase amphibolites

Texture. Plagioclase amphibolites show both nematoblastic and banded textures. Segregations of hornblende show a tendency to form bands alternating with light coloured minerals like quartz and plagioclase.

Orientation of hornblende within the bands is at random.

Mineralogy. The amphibolites consist of andesine,hornblende,chlorite,quartz,ilmenite and sphene(Table 10).

Hornblende. Hornblende forms prismatic grains of various sizes.In some sections hornblende grains show irregular forms with corroded borders. Some of the tabular grains show schiller structure due to a regular arrangement of minute inclusions of opaque grains (magnetite) and sphene along the cleavage planes.

Andesine($Ab_{62}An_{38}$). Aggregates of anhedral grains of andesine are observed in the interstitial spaces of hornblende and show a linear disposition. Some grains exhibit zoning.

Quartz. Primary quartz forms anhedral grains associated with the plagioclase.Few small inclusions are found in the hornblende.

Chlorite. Green coloured chlorite (ripidolite) is after hornblende forming the bulk of the chlorites. It occurs as flakes and shreds of light green colour.Penninite is found in veins associated with epidote group of minerals

Ilmenite,Sphene and apatite occur as accessory minerals having similar character as described in the earlier groups. Thin veins of epidote are observed in some sections.

(4) Hornblendites

Texture. These rocks are predominantly of non-foliated massive type. Long prismatic,tabular and platy grains are randomly oriented criss-crossing each other showing granoblastic texture. Big tabular grains contain inclusions of smaller grains of hornblende in different orientations.Many prismatic grains project into tabular grains.

Mineralogy. This rock is predominantly composed of hornblende with alteration. product, chlorite. Quartz, andesine, ilmenite and sphene occur in small amounts (Table 11).

Hornblende. Tabular grains of hornblende exhibit sieve structure with inclusions of quartz. Some of the prisms show simple twinning. Schiller structure is exhibited by certain bigger grains.

Chlorite. Chlorite is represented by ripidolite variety as flakes, fibrous aggregates and irregular patches, generally after hornblende. It is light green and pleochroic with straight extinction and low polarisation colours.

Among the accessories, sphene occurs as granules and aggregates of granules dispersed in the mass. It also forms rims around some grains. Ilmenite occurs as small irregular grains and skeletal patches. Quartz is found as small interstitial grains and as inclusions of hornblende. Secondary quartz forms constituent of veins.

4.1-4. GRANITES AND PEGMATITES

On the basis of their megascopic and microscopic characters the granites and pegmatites have been broadly grouped as: (i) granites and gneissose granites (ii) pegmatites and pegmatitic granites (iii) felspar rich rocks

(i) Granites and gneissose granites.

Megascopic characters. These are equigranular having greyish white and grey colours. Fine to coarse foliation has developed in some of the rocks. Quartz and felspars show elongation with preferred orientation. The gneissic character appears to have developed due to dynamic effects.

TABLE - 12

Modal analysis of the granites and the gneissose granites

Sp.No.	Quartz	K.Felspars	Oligoclase	Chlorite	Garnet	Mica	Total
1/146	47.12	38.92	9.12	4.83	-	-	99.99
1/1211	51.54	39.34	6.06	3.04			99.98
1/176	51.20	33.23	5.39	3.40	1.51	5.23	99.96
1/824	43.12	42.46	12.00	2.34+	-	-	99.92
1/37	46.15	36.51	15.84	1.5	-	-	100

+ including mica

Location: 1/146 Pauni-Khapri road. 1/1211 near Upashya nullah-Pauni Korambi road junction. 1/176 Near Diwanghat-Pauni. 1/824 Upashya nullah 1/37 Khadan nullah.

TABLE - 13

Modal analysis of the pegmatites and the pegmatitic granites Sub-group A

Sp.No.	Quartz.	Potash felspars	Oligoclase	Chlorite	Garnet	Total
1/508	34.82	54.14	7.62	3.32	-	99.90
1/1055	38.71	50.00	3.1	7.95+	0.04	99.80
1/1081	31.56	59.28	8.04	1.1		99.98
1/130	31.91	60.32	4.96	2.81+		100.00
1/885	22.12	66.17	3.06	8.00		99.35

+ includes mica

Location: 1/508 Pauni-Mahadeva temple road. 1/1055 "First Tributary of Upashayla nala west of Wainganga river. 1/1081 Upashay nullah. 1/130 Khadan nullah. 1/885 Quarry 2.SCS.

Microscopic features

Texture. The normal granites show hypidiomorphic texture. Subhedral grains of felspars are randomly oriented.Their interspaces are occupied by quartz,chlorite and mica. In the gneissose types the mineral constituents show a tendency for elongation and preferred orientation. Some small grains of potash felspars exhibit graphic intergrowth with quartz. Similarly oligoclase shows myrmekitic intergrowth with quartz.

Mineralogy. The essential minerals forming the granites are quartz (45 to 50%),potash felspars (40%) and oligoclase (5-15%). The average grain size of the minerals is 1-1.5 mm. .The accessory minerals include chlorite,muscovite,biotite,rutile and rarely garnet (Table 12)

Potash felspars. Among the potash felspars,orthoclase is the predominant constituent. Microcline is in subordinate amount or even absent in some specimens. Orthoclase forms sub-hedral to anhedral grains,having rugged and corroded borders. One set of cleavage(001) is well developed the other set (010) is less perfect. Twinning on carlsbad law is observed in some grains. Bigger grains of orthoclase contain inclusions of quartz and occasionally of oligoclase. Graphic intergrowth with quartz is found in some crystals. Alteration of the felspar is noted in several crystals,some of these are clouded due to kaolinisation while others are sericitised along the cleavage planes.

Oligoclase ($Ab_{75}An_{25}$). Oligoclase occurs as subhedral to anhedral grains and laths occupying the interstitial spaces of potash felspars. Some grains show rugged and corroded borders against quartz.Mutual interference during the growth of the crystals is observed in some sections. Twinning on albite and carlsbad law is seen. Twinning lamellae are bent in a few crystals. Myrmekitic intergrowth with quartz is often noted. Many of the plagioclase grains show sericitisation along the cleavageand fracture planes.

Quartz. It occurs as anhedral grains and granular aggregates occupying the interstitial spaces of felspars.Most of the grains show undulose extinction. Quartz grains have penetrated the earlier crystallised felspar grains. It also occurs as inclusions in the felspars.

Chlorite. It occurs as small flakes,films and fibrous aggregates.It is pleochroic in pale green or yellow green to pale yellow with the absorpiton as X = pale yellow green,Y = pale yellow green,Z= yellow (X = Y > Z). It shows straight extinction. It is secondary in origin and formed after biotite and garnet.

Among the other accessories biotite occurs as small flakes in green and brown colours with strong pleochroism. Muscovite is found as individual flakes and in aggregates,mostly along the grain boundaries of felspars. Rutile occurs as independent euhedralgrains in reddish brown and yellowish brown colours. Garnet is of very restricted occurrence and has been observed in a few sections only. It exhibits pale brown colour with pink tint and high relief. The grain size varies from 2 to 3 mm. The crystals are riddled with numerous inclusions of quartz (fig.135). Along the fractures of the garnet,flakes and fibrous aggregates of chlorite are observed which appear to have formed due to the alteration of the former.

(2) Pegmatites and pegmatitic granites

Megascopic characters.

These are very coarse grained and inequigranular rocks. Felspar is the dominant constituent. Felspars upto 5 cm. are common. Both pink and white felspars are present. Quartz, apart from occurring as interstitial grains in felspars, is also found as small inclusions in the bigger felspar grains. Clusters of chlorite and biotite give a spotted appearence to the rock. Some specimens show incipient foliation.

Microscopic features

Based on the modal analysis (Table 13,14) these rocks are divided into two subgroups A and B. In subgroup A the average percentages of essential constituents are as: quartz 35% potash felspars 55- and plagioclase 5-8%. In sub-group B the average percentages of the constituents are as: quartz 30%, potash felspars 50% and plagioclase 10%.

Texture. Most of the mineral constituents are subhedral to anhedral and are of variable grain sizes. The minerals in general show cataclastic effects. The plagioclase exhibits bent, dislocated and microfaulted lamellae and cleavages. Thin quartz-felspathic veins traverse the rocks along the microfaults and fractures. Intergrowth of quartz with orthoclase is common. In few sections intergrowth between quartz and microcline is seen. Plagioclase shows myrmekitic intergrowth with quartz.

Mineralogy. The essential mineral constituents of this group are potash felspars (orthoclase, microcline and perthite), oligoclase and quartz. The accessories are chlorite, muscovite, apatite, biotite, garnet epidote, hornblende and rutile.

TABLE -14

Modal analysis of the pegmatites and pegmatite granites

Sub- group- B.

Sp.No.	Quartz	Potash felspars	Oligoclase	Chlorite and mica	Hornblende	Total
1/35	31.76	53.61	13.49	1.47	-	100.23
1/90	20.37	65.22	13.81	-	0.58	99.98
1/868	26.61	50.14	14.15	-	9.10	100.00
1/869	10.05	64.11	21.0	1.05	3.76	99.97
1/137	38.5	49.28	12.21	-	-	99.99
1/721	29.33	55.78	13.27	1.6	-	99.98

Location: 1/35 Wainganga river bed near electric tower. 1/90 Wainganga river bank (right bank south of Pauni bridge). 1/868 G.C.S. Quarry 1/869 G.C.S. Quarry. 1/137 Upashya nullah. 1/721 Quarry 1.G.C.S.

Potash felspars. Orthoclase occurs as subhedral to anhedral grains having corroded and rugged borders. Apart from containing inclusions of small grains of quartz, some of the orthoclase grains exhibit cuneiform intergrowth with it. Twinning on carlsbad law is often noted. Sericitisation and kaolinisation have taken place to various degrees along the cleavage planes and grain boundaries. Microcline is formed of medium to coarse subhedral grains showing cross-hatched twinning. It contains inclusions of quartz and orthoclase. Many coarse grains of perthites (albite lamallae in orthoclase) are commonly observed in thin sections.

Oligoclase ($Ab_{70}An_{30}$). Oligoclase occurs as subhedral grains, laths and anhedral grains with rugged borders. Most of the grains have been sericitised to various degrees. Zoning is observed in a few crystals. Few grains of oligoclase have been broken or dislocated due to thrusting or projection of quartz grains into them. Some of the bigger grains contain inclusions of quartz, muscovite and chlorite.

Quartz. It occurs as anhedral grains and aggregates of smaller grains occupying the interstitial spaces of felspars. Many quartz grains project in to the felspars. Quartz shows much cataclastic effects with internal granulation, wavy extinction and mortar structure. Some of the bigger grains of quartz are girdled by much finer grained marginal aggregates. Quartz also forms around the borders of felspars, as linear anhedral grains.

Chlorite. Chlorite is a common secondary mineral present in these rocks. It occurs as flakes, fibrous aggregates, shreds and stringers along the boundaries of felsic grains. It shows absorption as: X = green, Y = green

Z = pale yellow green. (X = Y > Z). The flakes exhibit anomalous blue polarisation colours.

It is also present in veins associated with quartz cutting across other minerals. In some sections the vein chlorite shows colloform texture.

Biotite. It occurs as small irregular flakes of greenish yellow or pale green colours with a red tint. It is strongly pleochroic in honey brown or greenish red with absorption X = pale green, Y = reddish brown and Z= reddish brown (X < Y = Z). Alteration to chlorite is common in several flakes. It shows strong birefringence and straight extinction.

Muscovite. It is found as small flakes of various sizes upto 0.4 mm. in the interstitial spaces of felsic minerals and also as inclusions in the felspars. Its strong birefringence and straight extinction are salient characters.

Epidote. It forms irregular grains and small granules with pale green or lemon yellow colour with much pleochroism. Its high relief and birefringence make it distinct from other minerals.

Hornblende. It is observed as prismatic and irregular grains with corroded borders. It is pleochroic as X = greenish yellow, Y = yellowish green and Z = dark green (X < Y < Z). Inclusions of quartz and felspar are often noted. It appears to have been derived from the amphibolites into which the pegmatites are intruded

Other accessories include apatite, rutile and garnet. Apatite is found as small euhedral grains with hexagonal and rectangular outlines. Rutile occurs as reddish brown semi-opaque grains and needles and shows orange colour under reflected light. It has extreme birefringence. Garnet is observed in few sections only. It is light-brown with a pink tint and is isotropic. The grains are between 2 to 4 mm. and are highly fractured. The fractures have been pushed apart by quartz. Muscovite and chlorite flakes are seen along the fractures and around the borders of the grains.

(3) Felspar rich rocks

Megascopic characters.

These are medium to coarse grained, white and greyish white coloured rocks. It is predominantly composed of white felspars. Megascopically quartz grains are not observed.

Microscopic features.

It is a coarse grained granular rock and mainly composed of potash felspar(70-80%) and oligoclase (10-20%) constituting more than 90% of the rock(fig.130). Quartz is either absent or present only in minor amounts.

Felspars. Orthoclase forms the bulk of the felspars, it is partially sericitised. Some grains of microcline are also observed. Few perthite grains are always present in which blebs of oligoclase are seen across the cleavages of orthoclase. Oligoclase forms subhedral grains, associated with orthoclase.

Quartz. Oval shaped inclusions of quartz are noticed in oligoclase and orthoclase. Secondary quartz is present as a constituent of veins.

Chlorite. It occurs as small flakes, scales, shreds and stringers in the interstitial spaces of felsic minerals. It is light green and faintly pleochroic and exhibits anomalous polarisation colours. It also occurs as patches and veinlike stringers within the felspars.

Epidote. It is mainly found in veins where it occurs as irregular grains with pale greenish yellow or lemon yellow colours.Around some grains of epidote rims of zoisite are seen.

Prehnite. It occurs as veins cutting across other minerals. It is found in crystal aggregates developed across the veins.It shows characteristic sheaf like pattern and bowtice structure and abnormal interference colours under crossed nicols.

4.2 PARSORI FORMATION

4.2-1. CHLORITE-MUSCOVITE SCHIST

Megascopic characters. The chlorite-muscovite schists are medium to fine grained,well foliated and soft rocks. These rocks present a spotted appearence due to patches of different colours. They exhibit various shades of colours such as bronzy brown with shades of grey and greenish grey,brownish pink with patches of greenish grey,greyish white with shades of brown and pink and grey and greyish green on alternating layers. Fine to coarse muscovite forms the lighter shade,while fine to coarse chlorite forms the darker shades. Elliptical and rod like quartz aggregates are aligned along the planes of foliation.In some specimens dark brown to black grains of iron ores are observed along the foliations. As mentioned earlier corrugations and slip cleavages are observed in some specimens.

Microscopic features

Texture. Thin section across the foliations shows bands and layers of flaky and fibrous chlorite and muscovite enveloping irregular bands and lenticular patches of aggregate of quartz grains chlorite and sericite occur as small flakes and interstitial material in and around the quartz aggregates. In the corrugated varieties mica-chlorite layers show spindle forms due to the development of slip cleavages. Elliptical, and elongated patches of phyllite porphyroclasts occur in a coarse crystalline matrix of chlorite and muscovite. In general the rock represents a porphyroclastic-schistose texture.

<u>Porphyroclasts</u>. Most of the sections contain high amount of porphyroclasts (3-5 mm. in length and 1-2 mm in width) of sericites phyllite or of chlorite-sericite phyllite. These are formed of a fine mesh of chlorite, sericite, quartz and opaque minerals. The orientation of many of these porphyroclasts is incongruous with the enveloping chlorite-muscovite layers.

<u>Chlorite</u>. It is a major constituent of the schists. It is pale green with yellow tint and low first order interference colours. Fibrous aggregates of chlorite in linear pattern are separated by irregular bands and lenticular patches of quartz-grain aggregate.

<u>Muscovite</u>. It occurs as flaky aggregates in lenticular and linear patches enveloped by chlorite. It is white in colour and shows higher order interference colours.

<u>Chloritoid</u>. It is of restricted occurrence in varieties having good amount of phyllite porphyroclasts. In some sections chloritoid grains are strictly confined to the phyllite patches, while in other sections it was found scattered throughout the rocks. It occurs as small stumpy rectangular grains, aggregate of prisms and as anhedral grains. It

exhibits fairly high relief and straight extinction. It is light green, markedly pleochroic with absorption, X = olive or grass green: Y = pale green or greyish green: Z = yellowish green. Prismatic sections show multiple twinning. Polarisation colour is masked by the body colour. Some of the grains contain inclusion of quartz.

Biotite. A few biotite flakes occur as porphyroblasts oriented across the chlorite-muscovite layers. They are of brown colour strongly pleochroic and show strong birefringence.

4.3. BHIWAPUR FORMATION

4.3-1. PHYLLITES

Megascopic character. These phyllites are normal sericite-chlorite phyllite and show a wide range of variation in their colour index due to the corresponding variation in the content of chloritic, sericitic and ferruginous matter. They exhibit various shades of light greenish grey, pink and brownish pink with patches of different colours. Certain bands within the phyllites show a spotted appearence due to the presence of magnetite crystals. Most of the shades mentioned above are dull. The phyllites are soft and display characteristic sheen. These phyllites are garnet and biotite free unlike the associated quartz-phyllites. These rocks show well developed foliations. Some specimens show closely spaced laminations. Elongated quartz are often enclosed within the laminae. In few specimens the laminations are folded on microscopic scale (fig.133). As described earlier in Chapter III, the microfolds are sometimes of chevron or kink type due to the displacement along slip cleavages (fig. 51,131). Few thin

TABLE - 15

Modal analysis of the Phyllites

Sp.No.	Grain size * in mm.	Quartz	Chlorite + Sericite	Iron ores	Total
1/274	0.65-0.2	17.11	80.24	2.65	100.00
1/234	0.65-0.15 (0.3-0.5)	18.00	78.54	3.46	100.00
1/201	0.05-0.65	18.52	79.76	1.72	100.00
1/296	0.05-0.1	14.15	83.22	2.63	100.00
1/203	0.1	11.1	87.00	1.90	100.00
1/252	0.03-0.08 (0.2-0.3)	13.04	84.16	2.8	100.00
1/229	0.075-0.15	15.72	77.72	6.56	100.00
1/221	0.1-0.2 (.5-1)	24.11	72.04	3.85	100.00
1/268	0.1-0.15 (0.4)	18.71	80.66	0.54	99.91

* size of bigger grains in bracket

Location: 1/274 Exposure near Bhiwapur-Dongargaon road north of nullah. 1/234 Exposure near the railway track -Bhiwapur. 1/201 Pahungaon. 1/296 Dongargaon Hills. 1/203 Hills north west of Nishti. 1/252 Jogikhera hills. 1/229 Kotalpar. 1/221 Maru river. 1/268 Exposure near Tambakhana.

veins (5 -10 mm.) consisting of magnetite and chlorite with some quartz cut across the phyllites.

Microscopic features

Texture. The phyllites exhibit well developed schistose texture. Sericite and chlorite in combination or independently, majority of them showing preferred orientation, form bands or layers. Quartz grains are arranged within these layers with a parallel disposition. Some interlayered bands and lenses consisting mostly of bigger grains of quartz(0.1- 0.2 mm.) show an undulating pattern (fig. 46). The folia wrap around porphyroblasts of quartz, chlorite and magnetite (fig.45). In some specimens the folia have developed microfolds and flexures (fig.52) wherein segregation of quartz grains is observed in the crests and troughs. At certain places microfolds show displacements along number of closely spaced parallel or sub-parallel planes along the fold axes, forming slip cleavages(Fig.50,131) Along such slip cleavages granules of iron oxide have been dragged. Few thin bands containing chlorite and quartz exhibit complex patterns of microfolds.

Mineralogy. The chief constituents are quartz, sericite, chlorite, iron ore and rarely chloritoid. Tourmaline, epidote, apatite, rutile and zircon form minor accessories (Table 15).

Groundmass. The groundmass consists of slightly elongated quartz grains (0.05 -0.1 mm.) along with sericite and chlorite showing preferred orientation. Granules and small laths of hematite are interspersed in the mass. The matrix generally contains porphyroblasts of chlorite, quartz and magnetite. Few patches in the matrix containing sericite, fine grains of quartz and iron oxide appear to be recrystallised slate

PLATE No.XIV

Sketches (not to scale). Phyllites and quartz-phyllites under the microscope.

Fig.No.45 Microfolds in phyllite. Spindle like chlorite in the pressure shadow of a quartz-magnetite porphyroblast.

Fig.No.46 Phyllite. Zic-zag pattern of quartz rich layer in a fine chlorite-sericite-quartz groundmass showing simple flextures.

Fig.No.47 Quartz-phyllite-Biotite and iron oxides in the pressure shadows of quartz-porphyroblasts.

Fig.No.48 Quartz-phyllites. Alternating layers of quartz and phyllosilicates with porphyroblasts of quartz.

Fig.No.49 & 50 Slip cleavages in phyllites. Displacement of layers along closely spaced planes parallel to the axes of microfolds.

Fig.No.51 Chevron folds in phyllites (Megascopic)

Fig.No.52 & 53 Microfold styles in phyllites.

Fig.No.54 Quartz-phyllites. Linear arrangement of clusters of biotite.

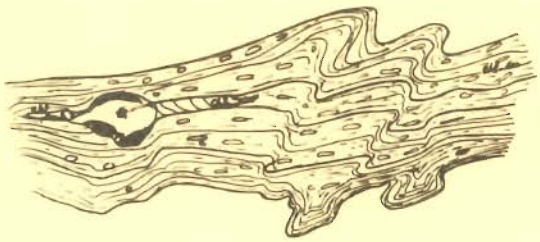

Fig.No.45

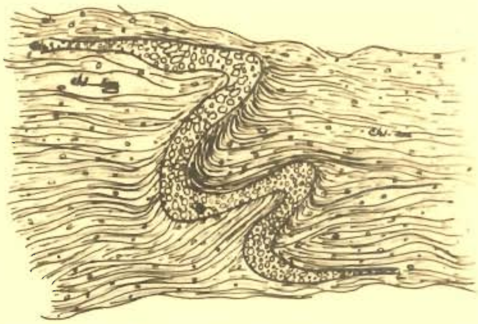

Fig.No.46

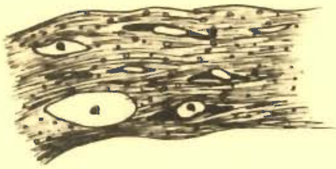

Fig.No.47

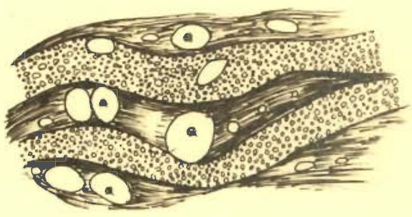

Fig.No.48

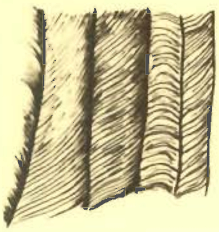

Fig.No.49

Fig.No.50

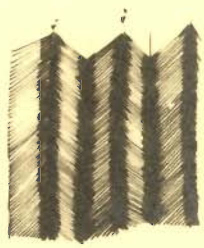

Fig.No.51

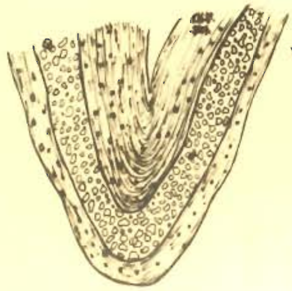

Fig.No.52

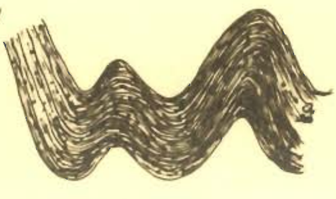

Fig.No.53

Fig.No.54

fragments which at times show discordance with the sericite-chlorite laminae.

The quartz percentage varies from 11 to 25. The average grain size lies between 0.05 - 0.2 mm. It is generally clean,a few contain iron and sericite particles.Undulose extinction is common. Sericite is colourless and distinguished from chlorite by its higher order polarisation colour. Chlorite is pleochroic from pale green to dark green and exhibits low order polarisiation colours.The chlorite and sericite together constitute 72 to 87 percent of the rock.

Porphyroblasts. Porphyroblasts of rounded and lenticular patches (2 -5 mm), knots and clusters of chlorite and magnetite,independently or in close combination, are often observed in all the phyllites. Quartz is sometimes associated with these porphyroblasts. The long diameter of the porphyroblasts at times shows discordnace with the fabric of the matrix. It is observed that the chlorite-sericite laminae enveloping these porphyroblasts have been pushed apart during their growth. The chlorite occurs as flaky or fibrous aggregates and as spindles form (fig. 45) showing pale yellowish green to green colours. It shows faint pleochroism and weak birefringence.

Some of the phyllites contain many idiomorphic grains of magnetite (0.1 - 1 mm.) which have undergone various degree of alteration to hematite. Spindles of chlorite flakes occur in the pressure shadows of these magnetite crystals.

Chloritoid. It is observed only in a few sections. It occurs as long prisms and plates, generally parallel to the foliation planes, (fig.132).

Accessory minerals. Small prismatic grains of tourmaline show two distinct colours: (i) exhibiting pale blue to greenish blue pleochroism and (ii) greenish yellow to green. Apatite occurs as small prismatic grains with round edges showing low first order polarisation colours and parallel extinction. Small epidote grains show neutral to light yellow colour pleochroism and second order polarisation colours. Few small euhedral crystals of zircons are observed in the matrix. It is generally colourless and has high relief and birefringence.

4.3-2. QUARTZ PHYLLITES *

Based on the megascopic and microscopic features the quartz phyllites have been classified into two sub-units:(i) biotite-quartz phyllites (ii) garnet-quartz-phyllites.

Biotite-quartz phyllites.

Megascopic character. These rocks show greyish white, greenish grey, and ash grey colours. Dark green or greenish black elongated clusters of biotite exhibit preferred orientation giving well developed lineations (fig. 54). In varieties where lineation is poorly developed biotite clusters show round patches. Due to the higher amount of micaceous minerals foliations have developed.

Microscopic features

Texture. The rock shows typical schistose texture. The flaky minerals sericite-muscovite form layers arranged in more or less

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* In phyllites, if the amount of quartz exceeds the amount of phyllosilicates (sericite + some chlorite ± biotite) the rock is called a quartz phyllite (Winkler,1965).

T A B L E -16

Modal analysis of biotite quartz phyllite

Sp.No.	Grain size of quartz in mm. *	Quartz**	Chlorite sericite	Biotite + some iron ore	Total
1/277	0.08-0.1 (0.5-0.7)	47.65	49.47	2.76	99.88
1/263	0.08-0.1 (1)	36.56	47.92	15.50	99.88
1/219	0.1 (3)	51.35	39.89	8.74	99.88
1/256	0.05 -0.08 (2 -2.5)	47.01	46.66	6.33	100

* size of bigger grains in brackets
** including minor amount of felspars.

Location: 1/277 Hills to the NW of Bhiwapur railway station. 1/263 Hills N of Bhiwapur railway station. 1/217 Exposure near Maru river. 1/256 Hills near Jogikhera Tank.

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T A B L E - 17

Modal analysis of garnet-quartz phyllite

Sp.No.	Grain size of quartz in mm. *	Grain size of garnet in mm.	Sericite muscovite	Garnet	Biotite +iron ore	Quartz**	Total
1/228	0.03-0.8 (2-3)	2-3	58.71	12.82	1.29	27.16	99.98
1/243	0.05-0.12	1.5	44.78	4.15	11.19	39.85	99.77
1/314	0.3-0.35	2.25	32.19	17.12	3.14	47.54	99.99
1/272	0.08-0.12	1.2	50.08	4.81	16.68	28.41	99.98
1/247	0.05-0.07	2.3	58.45	1.78	14.33	25.43	99.99

* size of bigger grains in brackets
** including minor amount of felspars.

Location: 1/228 Exposure near Bhiwapur-Dongargaon road south of the nullah. 1/243 Hill north of the small tank. 1/314 Hills to the NE of Jogikhera tank 1/272 Hills south of Pahungaon. 1/247 Hills east of Maru river.

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parallel bands. The folia at places are undulatory with lenticular wrapping around porphyroblasts of single or composite quartz grains. All these constituents show a tendency for preferred orientation. Some sections show two fabrics of the porphyroblasts.(i) quartz grains (0.2 - 0.4 mm.) with some interstitial sericite, are interlayered with or form lenses in finer grained quartz or sericite mesh,(ii) porphyroblasts as lenticles of quartz and clusters of biotite are common in the foliated groundmass (fig.47,48).

Mineralogy. The chief mineral constituents are quartz,sericite-muscovite, biotite and iron ore. Epidote, tourmaline,zircon and apatite occur as accessories (Table 16).

Groundmass. The groundmass of the biotite-quartz phyllites consists of quartz grains with sericite-muscovite along the grain boundaries and interstitial spaces. Sericite also occurs as long fibrous layers at intervals. This is conspicuous in the corrugated types due to readjustment of the constituents in relation with the stress distribution in the rock. Iron ore in granule and dusty form is dispersed in the mass. Many minute flakes of biotite(greenish brown to dark brown) are disseminated in the rock. Quartz grains vary in size from 0.05 to 0.2 mm. In some of the sections small amount of felspars is also associated. Sericite-muscovite is colourless and gives higher order of polarisation colours. Typical flakes of muscovite have not developed.

Porphyroblasts. Clusters of biotite flakes occur as parallel lenticles and streaks (2-5 mm.) in the groundmass (fig.47,54) In some sections biotite clusters are observed as round patches. Individual flakes vary from 0.2 - 0.4 mm. in length and are pleochroic from greenish brown or brownish yellow to dark brown. Small grains of quartz and epidote and flakes of muscovite are sometimes associated with biotite. A few biotite flakes contain pleochroic haloes with a core of allanite. In rocks which have developed corrugations lenticles and streaks of biotite clusters show thickening around the crests and troughs. These are also observed in the pressure shadows of some of the quartz-porphyroblasts (fig.47).

Ovoids and lenticles of quartz, varying in size from 0.5-7.0 mm. are present in most of the sections (fig.47,48) They occur either as single grain or as aggregates of smaller grains (0.3 -0.5mm.).The long direction of the lenticles is parallel to the foliation. The larger grains show strain effects with undulose extinction.

Accessory minerals. Few small irregular grains of epidote are dispersed in the matrix. It is pale lemon yellow in colour and pleochroic with second order polarisation colours. Tourmaline occurs as small prismatic grains. It is markedly pleochroic from pale green to greenish blue colours. Apatite occurs in colourless prisms with irregular edges. It shows high relief and gives parallel extinction; basal sections are isotropic. Few colourless 'lozenge' shaped zircon grains are observed under high magnification.

Garnet-quartz-phyllites

Megascopic character. These are greenish grey and green coloured, hard, coarse grained rocks with poorly developed foliations. These rocks are spotted with round grains of pink or brown coloured porphyroblasts of garnet.

Microscopic features

Texture. It also shows typical schistose texture with porphyroblasts of garnet, quartz and biotite, details of which have already been mentioned with biotite-quartz phyllites.

Mineralogy. This rock is composed of quartz, sericite-muscovite, garnet, biotite and iron ores. Tourmaline, epidote and zircon are present as accessories (Table 17).

Groundmass. It consists of quartz grains (0.03-0.3 mm.) with interstitial and intergranular sericite-muscovite. Some rocks contain minor amounts of felspars generally associated with quartz grains. Opaque iron ore (magnetite-hematite) is seen as anhedral grains and specks in the matrix.

Porphyroblasts. Garnet. Garnet porphyroblasts (1 - 3 mm.) are not fully developed and form as open meshwork (fig. 134) without regular faces (xenoblasts) enclosing many quartz grains showing sieve structure. It is neutral to pale pinkish yellow in colour and exhibits weak anisotropism. Some of the garnet grains have been partly limonitised. Clusters of biotite flakes are sometimes observed around the porphyroblasts.

Biotite. Clusters of biotite flakes in lenticular or irregular patches contain fine grains of quartz, epidote and hematite. It is strongly pleochroic from pale greenish brown to dark honeybrown. It has been noted that the amount of biotite increases with corresponding decrease in garnet (Table 17).

Quartz. Ovoids and elliptical patches (1-3.5 mm.) of quartz are present as independent grains and as composite grains. They show wavy extinction.

Accessory minerals. The characteristics of tourmaline,epidote and zircon are same as mentioned earlier for biotite-quartz phyllites.

4.3-3. IRON ORE BODIES

Megascopic characters. Megascopically the iron ores can be broadly grouped into two types (i) massive and (ii) banded. The massive type shows metallic to sub-metallic lustre with brownish black and deep brown colours. Granular character is apparent when closely observed. Gangue minerals like garnet,altered grunerite,and quartz occur in patches,streaks and specks. Thin quartz veins (3-5 mm.) traverse the ore along the weak planes. Sometimes the ore shows closely spaced (3-5mm.)curviplanar fractures. Along the weak planes and exposed surfaces supergene alterations have given rise to various colloform structures.

The banded type forms alternate bands of iron ore with bands of altered amphibole minerals and/or quartz and garnet in various proportions. These bands are irregular and at times merge with each other. The amphibole rich bands and patches are common near the contacts of iron ore bodies. These are coffee brown,pinkish brown and chocolate brown due to various degree of limonitisation. Irregular patches and specks of ore minerals are disseminated in them. At some places the rocks at the contacts of the iron rich bands consist predominantly of garnet with minor amounts of quartz and iron ore minerals. In these rocks quartz occurs as patches and lenticles in the groundmass with an imperfect parallel orientation.Dark brown coloured ore minerals form irregular patches in the ground mass giving a spotted appearence.

Microscopic Features. In thin sections the iron ore bearing rocks consist mainly of opaque minerals (iron ores), garnet, grunerite and quartz with biotite and actinolite as minor accessories. The texture is coarsely granoblastic.

Garnet. It is neutral to pale yellowish brown or brownish yellow colour. It is generally isotropic but in some sections weak isotropism is also noted. Mortar texture is exhibited by some garnet grains with undisturbed patches sorrounded by granulated rims. Larger grains of garnet contain numerous inclusions of quartz(poikiloblastic or diablastic structure). Sometimes it forms an open mesh work bounded by irregular faces in which quartz grains make up more than half the volume of the grains(xenoblastic structure). In large porphyroblasts several parallel to sub-parallel even fractures, appearing like cleavages, are observed. Some of these fractures show microfolds(Fig. 136). Minor cracks and slippage have developed across the folds. In some of the sections the garnet has been limonitised in which crack and fractures are filled with dark brown limonite. Some of the fractures are filled with secondary quartz showing strain effects. Incipient alteration of garnet to chlorite is rarely observed.

Grunerite. Fresh grunerite has been observed only in a few sections. It forms prisms of neutral colour, with one set of cleavage; basal sections show two sets of rhombic cleavages. Its relief is high and has maximum extinction 15° ($C \wedge Z$). It is generally altered and has been replaced by limonite, and quartz. Pseudomorphs of limonite and quartz after the amphibole showing typical forms and cleavages, are quite common. Tabular and prismatic limonitised grains are partly replaced by quartz along the cleavages. Patches of garnets and small magnetite crystals are found as inclusions.

Quartz. Three types of quartz are associated with the iron ores: (i) metamorphic, (ii) secondary (a) pseudomorphs and (b) vein. The metamorphic quartz occurs as coarse grains (3 -5mm.) and as aggregates of smaller grains closely interlocked together in the interstitial spaces of other minerals. They show both sharp and undulating extinction. Inclusions of dust and iron ore particles are quite common. Replacement quartz occurs as pseudomorphs after grunerite. Vein quartz forms as vein fillings and shows strain effects.

Biotite. Minute flakes of biotite are associated with quartz. It is pale brown in colour and strongly pleochroic from light brown to dark brown.

Actinolite. Slender needles of pale green actinolite are seen in quartz grains either in parallel form or with criss-cross pattern.

Iron ore minerals.

In thin sections the iron ore minerals show corroded and crenulated borders. Embayed portions are filled with quartz. Some small idioblastic grains (0.5-2.0 mm.) exhibit corrosion effects at some faces. Inclusions of quartz and garnet are present in larger grains. A few grains show linear streaks of quartz arranged in an elliptical pattern.

In polished sections the following ore minerals are identified under reflected light : magnetite, hematite, goethite-lepidocrocite

Magnetite is greyish white with faint pinkish tinge and has moderate reflectivity. It occurs as hypautomorphic to idiomorphic grains which are isotropic. Hematite is white in colour, anisotropic and exhibits high reflectivity. It occurs as pseudomorphs after magnetite(martite). Goethite-lepidocrocite are greyish white to bluish grey in colour with moderate reflectivity and weak anisotropism.

Texture and paragenesis of the ore minerals.

In most of the polished ores hematite is found to replace magnetite (martitization). In general the ore shows relict texture with irregular patches of magnetite in a matrix of hematite. Under high magnification some of the polished sections exhibit replacement crystallographic and oriented intergrowth texture shown by hematite lamellae occurring along the octahedral planes of magnetite(fig.142). Hematite has replaced along the borders, the cleavage planes and fractures of the magnetite. Well developed octahedra of magnetite occur sporadically (fig.140). Partial to complete replacement forming pseudomorphs of hematite after magnetite crystals are often observed.

Goethite along with lepidocrocite is found replacing both magnetite andhematite. In some specimens they exhibit typical colloform texture(fig.141). Goethite has filled and replaced mainly along the fractures and borders of magnetite and hematite and also of quartz and silicate gangue (described earlier as limonite).

From the above discussion it is quite evident that magnetite was formed during the metamorphism of the country rocks. Hematite occurring as martite was formed later due to oxidation of magnetite.

Goethite and lepidocrocite are of supergene origin. The paragenesis of the ore minerals can be tabulated as:

MINERALS	Time		
MAGNETITE	———		
HEMATITE		———	
GOETHITE AND LEPIDOCROCITE			———

4.4. GAIDONGARI FORMATION

4.4-1. QUARTZITES

Megascopic character. The quartzites are very fine grained, highly indurated and compact and occur in light brownish grey, pinkish grey, reddish brown and rarely greenish grey shades. They are generally massive but a few samples show poorly developed foliations.

Microscopic features.

Texture. The quartzites exhibit granoblastic texture in which quartz grains are closely interlocked together. Some of the thin sections show shear planes in different directions with the development of elongated quartz grains around them. Along these planes granulation and recrystallisation of quartz grains are often observed. Some of the shear planes show concentration of chlorite and iron oxide.

Mineralogy. The chief constituent of the rock is quartz (>80%). Other minerals are chlorite and sericite with small amount of hematite. Rounded to subrounded grains of epidote, zircon and hornblende are often observed as minor accessories (Table 18).

T A B L E -18

Modal analysis of the quartzites

Sp.No.	Grain size in mm. *	Quartz	Chlorite hematite	Total
1/349	0.2 (0.8-1.4)	86.27	13.73	100.00
1/351	0.3-0.5 (1)	79.46	20.53	99.99
1/385	0.3 (0.8-1.2)	79.41	20.58	99.99

* size of bigger grains in bracket

Location: 1/349 South of Gaidongari tank near the village. 1/351 North west of Nimgaon. 1/385 East of Mahalgaon.

T A B L E -19

Modal analysis of the meta-argillites

Sp. No.	Grain size in mm. *	Quartz	Chlorite +Sericite+ very fine quartz	Iron oxide	Total
1/387	0.05-0.1	38.11	54.52	7.36	99.99
1/359	0.03-0.6	26.75	69.11	4.12	99.98
1/335	0.25-0.5(1)	25.45	69.67	4.87	99.99
1/372	0.3-0.7(0.9)	29.09	65.84	5.05	99.98
1/366	0.2-0.3(0.8)	29.24	67.46	3.32	100.02
1/406	0.2-0.4	64.09	35.90	-	99.99
1/356	0.3(0.65)	45.46	50.96	2.44	98.86

* size of the bigger grains in bracket

Location: 1/387 Hill slope east of Khapri. 1/406 Hill slopes NE of Khapri 1/335 SW of Gaidongari hill range. 1/372 South of Gaidongari hill range 1/359Southeast Gaidongari hill range 1/366 E part of Gaidongari hill near Pauni-Khapri road. 1/356 Hill slopes-Eastern part of Gaidongari hills.

T A B L E - 20

Modal analysis of the meta-greywacke

Sp.No.	Grain size of quartz in mm.	Quartz.	Rock fragments	Sericite+ chlorite+ iron oxide	Total
1/391	0.4-0.7	13.42	23.67	62.90	99.99
1/395	0.15-0.2	19.58	25.47	54.94	99.99

Location: 1/391 S.W. Part Hill slopes -Gaidongari hill range. 1/395 N.W. part Hill slopes, Gaidongari hill range.

Quartz. Generally the quartz grains have a uniform size between 0.1 and 0.2 mm. Within the mass of the smaller grains few bigger grains varying in diameter from 0.5 -1.0 mm. are observed. The bigger grains show internal granulation and undulose extinction. Inclusions of fine iron ore are often noted in several grains of quartz.

Chlorite-sericite. Chlorite occurs as an intergranular mineral in patches. It is also found dispersed in the rock as fibrous aggregates and clusters of flakes. Minor amount of small sericite shreds is found along the grain boundaries and interstitial spaces of quartz.

Accessory minerals. Small sub-rounded grains of epidote are of pale yellow colour, faintly pleochroic and have fairly high relief. It shows second order polarisation colours. Zircon occurs in small euhedral grains with high relief and dark borders. Few small prisms of green hornblende with irregular borders are observed in the groundmass.

4.4-2. SLATY SHALES AND BANDED SLATY SHALES

Megascopic character. The slaty shales are grey to ash grey in colour and exhibit a dull sheen. They show high degree of fissility with closely spaced laminations. Careful examination shows bands having different shades of grey and ash grey with slight difference in their grain size. The banded slaty shales exhibit distinct alternate bands of light and dark shades varying in thickness from 1 mm. to 6 mm. Black and greyish black form the darker bands, while pinkish red, brownish red, brownish grey and ash grey form the lighter bands. Dark coloured bands are very fine grained while the lighter coloured bands are comparatively coarser. Some of the bands are discontinuous showing a lenticular form.

In a few specimens,particularly those collected from the contact of Pauni Formation,minor faults with displacement of 2 to 3 mm. are often observed. These miniature faults strike at right angles to the bands with a dip of about 70°. Bending and buckling of the bands are also noticed. Slaty cleavage is generally well developed.

Microscopic characters. In the banded varieties the thin sections show light and dark coloured layers due to the compositional variation. Light coloured bands are composed predominantly of quartz (0.05 mm.) rarely with small amounts of felspars, and subordinate amount of chlorite, sericite and ferruginous matter. Dark layers are predominantly of chlorite and sericite with subordinate amount of quartz grains. These quartz grains are finer in size than those present in the light coloured bands. Ferruginous matter is often found along the grain boundaries. Granules of iron-ore (limonite and hematite) are seen in linear aggregations. Within the darker layers,the irregular bands consisting exclusively of aggregates of chlorite flakes occur. The chlorites are pleochroic in greenish yellow to brownish yellow and show first order interference colours.

The slaty shales show discontinuous bands and lenticular patches in a fine mesh of quartz,chlorite-sericite and iron oxide. The proportion of quartz and chlorite-sericite varies considerably in different samples. Imperfect development of quartz rich and chlorite-sericite rich layers are often observed. Some slaty shales show fracture fillings with quartz,chlorite and iron oxide either independently or mixed together. The fillings are observed both along and across the bedding planes.

4.4-3. META-ARGILLITES

Megascopic characters. The meta-argillites are softer and less indurated as compared to the quartzites. These are generally fine grained in the south and comparatively coarser towards the north of the area. The argillites present a wide range of colour variation e.g. brownish yellow, pale violet, brownish pink, greyish yellow, greyish brown, brownish green, greenish grey and buff colours. The different shades in the argillites are chiefly due to the variations in the mineral composition particularly iron oxide. A few specimens show foliation planes.

Microscopic features.

Texture and Mineralogy. In thin section, the meta-argillites show a uniform composition, with fine grained quartz in a matrix consisting of sericite-chlorite, fine quartz (0.02 mm.) and varying amount of iron oxide. Small amount of rock fragments is often present. From the modal analysis (Table 19) it is evident that the amount of chlorite-sericite matrix far exceeds that of quartz grains. Certain varieties differ from this normal type due to local variation. Such types show either an abnormal rise in the amount of rock fragments or quartz grains with a corresponding decrease in the amount of chlorite-sericite. Many of the thin sections show reaction of the matrix with the bigger quartz grains. Some samples collected near Thana contain upto 8% of felspars, which was conspicuously absent in other types.

Quartz. It is sub-angular to sub-rounded varying in size between 0.05-0.2 mm. Some bigger grains between 0.5-1 mm. occur enveloped by the finer grains. Elongated grains show some degree of preferred orientation with strain effects. Majority of the smaller grains is nearly free of inclusions. Some of the longer quartz grains contain very fine particles of opaque minerals.

Sericite-chlorite. They occur as fine mesh in the interstitial spaces and around the grain boundaries of quartz. Fibrous aggregates of chlorite show pale green to green colours. Small colourless flakes of sericite are intimately interspersed with chlorite.

Muscovite. Long slender flakes and aggregates of small flakes of muscovite are concentrated along the bedding planes. These flakes form small flexures. It is colourless and shows high order polarisation colours.

Hematite. It occurs as opaque anhedral grains and stringers and lenticles along the grain boundaries of quartz. In some sections iron oxide particles are concentrated in thin layers showing microfolds.

Rock fragments. The meta-argillites occurring near the slate boundary contain fairly good amount of rock fragments. They are sub-angular to sub-rounded in shape and vary in size from .5 to 5 mm. These are mainly composed of vein quartz,phyllites quartzites, sericite quartzites, and shales. Reaction between the fragments and sericite-chlorite matrix is often observed.

Accessory minerals. Tourmaline, epidote,zircon ,staurolite and rutile are the common accessories. Tourmaline , the most common among the accessories,occurs as small prismatic grains with marked pleochroism from pale yellow to greenish blue. Epidote is rounded to subrounded, having pale green or greenish yellow colour with bright second order polarisation colours. Zircon occurs as sub-angular to sub-rounded grains which are colourless to pale yellow or brown. Few sub-angular grains of staurolite present are identified by their pale yellow to bronze yellow pleochroism and first order polarisation colours. Rutile is present as small euhedral deep red grains.

4.4 -4. METAGREYWACKE

Megascopic character. It consists of angular to subrounded grains of quartz, small fragments of siliceous slate, phyllite and other rocks all bound together by a fine grained matrix which imparts a great toughness and hardness to the rock. It is greyish white to ash grey in colour, having rock fragments of different sizes (upto 1 cm.) and shapes in a matrix of white and greyish white colours. Small scattered vitreous, quartz fragments are evident to the naked eye. This is a very unassorted rock.

Microscopic features.

Matrix. The matrix consists of fine sericite flakes with subordinate amount of chlorite. Minute granules of iron oxide are often dispersed in the matrix. There is an incipient development of parallel thin layering in the matrix. Randomly oriented big angular grains of vein quartz and rock fragments are embedded in the matrix. Several long slender muscovite flakes are often observed.

Rock fragments. The fragments are composed of vein quartz, sericite-phyllite (some with microcrenulations), hematite phyllite, fine grained quartzites, mica schists and shales. The bulk of the rock fragments is of quartz and phyllites. Many of these quartz fragments. exhibit effects of reaction with the sericite matrix. The fine and irregular folia of sericite-chlorite from the sorrounding matrix penetrate the boundaries of the quartz fragments(fig.139). The contact between the quartz fragments and the matrix gives serrated borders,with the acicular sericite-chlorite folia projecting into quartz.Some quartz grains show embayed borders in sericite matrix.In few quartz fragments sericite has reacted with quartz along the fractures to various degrees forming a network. The relict quartz grains in the sericite matrix show optical continuity.

Accessory minerals. The chief accessory minerals are tourmaline, zircon,epidote,staurolite and iron ore,having similar characters as described in the meta-argillites.

4.4-5. SLATES AND THE ASSOCIATED ROCKS

4.4-5 A. SLATES

Megascopic character. As mentioned in geological set up (Chapter II) the slates of the Gaidongari Formation are associated with hematite-quartzite and quartz veins at a few places. Their petrography has been discussed together. Slates occur in a wide variety of colours viz. violet,pinkish brown, dark ash grey,greenish grey,brownish grey with pink tint,and dark-grey. Individual grains cannot be observed with the naked eye. Minor amount of rock fragments is often present. Close examination of the rocks show a dull sheen.Foliation is well developed in most of the rock types. The slates occurring at the contacts of hematite quartzites are highly ferruginous and of black colour. They are hard and well foliated.

Microscopic features. Under the microscope the typical slates show a homogeneous character in the size of their constituents and texture. Fine grained quartz mostly between 0.02 -0.03 mm. is dispersed in a sericite-chlorite matrix,or aggregates of fine quartz form alternate bands with chlorite-sericite. All these elements show linear orientation and parallelism. The amount of iron oxide varies in different rocks. It occurs as clusters of granules and as large grains. Elongated granules of iron oxides are either interspersed in the chlorite-sericite matrix or form thin bands. In these rocks sericite predominates over chlorite. Slender flakes of muscovite are also present in the matrix. In the types grading into the adjoining variegated slates there is much variation in the grain size. Rock fragments of vein quartz, quartzites,phyllites,shales etc. mark their appearence.

4.4-5 B. HEMATITE QUARTZITE

Megascopic characters. This rock consists of quartz grains of uniform size cemented together by hematite matrix. It is greyish black in colour,sometimes with a sub-metallic lustre. Few thin fracture filling veins(5-10 mm.) of hematite having fibrous nature and metallic lustre, are observed in these rocks. The fibres are perpendicular to the walls of the veins. Many thin quartz veins(0.2-1.5 cm.) containing hematite matter traverse the quartzites. Joint planes of these hematite quartzite show slickensided surfaces. Some angular to subangular quartz pebbles are noted in these rocks.

Microscopic features. In thin sections it shows sub-rounded to round quartz grains varying from 0.4 -0.8 mm. in diameter with fragments of fine grained quartzites,phyllites and shales in hematitic matrix.

A few detrital opaque iron ores are also observed. Grain boundaries and interstitial spaces are occupied by hematite as a cementing matter, which appears to have replaced the sericite. The relict patches of sericite are still observed.

In polished sections under reflected light the detrital idiomorphic to subrounded grains are pseudomorphs of hematite after magnetite. These grains have been wholly or partly altered to hematite (martitisation). Relict patches of magnetite can be seen in the martite grains. The hematite matter which forms the bulk of the rock exhibits the typical cement texture. It occurs as fine laths, plates and fibres. Due to recrystallisation big plates of hematite have formed. The plates have well distinct cleavages in one direction. At some places triangular pits have developed along the cleavages (fig.138). The cleavages show flexures, microfolds and radiating pattern, probably as a result of plastic movements during recrystallization. Some of the fibrous hematite show several small spherulitic structures (fig.138). Goethite is observed in minor amounts replacing hematite.

4.4-5 C. QUARTZ VEINS

Some milky white thick quartz veins (2 - 3 m.) traversing the adjacent slates contain platy crystals of hematite along their weak planes. These crystals are 1 to 4 mm. thick and upto 4cm. in length. They are silver grey in colour with metallic lustre and well developed rhombohedral cleavages. The hemetite associated with the quartz veins shows well developed polysynthetic twinning in polished sections.

4.4-6. VARIEGATED SLATES

Megascopic character. As mentioned earlier the slates gradually passes into variegated slates with the increase of rock fragments. These are different from the slates due to their heterogeneous character. The variegated appearence of these slates is due to the lenticular pieces of rock fragments of various shades, representing shales, slates, phyllites and quartzites and vein quartz. The fragments are of different sizes varying from few mm. to as much as 8 cm. in their long direction (fig100,101) Angular to subrounded quartz grains upto 2 cm. are observed in the matrix. The slates are well foliated due to parallel orientation of the foliated rock fragments and the groundmass. These show different shades of pinkish brown, ash grey, greenish grey and slaty grey colours. On close examination these rocks show a dull sheen.

Microscopic features.

In thin sections rock fragments of various dimensions are observed in a matrix of chlorite-sericite, fine quartz grains and iron oxide granules. Generally the constituents exhibit a parallel orientation. At times bigger quartz grains are randomly oriented. The amount of iron oxide(chiefly hematite) is variable. Sometimes the matrix shows parallel bands having marked variations in the iron oxide content.

Rock fragments. Fragments of vein quartz, sericite quartzite, sericite phyllite, foliated quartzite, chlorite quartzites, shales and chlorite schists are often observed in these rocks. Quartz and quartzite fragments are sub-angular to sub-rounded. Fragments of phyllites and shales are elliptical or augen shaped and show linear alignment (fig.137). Reaction between rock fragments and chlorite-sericite matter is a common feature giving rise to serrated borders in the former. There are few oval or round fragments of chlorite schists consisting of chlorite and magnetite or chlorite and quartz. This chlorite is fibrous to flaky in nature and pleochroic from pale yellow to dark green.

Accessory minerals. Tourmaline,epidote,magnetite and apatite are the common accessory minerals showing typical characters.

4.4-7. CONGLOMERATIC SLATES

Conglomeratic slates consists of an unassorted assemblage of phenoclasts pebbles,cobbles and boulders in a fragmentary matrix of slates and phyllites. The matrix is foliated and the folia are distorted near the larger phenoclasts. The folia bend down beneath them as well as arch over them. As mentioned earlier, the phenoclasts are of different sizes,and boulders of 30 cm. in diameter are not uncommon. They are mostly subrounded.Many of the smaller phenoclasts(pebbles) are elongated. The phenoclasts are dominantly composed of quartzites (Fig.102). A few boulders and pebbles of banded-hematite jaspar and hematite quartzites have also been noted.

Some thin sections of quartzite phenoclasts and polished sections of iron ores have been studied.

Chlorite quartzite. It shows granoblastic texture with wide spread granulation of many quartz grains. Mortar texture is observed with the bigger grains of quartz girdled by smaller grains. Average size of quartz grains is between 0.5 -0.8 mm. Undulating extinction is conspicuous. Fibrous and flaky green chlorites are seen in the interspaces of quartz grains.

Ferruginous quartzites. It also exhibits granoblastic texture with grains slightly interlocked. Quartz grains vary in size from 0.2 to 1 mm. Brown iron oxide with subordinate amount of chlorite occupy the grain boundaries and interstitial spaces. Fragments of quartzites and chert are noted.

Banded iron ore. The polished sections of the banded iron ore under reflected light show magnetite, hematite, and minor amount of goethite. Magnetite forms big anhedral grains with rugged borders, forming bands in quartz gangue. The magnetite has been partly altered to hematite. Several small idiomorphic grains of magnetite are dispersed in the gangue. Goethite showing colloform texture occurs in veins along with colloidal silica.

Massive iron ore. The polished sections of massive iron ore boulder consists mainly of hematite. Relict patches of magnetite are often seen in the hematite and the latter often preserves the octahedral cleavages of magnetite. It can be safely concluded that the hematite has formed after magnetite. Small streaks and stringers of hematite are also seen in the gangue.

4.5 YOUNGER SEDIMENTARIES

4.5-1. CONGLOMERATES

The conglomerate consists of sub-rounded to rounded pebbles, cobbles,and few boulders in a matrix of ferruginous sandy clays. Among these phenoclasts cobbles form the largest constituent. Granule size rounded fragments are observed in some specimens. The phenoclasts are mostly composed of white and grey vein quartz and quartzites. A few smaller phenoclasts are of quartz-mica schists. The size of the phenoclasts and other field features have already been described in Chapter II. The matrix shows various shades of brown and grey Sandsize particles dominate over the clays. Its mineral composition is similar to the overlying sandstones as described later.

4.5-2, SHALES

The shales are soft, fissile and laminated. They give earthy smell on moistened surfaces. These show various shades of light brown, pinkish brown and greenish grey colours. The colours appear to be due to different amount and state of oxidation of iron. On fresh cleaved surface a dull sheen is observed in some specimens due to presence of fine particles of mica (sericite). Some specimens contain thin lenses of siltstone and sandstones with sharp contacts. Under the microscope the grains are extremely fine and difficult to identify the minerals with certainty. Under high magnification,however, sericite,chlorite, quartz and iron oxide have been recognised. In certain sections thin layers of coarser materials of silt size are banded with finer material.

4.5-3. SANDSTONES

The sandstones are of buff, brown, white with red spots, yellowish brown, greyish white and brownish red colours. A few sandstones of greywacke nature are of olive green to greenish grey colour and hard in appearance. The matrix appears to be clayey with various amount of ferruginous matter. Mica is visible to the naked eye. Most of the sandstones are soft and can be disaggregated easily. Some of the sandstones are hard and highly indurated. The detrital grains (mainly of quartz and felspars) are sub-angular to subrounded of varying sizes from 0.2 mm. to 2mm. in diameter with an average grain size of 0.5 mm. Ferruginous matter and chlorite occupy the grain boundaries and act as cementing material. Some of the thin sections contain many smaller quartz grains occupying the interstitial spaces of the bigger grains. The major constituents of the sandstones are quartz, felspar, rock fragments, chlorite and iron oxides. The common accessories are garnet, tourmaline, sphene, hornblende, zircon, iron ore, muscovite and biotite.

Quartz. Three varieties of quartz have been observed: (i) strained variety showing undulose extinction (ii) quartz showing sharp extinction (iii) quartz containing small inclusions of chlorite, biotite and felspar, having both sharp and undulose extinction. The first variety appears to have been derived from quartz veins while the second and third from igneous and metamorphic sources respectively.

Felspars. Felspars are comparatively smaller in size. Most of the felspars are microcline and perthite. Minor amount of plagioclase felspars is also noted. Many of the felspar grains exhibit incipient sericitisation.

T A B L E - 21

Modal analysis of sandstones of the younger sedimentaries

Sp.No.	Grain size in mm. *	Quartz	Felspars	Rock fragments	Matrix	Total
1/1302	0. 70 (2)	74.8	6.8	8.4	10.0	100
1/1508	0.50(1.7)	79.0	4.8	2.1	14.1	100
1/1314	0.45(1.0)	59.4	22.5	4.2	13.9	100
1/1323	0.50 (1,5)	73.8	8.10	7.3	10.8	100
1/1317	0,50(1.5)	57.5	19.4	5.8	17.3	100
1/1519	0.2 (2)	55.6	22.0	5.05	17.35	100
1/1327	1.2(1.7)	79.0	4.7	5.0	11.3	100
1/1330	0.5	78.5	10.8	5.9	4.8	100
1/1320	0.55(2)	69.1	15.5	3.7	11.7	100

* size of bigger grains in brackets

Location: 1/1317 Near the junction of Fauni road and DOnrich nullah 1/1319 The hills west of Dhanori. 1/1320,1/1327 & 1/1330 Hills and nullahs south-west of Dharori. 1/1302,1/1308,1/1314 & 1/1324 Donrich Nullah.

Rock fragments. The rock fragments are generally bigger in size compared to the quartz grains. They are of varied composition. The following rock fragments have been observed in the sandstones: pegmatite, granite,chert,slate,quartzites (fine and coarse grained),phyllite and quartz-chlorite schists. These are sub-angular to subrounded.

Accessory minerals. The accessory minerals identified in thin section are chlorite,muscovite,biotite,tourmaline,zircon and epidote. Some of these conspicuous minerals have been described later in heavy minerals.

Mechanical analysis of sandstones

In order to study the environmental conditions of deposition and to correlate them with the sandstone formations from elsewhere in India. three samples each from two distinct horizons A(lower part of the Lower Sandstones) and B (upper part of Lower Sandstones) were analysed for size frequency distribution and for heavy minerals.

Horizon A represents 7 metres thick sandstone beds on the left bank of the Wainganga river approximately one kilometre south of Pauni bridge and 1½ Km. north of Kodurli. Specimens 1,5 and 8 belong to the bottom,middle and top portions respectively, of this horizon. The horizon B represents sandstone beds of about 13 metres thick exposed about 2 Km. northwest of Dhanori. Specimens 9,14 and 18 represent the lower,middle and upper portions respectively of this horizon.

The samples were thoroughly disaggregated by gentle crushing and the different mesh size fragments were separated by sieving 50 gms. each of the disaggregated material. Table 22 shows the details of the sieved samples with the weight percentages and cumulative percentages.

<u>T A B L E - 22</u>

<u>M E C H A N I C A L A N A L Y S I S O F S A N D S T O N E</u>

HORIZON-A

		SAMPLE No.1			SAMPLE No.5			SAMPLE No.8		
Mesh No.	Screen opening (Eq. diameter in Ø)	Wt. of retained sand (gms.)	Wt.%	Cumula-tive %	Wt. of sand retained (gms.)	Wt. %	Cumula-tive %	Wt. of sand retained (gms.)	Wt. %	Cumulative
25	0.7418	25.065	50.13	50.13	18.055	36.11	36.11	1.50	3.00	3.00
36	1.2460	9.860	19.72	69.85	6.320	12.64	48.75	6.22	12.44	15.44
52	1.7630	5.590	11.18	81.03	6.615	13.23	61.98	9.40	18.80	34.24
72	2.2460	3.895	7.79	88.82	8.125	16.25	78.23	13.11	26.22	60.46
120	3.0066	2.705	5.41	94.23	5.620	11.24	89.47	11.00	22.00	82.46
150	3.2642	1.470	2.94	97.17	2.885	5.77	95.24	4.67	9.34	91.80
170	3.4916	0.590	1.18	98.35	0.765	1.53	96.77	1.12	2.24	94.04
200	3.7140	0.345	0.69	99.04	0.745	1.49	98.26	1.10	2.20	96.24
240	3.9775	0.470	0.94	99.98	0.860	1.72	99.98	1.86	3.72	99.96
		49.990			49.990			49.98		

HORIZON -B

		SAMPLE No. 9			SAMPLE No. 14			SAMPLE No.18		
25	0.7418	1.245	2.59	2.59	31.20	62.40	62.40	25.610	51.22	51.22
36	1.2460	4.535	9.07	11.66	5.71	11.42	73.82	11.870	23.74	74.96
52	1.7630	6.880	13.76	25.42	3.79	7.50	81.40	5.150	10.30	85.26
72	2.2460	10.265	20.53	45.95	3.19	6.38	87.78	2.530	5.06	90.32
120	3.0060	12.820	25.64	71.59	2.20	4.40	92.18	1.675	3.35	93.67
150	3.2642	7.330	14.66	86.25	1.49	2.98	95.16	1.440	2.88	96.55
170	3.4916	1.720	3.44	89.69	0.50	1.00	96.16	0.350	0.70	97.25
200	3.7140	1.475	2.95	92.64	0.41	0.82	96.98	0.420	0.89	98.09
240	3.9775	3.670	7.34	99.98	1.00	2.00	98.98	0.940	1.88	99.77
		49.900			49.49			49.985		

Analyst : N.G.K.Nair

The cumalative weight percentage of the samples were plotted on a probability paper against their respective grain size(in phi units).Phi units have been used as the abscissa,and the cumulative weight percentage of the samples as the ordinate (fig. 55).

Interpretation of the cumulative curves.

Table 23 shows the calculated values of average grain,sorting, skeweness and Kurtosis of the different samples and the values in the two horizons A and B. The method followed for the interpretation of the above statistical parameters of grain size is that of Folk(1957).

The horizons A and B, are in general, coarse grained and poorly sorted. The skewness and Kurtosis values indicate steady conditions of deposition. The coarseness of grains and their poor sorting,therefore, indicate a very near provenance for these sediments.

The horizon A is finer and better sorted than the horizon B. This indicates that the sediments of the former haveundergone more transportation in comparison to the latter, assuming that the medium of deposition has not played much role in the sorting of the sediments. This is further indicated by nearly symmetrical distribution of grain size with the kurtosis values reaching as nearly as one.

In horizon A, the grain size gradually decreases from the base towards the top while in horizon B the grain size gradually increases towards the top. In view of the fact that the grain size decreases, and sorting improves with the transport, it becomes apparent from the table that horizon A and B have somewhat different provenances. This conclusion has been corroborated by the heavy mineral studies of the same specimens.

Heavy Minerals

Heavy minerals of the sandstone samples of the two horizons were separated from + 120 and -150 mesh sieve fractions. The following heavy minerals have been recognized: Horizon A - zircon,tourmaline, sphene and rutile with few grains of dumorterite and garnet. Horizon B-kyanite,sillimanite,garnet,staurolite,dumorterite,tourmaline,zircon, sphene,rutile,corrundum,chlorite and hornblende.

Horizon A.

Zircon- The zircon grains are generally brown and occur as euhedral prismatic crystals. Few spherical grains are also found: High relief, marked dark borders and high polarisation colours are distinct characters

Tourmaline.It is the most common heavy mineral present in the various samples. The grains are generally sub-rounded to rounded, though, euhedral prismatic crystals and anhedral grains are not uncommon. Two coloured varieties of tourmaline are recognised. (i)light to dark brown,sub.rounded elongated grains (ii) light to dark green rounded grains. Strong pleochroism and straight extinction and masking of the polarisation colours by the body colours are characteristic properties.

Rutile. It is cherry red in colour and occurs in prismatic grains with rounded edges.

Sphene. It occurs as sub-angular to sub-rounded grains of small size with several fractures. The brown body colour masks the interference colours. It is distinctly pleochroic.

Dumortierite. Only few grains have been observed. Marked pleochroism from blue to deep blue colours is observed. The grains are sub-angular, prismatic and elongated with conchoidal fractured surfaces.

Garnet. Very few grains of garnets have been observed. The grains are sub-rounded, pink in colour and isotropic.

Horizon-B.

Kyanite. It is colourless and prismatic to elongated grains with semi-rounded edges. Cross fractures and inclined extinction are characteristic.

Sillimanite. It occurs as platy and elongated colourless grains having rounded edges, and shows straight extinction and second order colour.

Corrundum. It occurs as sub-angular, colourless grains having many inclusions and exhibits very high refractive index.

Staurolite. The grains are angular to sub-rounded and fractured. Varieties having lemon yellow, greenish yellow, olive green and reddish brown colour are common. They are markedly pleochroic. The reddish brown variety gives the maximum absorption.

Garnet. The grains are generally angular to subrounded, riddled with quartz and magnetite inclusions. The surface is irregular due to conchoidal fractures. It is colourless and isotropic.

Hornblende. It occurs as sub-hedral grains with marked striations across their cleavages. It is pleochroic in green to brownish green. Extinction upto 20° is noted.

Tourmaline. It occurs as sub-rounded pink to greenish blue colours with abraded secondary overgrowth having light blue colour. The grains are pleochroic and the polarisation colours are generally marked by body colour.

Zircon,sphene,dumorterite and rutile exhibit the same characters as mentioned earlier in horizon A.

It is quite evident from the above studies that the horizons A and B show marked variation in the characters and distribution of heavy minerals. Horizon A is characterized by a heavy mineral suite probably derived from acid igneous rocks. Horizon B is marked by a different suite of heavy minerals characteristic of a metamorphic provenance. The difference in the provenance of the two horizons amply supports the conclusions derived on the basis of the mechanical analysis as mentioned earlier.

CHAPTER - V

PETROGENESIS AND METAMORPHISM

5.1. INTRODUCTION

An attempt has been made in the following pages to investigate the genetic aspects of the various rock types described in the preceding chapter, based mainly on their field relations, mineral paragenesis and grade of metamorphism. The chemical aspect involved in the formation of minerals, has been discussed wherever possible, in the light of the knowledge from the available literature on identical rock and mineral associations of other districts. In the absence of chemical data of the rock types of the present area, the objective of the discussion is to compare the mineral and rock assemblages of the area under investigation with that of similar types elsewhere and to elicit inferences therein. During the discussions emphasis has been given on the origin of amphibolites, granites and the iron ore bodies, while the genesis of the ultrabasics and the chromite deposits have been dealt in Chapter VI & IX respectively.

The discussion has been presented following the stratigraphical succession i.e. the Pauni Formation, the Parsori Formation, the Bhiwapur Formation and the Gaidongari Formation, which form separate structural and metamorphic domains. The depositional conditions of the Younger Sedimentaries have already been mentioned in Chapter IV along with the petrography.

5.2. PAUNI FORMATION

As mentioned earlier the Pauni Formation chiefly consists of chlorite-schists with few thin layers of magnetite-quartz-grunerite rocks and with intrusives of ultrabasic,basic(amphibolites) and acid rocks (granite and pegmatites).

5.2-1. CHLORITE SCHISTS AND QUARTZ-MAGNETITE-GRUNERITE ROCKS

The composition of the country rocks indicates that originally the sediments were deposited mainly as ferruginous clays with few iron rich siliceous bands. Presence of chlorite indicates that clays were rich in iron-oxide and alumina and poor in alkalies. During the regional metamorphism in the greenschist facies the clays were converted into chlorite schists. Locally few ferruginous silica rich layers gave rise to quartz-magnetite-grunerite assemblage. Stress environment is generally considered to be conducive to the development of grunerite. The formation of grunerite in regionally metamorphosed iron rich siliceous sediments has been discussed by many authors(Gruner 1922, Tilley 1935,Tyler 1949).Grunerite is believed to have been developed either from siderite or from greenalite,which were formed during diagenesis of the sediments. The following equations represent the trend of formation of grunerite.

$$\underset{\text{Siderite}}{7\,FeCO_3} + SiO_2 + H_2O \longrightarrow \underset{\text{Grunerite}}{(OH)_2Fe_7Si_8O_{22}} + 7\,CO_2$$

$$7\,\underset{\text{Greenalite}}{Fe_3Si_2O_3(OH)_4} + 10\,Si_8O_{22} \longrightarrow 3\underset{\text{Grunerite}}{(OH)_2Fe_7Si_8O_{22}} + 11\,H_2O.$$

Harker(1932)considers that siderite or greenalite is converted to magnetite during the first stage of metamorphism and grunerite is formed in higher grade,preserving some magnetite. The grunerite rich rocks of West Manquette,North Michigan are considered by James(1955) to have derived from both carbonate and silicate facies of primary iron formation. The change from lower grade silicates to grunerite is simply a transformation from one silicate structure to another. As the carbonate facies is entirely absent from the present area, it is quite possible that the grunerite was derived from the lower grade silicate i.e. greenalite. Pure iron rich and silica rich portions were transformed to magnetite and quartz.

5.2-2. AMPHIBOLITES

Metamorphic rocks composed principally of hornblende and plagioclase are grouped as amphibolites. Genetically amphibolites are grouped into two divisions (1) ortho-amphibolites and(2) para-amphibolites. The former is metamorphosed derivatives of dolerites, gabbros,basalts and basic tuffs,while the latter generally results from the metamorphism of calcareous or dolomitic sediments. In many regions both para-and ortho-amphibolites occur together which have posed many problems for their proper grouping. The problem is complicated because of the identical mineralogical composition and general absence of relict minerals and textures. In ortho-amphibolites,the initial cross-cutting relationship between the dikes and country rocks is destroyed by subsequent recrystallisation and differential movements. Many workers have discussed the genetic aspect of the amphibolites (Engel and Engel,1962,1964,Kulp and Poldervaart,1956;Wilcox and Poldervaart1958;Walker 1960;Evans and Leake,1960;Leake 1964).

Yodar and Tilley(1956) during their experimental investigations on the basalt-water system have found that basaltic magma with high water content would crystallize directly to amphibolites or hornblendites. Wilcox and Poldervaart(1958) have raised the question,whether some of the amphibolites and hornblendites described in the literature as being of metamorphic origin were not really of primary magmatic origin. This view has added a new significance to the amphibolite problem. However, this has yet to be corroborated with proper field andlaboratory evidences.

Table 24 gives a broad outline to distinguish between para and ortho-amphibolites. The salient features of the 2auni amphibolites are also given for comparison. On the basis of the field characters, the inter-relations of various rock types,and the microscopic features it has been concluded that the amphibolites of the present area were intruded originally as sills of basic composition into the country rocks undergoing regional metamorphism. During the regional metamorphism,the pyroxenes were completely converted into hornblende. The silica released during the process formed interstitial quartz. The original labradorite was changed into andesine. The calcium left in this process was consumed in the formation of sphene and epidote. From the mineralogical evidences it is assumed that the the original basic rocks did not undergo the preliminary stage of conversion to albite-actinolite or albite-hornblende assemblage of the greenschist facies, but were directly transformed into the hornblende-andesine assemblage of the almandine-amphibolite facies; whereas the country rocks of the area belong to the greenschist facies. The anomalous metamorphism of the basic rocks is probably due to the varying water content and their difference from the country rocks in susceptibility to the same intensity of stresses. The chlorite observed in the amphibolites appears mostly as secondary alteration product after hornblende.

As mentioned in Chapter II the marginal zones of some of the thicker amphibolites, are finer grained and well foliated while the inner portions are either very poorly foliated or even massive. The reduction in grain size and the change in texture along the margins of amphibolites may be due entirely to crushing and only incipient recystallization during metamorphism (Poldervaart, 1953). The amphibolites of northeastern part of Edward area, Adirondack mountains, New Yrok showing such fine grained margins, give the appearance of relict chilled zones (Engel and Engel, 1962). However, it has been doubted if such margins are really chilled zones. In the absence of positive evidences of crushing effects in the amphibolites of the present area, it has been assumed that they most probably represent the relict chilled margins.

5.2-3. GRANITES, PEGMATITES AND MIGMATITES

GENERAL CONSIDERATIONS

Since the middle of the last centuary, the origin of granites has been one of the most debated and disputed problems of geology. It still continues to be so, inspite of the great strides made in the fields of petrology and petrochemistry. The granite controversy has arisen due to the fact that rocks of similar composition have been observed in different settings varying in shape, size, structure, association, and distribution in space and time. Hence different schools of thought have been established around this problem. Some of the renowned geologists like J.J.Sederholm,C.E.Wegmann,P.Eskola, N.L.Bowen H.H.Read,E.Raguin and A.F.Buddington, devoted many years of fruitful research on the problem of granites. Accordingly vast amount of literature has accummulated on this problem. Though it is beyond the realm of this work to go deep into the granite controversy, an attempt has been made in the following pages to discuss briefly some of the salient points with a view to understand the genetic aspect of the granites and allied rocks of the present area.

Broadly, there are two different lines of approach to the origin of granites, one followed by the 'magmatists' and the other by the 'transformists'. The magmatists consider that granites are of igneous origin, as a result of consolidation of a magma or a fluid rock substance, intruding into the country rocks. According to the 'transformists' granites are formed by a process known as granitisation by means of which the country rocks are converted into or replaced by rocks of granitic character without undergoing a magmatic stage. Among the magmatists, there is difference of opinion with regard to the source of the granite magma. Similarly the transformists disagree on the process of granitisation. In many granite districts, there is an intimate association of granites , pegmatites and migmatites. Hence the problem of granites is interlinked with that of pegmatites and migmatites.

Origin of granite magma. As mentioned earlier, opinion varies on the origin of the magma which on cooling forms granites and related rocks. The various sources of magma envisaged by different workers are given below;

(a) Refusion of the base of the granitic layer (Sial) of the earths crust by melting.

(b) Fusion of geosynclinal sediments giving rise to a magma of granitic composition (palingenesis of Sederholm). Similarly, granite magma is produced by differential fusion of mixed rocks in the continental basements(anatexis of Eskola).

(c) By assimilation and differentiation - differentiation of a syntectic magma formed by the solution of granitic or other salic material in basaltic magma.

(d) As product of differentiation of basaltic magma as such.

Sederholm(1923,1926) has also considered that under the influence of either the ichors (refused melt of granitic composition) or of a magma the country rocks would be converted into a new anatectic magma, that on consolidation gives igneous rocks.

Bowen (1948) strongly supports the view that most most granites have been produced throughout the geological time by the differentiation of a basaltic magma, in part somewhat modified in the course of its rise, from the depths. The granite is the normal uppermost differentiate produced by repeated gravitational and tectonic(filter pressing) separation of series of crystals from a continuously changing mother liquor.Turner and Verhoogen(1961) accepts the hypothesis that most large bodies of granite rocks have formed from a granitic magma. They think it probable that largely liquid and granodioritic magmas formed by almost complete fusion of deep seated rocks, or squeezed upwards from deep zones of partial fusion have repeatedly invaded the upper crust on large scale. In addition to the above extensive magmas, these authors envisage the existence of small bodies of granite magmas derived from the differentiation of basaltic magmas. According to Winkler(1965) granites,like the granitic portions of migmatites, have crystallised from anatectic magmas. He agrees that metasomatism on a local scale takes place in the vicinity of intrusive contact to produce granite like rocks by felspar metasomatism.

The following field and laboratory evidences are often called in support of granites of magmatic origin.

1. The acid bodies show intrusive characters and discordance with the regional trend of the country rocks. They inject apophyses into the earlier rocks and enclose angular to sub-angular shaped fragments of the surrounding rocks.

2. It shows several evidences of magmatic stoping.

3. It shows contact metamorphism on the country rocks without any gradation.

4. In bigger bodies there is progressive increase in grain size from the outer cooling surface towards the core of the mass.

5. It generally exhibits flow structures and typical joint pattern caused by the mass flowage of the magma.

6. Gradational features in the mineral composition within the granites, but not with the wall rocks. The overall texture is of uniform character.

7. In most of the granites of confirmed magmatic origin the predominant potash felspar is microperthite whereas in rocks which are definite products of granitisation the predominant potash felspar is microcline

(or orthoclase) with little or without microperthitic intergrowth. Further, the plagioclase present commonly exhibits zoning.

8. Included minerals represent those of the earlier crystallization from the magma. They show sharp boundaries with the host.

9. Xenoliths and xenocrysts may show reaction effects.

10. Presence of unusual accessory minerals.

11. Deuteric alteration or autometamorphism exhibited by the minerals may be considered as the end phase of magmatic crystallisation.

Views against magmatic origin. The most important argument opposed to the magmatic origin of the granites is the space problem posed by huge batholiths. How could such enormous volume of space was made available in the earths crust? The hypothesis of granitisation developed as a corollary to this unexplained question.

It is logically explained that only a small quantity of granite can be formed by the fractional crystallisation of a basaltic magma. Daly(1932) has remarked thus,"a stupendous quantity of basalt would have to crystallize in order to make a batholith of granite". The transformists agree that small bodies of granite can form by the above processes but vehemently oppose the idea that bigger bodies of batholithic dimension result from this process.

Granitisation

Grout(1948) defines granitisation as follows " It is a group of processes by which solid rock(without enough liquidity at any time to make it mobile or rheomorphic) is made more like granite than it was before, in minerals, in texture and structure or both."

The earlier advocates of granitisation considered that metasomatic replacement took place in a pervasive fluid medium variously designated as 'emanations' 'ichor' or 'juice'. In these metasomatic processes only small part of the mass would be liquid in a disseminated or pervasive state. The above process has been termed as 'wet' granitisation by Bowen (1948). Later, the idea of solid diffusion ('dry' granitisation) was advanced, wherein the migration of ions through crystals, devoid of a pervasive liquid, caused granitisation.

'Wet' granitisation

According to the differntial anatexis(selective fusion) theory of Eskola(1933) quartzofelspathic portions of silicate rocks in deep zones melt, and the intergranular liquid produced would be injected along the shear planes of the rocks, migrating over great distances. The mobilised material by metasomatic replacement gives rise to great masses of granite of batholithic dimensions.

Read (1948) visualises granitisation as a plutonic problem closely linked up with migmatitisation and metamorphism. The formation of a series of metamorphic zones is attributed to changing physico-chemical controls caused largely by the permeation of metasomatising solutions. Read opines that only by this process can original sedimentary textures and structures be preserved. Goodspeed(1948) explains the following mechanisms for the formation of granite masses during the climax of progressive metamorphism; (a) gradual permeation of activating solution,(b) recurring fracturing permitting solutions to act progressively upon the wall rocks. (c) crystalloblastic growth from centres of recrystallisation replacement (d) solid diffusion.These mechanisms may act independently or in combination of varying strength in different areas.

According to Marmo(1962) the formation of granites is closely related to regional metamorphism of geosynclinal sediments. During regional metamorphism potassium and water are released from the sediments creating hydrothermal solutions,which transport the material necessary for the formation of granite composition. Marmo considers that "if the regional metamorphism is tectonically simple, granodioritisation of sediments with local granitisation phenomenon will probably result. If, on the other hand, the regional metamorphism is accompanied by strong tectonic features, the places of lower free energy will certainly attract the hydrothermally removed materials and they will be accumulated there forming aplitic, pegmatitic or granitic veins, dykes or large bodies, often appearing as the metasome of migmatites".

Among the Indian workers Sharma(1953),Bagchi (1957) and Jhingran (1958) have cited several field and laboratory evidences in support of granitisation processes. Sharma has opined that the banded gneisses and migmatites of Rajasthan are mainly the result of granitisation of the country rocks. Bagchi, while discussing the gneisses, granites, pegmatites and migmatites of Ranchi Plateau, Bihar, has concluded that these acid rocks have formed due to syntectonic granitisation of the pelitic and semipelitic schists by the permeation of the granitic fluids. He has further correlated the granitisation with the Satpura orogenic cycle. According to Jhingran (op. cit.) the extensive Bundelkhand granites and gneisses have originated as a result of intrusion of magmas formed by anatexis and palingenesis, followed by metasomatism of the country rocks.

Solid diffusion ('Dry' granitisation)

Solid diffusion was advanced as a hypothesis in opposition to transport by a pervasive liquid (ichor) by Perrin and Roubault(1937). They rejected the medium of liquids or fluids entirely. Many workers like Ramberg(1944),Bugge(1945),Backlund(1946), and Reynolds(1947) have discussed in detail the merits of solid diffusion to produce granites of batholithic dimensions. Ramberg cites an activity grandient for the migration of ions while Bugge suggests a gradient of chemical potential. Certain nucleii in the earth's crust with concentration of temperature or pressure are envisaged. From thse centres of activity or potential,migration of ions take place towards areas of normal pressure and temperature conditions. Migration of ions causes replacement leading to the formation of granites. During the migration the rocks are immersed in a molecular and ionic system of particles through the interstices of the minerals themselves altering the rocks metasomatically into granites. Reynolds(op. cit.) concludes thatduring the complex series of ionic migration, there is a balanced addition and subtraction of the materials, as a result of which while the rocks approach the composition of granite, others receive additions including Fe, and Mg expelled from them and become more basic. Migration of ions is supposed to take place through space in the crystal lattice from one lattice point to another within the crystal mesh,and the boundaries of theclosely packed crystal grains. Backlund(op.cit.) states that "granitisation is a migration of ions within solids by way of structural faults,deformations and crystal discontinuities and by means of potential differences of lattice energies, the result being remodelling and substitution".

Migmatitisation. As migmatitisation is generally related and coeval with the formation of granites the following three mechanisms are accepted in its evolution on the basis of the foregoing discussions:

(1) Injection of magma along the planes of weakness, the resulting migmatitites are termed as arterite or injection gneiss.

(2) Metasomatism of the country rocks by the permeation of 'ichor' or granite juice.

(3) Differential fusion of host rocks yielding granitic liquides which segregate into thin bands, discontinuous streaks and veins.

Evidences in support of granitisation. The following evidences are generally cited in favour of granitisation.

1. In many granite districts sections across the strike show a transition from country rock to granite through an intermediate zone of migmatitisation and felspathisation.

2. Preservation of sedimentary and tectonic structures in the granites.

3.. Regional orientation of skialiths in conformity with the country rocks.

4. The strike and dip of foliations of the granites(gneisses) are in continuity of the identical directions with foliations in the surrounding metamorphic area.

5. The shape of unreplaced remnants in replacement bodies is normally rounded, irregular and scalloped in outline.

6. The large metacrysts of felspars occurring in the country rocks are identical mineralogically and chemically with the phenocrysts of the granite bodies.

7. The ptygmatic folds are proof of deformational movements, during granitisation when the environment was at a maximum state of mobilisation.

8. The granitic material may grade from one point to another from the pegmatitic facies to the aplitic facies or to real granite.

9. Where intersecting joint cracks have formed the initial channels, progressive replacement at right angles to these fissures will first produce block like masses of country rocks which will appear to be fragments but are only relicts.

10. Abundance of myrmekites in the granites and migmatites and frequency of sutured textures.

Objections to granitisation process. Bowen (1948) notes that the heat supply to keep the metasomatising solutions fluid as they permeate miles of relatively cold rocks must be enormous and it cannot be available at the source of the solutions. Further the conversion of the low grade minerals of the geosynclinal sediments to high grade minerals of granite requires very large heat energy. The ichor is incapable of producing the required energy. Regarding the solid diffusion process, its advocates have not given any satisfactory explanation regarding the nature of migration of the ions. In areas of chemical potential, all the atoms of the various constituents of the rocks are equally affected. Few questions on this arise, which of the ions would migrate and which would be left behind? What happens to the Fe, Mg, Al ions which are removed from the replaced sediments? The 'basic front' idea of Reynolds is not supported universally by field evidences.

The granites, pegmatites and migmatites of the area.

The acid bodies of the area show the following field and laboratory evidences in support of a magmatic origin:

(1) The granites, pegmatites and the quartzofelspathic veins forming migmatites are interrelated in their field features and mineralogical composition.

(2) Majority of the acid bodies shows concordant relation with the chlorite-schist country rocks. Some of them exhibit discordant relation with the ultrabasic and basic intrusives.

(3) They show sharp contacts with metamorphic effects, on the intruded rocks particularly on the ultrabasics.

(4) They generally have lenticular form and pinch and swell structure.

(5) Individual bodies exhibit uniform texture.

(6) Zoning of plagioclase (oligoclase) minerals and Corrosion effects on the felspars are often observed in thin sections.

The genetic relationship of the granites, pegmatites and the migmatites is clearly apparent in the field. Where large number of acid bodies occur at close distances the quartzofelspathic veins are fairly thick and continuous. Away from these bodies or where the lenses are at wider intervals, the metasome is thinner and discontinuous. Further, the mineralogical characters of the quartz felspathic veins and bigger acid bodies are quite identical.

The cross-cutting relations shown by the granites and pegmatites on the hard ultrabasics (including chromite bodies) and amphibolites clearly indicate that they forced their way into the host rocks. The contacts of the acid bodies with the ultrabasics are rather sharp with contact metamorphic effects. Further these evidences contradict the idea that they were formed by granitisation(or metasomatic replacement).

The chlorite-schists of the Pauni Formation have been migmatitised to varying degrees. It is clearly deciphered that a melt of quartzo-felspathic composition penetrated or injected along the foliation planes of the chlorite schists to form migmatites (injection gneisses or arterites). The quartzo-felspathic material(metasome of the migmatites) form discontinuous streaks and lenticles in the folia of the schists. Probably during the initial deformational movements, the melt gradually penetrated the country rocks through the weaker planes. Later, when the deformational activities became intense, injection of large amount of melt took place, giving rise to lenticular bodies of granites and pegmatites of varying dimensions.

It is assumed that the magma or melt was formed in the deeper parts of the earths crust and they migrated upwards during the later phase of first fold movements and entered the weaker planes of the chlorite schists and earlier intrusives to form granites, pegmatites and migmatites. Hence it has been concluded that the acid bodies of the Pauni Formation are co-magmatic in origin.

5.3. PARSORI FORMATION

The area investigated contains only part of the Parsori Formation represented by chloritoid-chlorite-muscovite-schists showing spotted and cataclastic structures. The composition of the schist indicates that it was originally deposited as argillaceous sediments. Chloritoid forms from sediments which are poor in lime and potash and rich in alumina and iron oxides (Harker, op. cit.). In the present area the chloritoid muscovite-chlorite-schists occupy a shear zone indicating that chloritoid has developed as a result of high shearing stresses. The occurrence of chloritoid associated with shear zones has been mentioned by many workers e.g. Leith,(1923),Atkinson,(1956) Naha(1965) and Pande and Mahajan(1967). The texture,structure and the mineral composition of the schists clearly indicate that these rocks have undergone two stages of metamorphism; the first is of low grade regional type (greenschist facies) and the second is presumably due to dislocation metamorphism(directional stresses dominant) developed during the faulting f_2. Further work on this formation towards north and northwest may prove the above concept.

5.4 BHIWAPUR FORMATION

The Bhiwapur Formation consists of the phyllites,quartz-phyllites (garnet and biotite bearing) and iron ore bodies. These rocks were originally deposited as pelitic to semi-pelitic sediments, with linear lenses of siliceous iron rich sediments. On regional metamorphism, these sediments were transformed to different rock assemblages of the green schist facies.

In the quartz-phyllites of Bhiwapur the co-existence of chlorite, biotite and garnet makes an interesting metamorphic assemblage. The chlorite in the biotite-quartz-phyllites and the garnet-quartz-phyllites is of primary nature(There is lack of evidence to show that the chlorite is an alteration product of biotite and garnet). In garnet bearing rocks the stability relation of garnet with chlorite is explained as follows (Atherton,1964).

$$\text{Chlorite}_1 + \text{Quartz} \longrightarrow \text{Garnet} + \text{Chlorite}_2 + H_2O$$

Chlorite_2 is magnesium rich compared to chlorite_1

Almandine is the typical garnet of the garnetiferous schists resulting from the regional metamorphism of argillaceous sediments. The standard reactions suggested(Tilley,1926;Harker,1932) for the development of garnet are:

(i) Chlorite + Muscovite + Quartz $\rightarrow$ Garnet + Water with some ores also taking part.

(ii) Biotite + Quartz $\longrightarrow$ Almandine + K.felspar.

The biotite,garnet and some quartz of the quartz-phyllites occur in the matrix generally as porphyroblasts. Biotite flakes form xenomorphic clots with minor amounts of quartz,epidote and muscovite. It appears that they formed around several nucleii. The linear feature of many of these clots of biotite suggest that they are syntectonic in origin and grew parallel to the direction of movement (fig. 54). It is apparent that the porphyroblasts have developed and grown into their present size from smaller constituents during recrystallisation. Similarly the coarser quartz grains observed in thin layers and lenses have recrystallized along structural planes.

It has been observed that the phyllites adjacent to the quartz-phyllites are free from biotite and garnet. This can be explained due to the differences in chemical composition of the sediments. According to Atherton(1964) biotite forms in more quartzose rocks and is absent in the more aluminous and quartz-poor rocks. Biotite develops in the greenschist facies if the rock is deficient in alumina and fairly rich in potash where the rock composition does not allow chlorite as the only phase. The simultaneous development of chlorite, biotite and garnet within the same rock unit indicates that the chemical variation in the sediments is sufficient to produce different assemblages at the same pressure temperature conditions.

The phyllites are formed of chlorite, sericite (muscovite) and quartz. There has been general recrystallization due to the stresses developed during folding. Recrystallization and re-arrangement of quartz, chlorite etc. in the microfolds were controlled and conditioned by minor folds. Corrugation and microfolds (fig.52,53) observed in some of the phyllites and the development of slip cleavages (fig.49,50), indicate different phases of deformations suffered by these rocks.

Porphyroblasts of magnetite and chlorite occur independently or together. Sometimes quartz is associated with them. These porphyroblasts appear to have been formed by the recrystallisation of detrital matter during metamorphism.

Pressure-shadows. In the quartz phyllites, biotite sometimes occurs in the pressure-shadows of quartz-porphyroblasts. Similarly chlorite occupies the pressure shadows of magnetite porphyroblasts in the phyllites. The pressure-shadows are generally V-shaped with apices pointing in the direction of foliation. Pabst(1931) considers pressure-shadows to be the result of extension in the host rock in the plane of schistosity which tended to pull the matrix from the sides of the porphyroblasts, the potential opening being continuously filled in by other minerals. This may involve some rotation of the porphyroblasts. In the phyllites and quartz phyllites of Bhiwapur Formation, the porphyroblasts do not exhibit any sign of rotation. It appears that in these rocks, after the development of porphyroblasts, the superincumbent pressure created stress free zones around their fringes in the direction of foliation producing pressure shadows,where neo-crystallization of biotite and chlorite took place(Fig.47).

5.4-1. THE IRON-ORE BODIES

The origin of iron formations associated with metasediments has been a disputed problem. There are two views on the genesis of magnetite of the metasediments, (i) it is either a primary precipitate or has formed by diagenetic reduction of ferric hydroxide and (ii) it is the result of metamorphism and oxidation of earlier ferrous iron minerals.

Many workers have supported a primary origin for the magnetite, particularly with regard to the Iron-formations of Lake-Superior region (Castano and Garrels,1959;Krumebin and Garrels,1952; Huber 1958,1959;James,1951,1954). According to these workers the Eh(oxidation reduction potential) and pH (hydrogen ion concentration) of the sedimentary environment govern the type of iron minerals precipitated. As the iron rich sediments are considered to have been deposited in restricted basins where hematite cannot be stable due to the prevalence of reducing conditions magnetite forms by the settling of ferric oxide from the sediments.

The formation of magnetite as a product of regional or thermal metamorphism has been supported by Gill (1927),Goodwin(1951) and Laberge(1964), They conclude that magnetite is not a primary mineral, and it has developed by the oxidation of pre-existing ferrous iron minerals mainly greenalite and siderite. Magnetite also forms by the reduction of hematite during regional metamorphism. In open basins the iron hydroxides in the sediments, on dehydration become hematite,which convert into magnetite ore during the regional metamorphism. The banded magnetite-quartz rocks, associated with the Pre-Cambrian rocks of Madras and Bihar are the products of regional metamorphism of the original banded ferruginous sediments (Krishnan,1955). The magnetite in the iron-ores of Bailadila range-Bastar district are considered to have formed during the regional metamorphism (Chatterjee,1962).

The absence of appreciable amount of magnetite in sediments that have undergone only diagenesis in many areas, and its occurrence in considerable amount in the metamorphosed equivalents,strongly support the metamorphic theory. La Berge (op. cit.) is of the opinion that large amount of magnetite forms in the iron rich sediments by low grade metamorphism in the chlorite and biotite zones.

The magnetite in the iron ores of Bhiwapur is intimately associated with garnet, grunerite and quartz. While discussing the regional metamorphism of iron rich sediments Harker (1932) has cited similar examples for the iron ore deposits of Tumaberg, Sweden where some of the associated rocks are entirely composed of grunerite and garnet and similatly in parts of Lake Superior regions, grunerite and garnet are closely associated with magnetite. In the Banded Iron Formations at Broken Hill, Australia, the iron ore bodies are associated with garnet quartzites (Richards, 1966) and garnet forms an important constituent of the gangue.

The quartz-phyllites enclosing the iron-ore lenses are garnetiferous. Further, the quartz phyllites and phyllites contain porphyroblasts of magnetite crystals. From the mineralogical studies it has been observed that hematite has formed after magnetite (martitisation) and is of secondary origin. From the above evidences it has been concluded that the iron ores of Bhiwapur were formed by the regional metamorphism of linear lenticular layers of iron rich sediments. It is difficult to conclude regarding the nature of the original minerals (ferrous silicate or hematite) from which the magnetite was derived. The association of the magnetite with the undoubted metamorphic mineral assemblages (garnet and grunerite) leads to the inevitable conclusion that the magnetite formed during the regional metamorphism of the Bhiwapur Formation.

The hematite in the iron ores of Bhiwapur is a product of alteration of magnetite (Martitisation). The goethite and lepidocrocite are of supergene origin.

5.5. GAIDONGARI FORMATION

The Gaidongari Formation consists of slaty shales and banded slaty shales,quartzites,meta argillites meta-greywacke,slates, variegated slates and conglomeratic slates. These rocks represent the originally deposited mudstones,siltstones, clays and sandstones and paraconglomerates,which have undergone very low grade regional metamorphism of the green-schist facies. Metamorphism has not exceeded beyond the development of chlorite and mica(mostly sericite). Foliations and cleavages are developed fairly well. The directional pressure effects on the minerals are well apparent under the microscope.

It is concluded that the basin of deposition was very deep considering the predominantly argillaceous character of the rocks and the absence of shallow water sedimentary structures. In the early period of sedimentation, the deposition of the sediments was steady and the tectonic conditions were stable. However, in the later part, the tectonic environment was unstable causing rapid erosion,transportation and deposition. This is evidenced by the occurrence of greywacke and para-conglomerate horizons and the large amount of rock fragments contained in the rocks of the upper part of the Gaidongari Formation. The para-conglomerates(tilloid) are normally a product of turbidity currents caused by sub-aqueous mudstreams and slurries (Pettijohn 1957).

CHAPTER -VI

THE ULTRABASICS

6.1. INTRODUCTION

As in other chromite occurrences in the world the chromite deposits of Pauni are genetically and structurally associated with the intrusive igneous rocks grouped as the ultrabasics(ultramafics). The chief characteristics of ultrabasics are low silica content and high percentage of magnesium. They are extremely rich in basic magnesium-iron silicate minerals like olivine and pyroxene. Fresh ultrabasics were not encountered during the course of the present study in the area upto a depth of 25 m. from the surface. The ultrabasic rocks have been completely altered due to hydrothermal processes,and except for the chromite,no primary mineral is preserved in these rocks. Further due to the mineralogical changes and the deformations suffered by these rocks, the primary textures and structures have been mostly obliterated. Hence, it was not possible to determine properly the textural and paragenetic relations the chromite grains have had with the magmatic silicates.

As the rock types representing the ultrabasics are derivatives of the hydrothermal metamorphism,their nomenclature does not follow the classifications adopted for unaltered ultrabasics. Several assemblages consisting of the following minerals represent the altered ultrabasics:serpentine(antigorite and chrysotile), talc,tremolite, actinolite,anthophyllite,chlorite(penninite,clinochlore,and kammererite),chromite, phlogopite,vermiculite,quartz and chalcedony. In the field it is very difficult to recognize the rock types except to identify them as talc rich, amphibole rich, chlorite rich and chertified, ultrabasics and chromitites.

6.2. DISTRIBUTION, SHAPE AND SIZE

The majority of the ultrabasic bodies lie in the area between the Pauni-Belgatta-Khapri road and the Khadan nullah(Map 2). North of this nullah few exposures of the ultrabasics have been observed in the Upashya nullah. The ultrabasics occur as intrusives confined in the chlorite schists of the Pauni Formation. The general trend of these intrusives is WSW-ENE. The width of the belt as exposed along the Wainganga river is for about 2 Kms. Strike wise extension has been established over 2 Km. towards southwest from the Wainganga while the northeast extension is obscured by a thick cover of alluvium. The ultrabasics occur within a plain area and most of the outcrops are mantled with 2-3 m.thick soil cover. Generally patches of greenish white to greenish yellow or greyish brown soil suggest proximity of ultrabasic exposures. Along the Wainganga river the ultrabasics have been limonitised and the altered rocks show brownish yellow, reddish yellow, or yellowish white colours and earthy appearance.

The ultrabasic intrusives are of the nature of discontinuous linear series of the alpine type. Several steeply dipping lenticular and tabular bodies have intruded the chlorite schists broadly conforming to their strike. These are discontinuous bodies occurring as disconnected parallel lenses of various dimensions. Although essentially concordant, these sill like bodies commonly transgress identify them as talc rich,amphibole rich,chlorite rich and chertified, ultrabasics and chromitites.

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The ultrabasic intrusives are of the nature of discontinuous linear series of the alpine type. Several steeply dipping lenticular and tabular bodies have intruded the chlorite schists broadly conforming to their strike. These are discontinuous bodies occurring as disconnected parallel lenses of various dimensions. Although essentially concordant,these sill like bodies commonly transgress the country rocks and pinch and swell in short distances. The bodies are usually of small dimensions; the lenses range in length from 50 m. to over 1000m. and vary in width between 3 to 15 m. They occur in a swarm consisting of several sub-parallel bodies arranged in a linear series along the strike of the belt. Structural features indicate (p.69) that this belt occupies a synform axis of a major fold trending roughly NE-SW direction. Concentration of major lenses lies along the alignment connecting Nimgaon to the southwest and Nilkanteswar temple on the right bank of Wainganga river. These ultrabasic masses have been subjected to deformations like folding, faulting and shearing (Figs.90,94)causing repetition,disappearance and crushing. As mentioned earlier(p. 42) the ultrabasic rocks show several sets of joints and at places they have been subjected to intense shearing. These shear planes are often very smooth with a soapy feel,but occasionally striations due to slickensides are noticed on them. Some of the shear planes show a curved or convex surface(fig. 84). The shear surfaces are also stained due to iron oxides giving specks and streaks or coating of black or brownish yellow colour.

6.2-1. CONTACT EFFECTS

Though the ultrabasic bodies exhibit a distinct intrusive relation with the country rocks, it is noteworthy that marked contact effects on the country rocks are lacking. Whatsoever the contact effects, the ultrabasics might have produced, have been destroyed due to intensive hydrothermal changes and the later basic and acid intrusives. Along some of the contacts between the acid and the ultrabasic rocks thin irregular bands of tourmaline-quartz rocks are observed. At few other places small concentrations of vermiculites have been noticed along the contacts of acid and ultrabasic rocks. The ultrabasic rocks near the amphibolites contain high amount of fibrous minerals. At some places regular and irregular bands consisting of cross-fibre chrysotile asbestos are observed.

6.3. MEGASCOPIC CHARACTERS

Rocks predominantly composed of talc is comparatively soft and give a waxy feel. Increasing amount of amphibole minerals makes the rock rough and harder. Chlorite rich rocks show closely spaced foliations.

Talc rich rocks exhibit various shades of green,grey and white colours. Small aggregates of flaky chlorites give dark green or greenish black patches. Tremolite rich rocks are of dark grey, greenish grey,brownish green and brownish grey colours. With the increase of chlorite and talc lighter shades pervade. Actinolite rich rocks display light and dark green shades with aggregates of prismatic and needle like minerals. Anthophyllite rocks of minor occurrence contain hard fibrous needles and show brownish,reddish brown and greenish grey colours. Chlorite rich rocks containing talc and serpentine are generally flaky and platy and exhibit pale green,yellowish grey,and silver grey colours. Near some of the chromite bodies silvery grey flaky chlorites are observed. In vermiculite-schists, the mineral occurs in small flakes having earthy brown to greenish brown colour. The flakes easily crumble to powder under pressure. The individual flakes show bronzy brown colour with sheen under light. Small quartz grains are enclosed between the flakes.

Chertified rocks occur as irregular bands and pockets in the ultrabasics. Some of the highly silicified ultrabasics are jaspery looking. They are hard, compact, flinty and break with conchoidal fracture. They show various shades of brownish pink, greenish black, pale greenish grey with brown or yellow patches. Disseminated chromite grains in variable amount give specks of black colour to the rock and show a spotted appearance. Veins of cryptocrystalline silica and quartz cut across these rocks. Banded types represent selective chertification. Sub-parallel and irregular bands (varying between 0.5 mm. to 10 mm. in thickness) of chert alternate with silicate bands. Some of the bands are fibrous and appear to be pseudomorphs after crossfibre chrysotile bands (Fig.123). Few lenticular pockets (10 to 20 cm. in the long direction and about 5 cm. in the short direction) of chertified rocks have been observed in the ultrabasics (Fig.124). Partially silicified ultrabasics show numerous thin chalcedony and quartz veins. The silicate mass lying in between the closely spaced veins, has been almost completely silicified, while the silicate mass between the widely spaced veins shows silicification near the veins only.

Stringers and irregular bands of chrysotile asbestos (0.5 - 1 cm. thick) occur in the ultrabasic rocks near their contacts with some of the amphibolites. Some regular bands upto 4 cm. thick have developed near such contacts. Theyare crossfibre type - the fibres being perpendicular to the long direction of the bands and stringers (Fig.122). They are white in colour and flexible.

6.4. MICROSCOPIC FEATURES

Mineralogy

As mentioned earlier the ultrabasic rocks of Pauni represent various assemblages consisting of secondary minerals like talc, chlorite,tremolite etc. derived from the magmatic silicate minerals due to hydrothermal alterations. On the basis of the variations in the amount of the constituent minerals, the following mineral assemblages have been recognized as different rock types:talc-schist, tremolite-schist,chlorite-schist,actinolite-schist,talc-tremolite schist,tremolite-talc-chlorite-serpentine schist.,tremolite-talc-phlogopite schist,tremolite-actinolite schist,talc-chlorite-anthophyllite schist. Some of these rock types contain chromite as an important accessory mineral. Sphene,epidote and apatite may be present as minor accessories.

As the chromite deposits form part of the ultrabasics these along with their gangue have been grouped as rock units known as chromitites. According to Johannsen(1951) chromitites are composed of about 95% chromite and less than 5% gangue. However, the term chromitite has been used in this work for rocks having as low as 30 - 40% by volume of chromite,with a prefix of predominant gangue minerals. On the basis of the predominant gangue minerals they form few distinct assemblages. The following chromitite assemblages have been recognized: talc-chromitite,tremolite-chromitite,chlorite-chromitite.talc-chlorite-chromitite,talc-chlorite-serpentine-chromitite, chlorite-phlogopite chromitite and chert-(chalcedony)chromitite.Ore deposits with less than 5% gangue have been referred as normal chromitites.

In some of the chromitite sections pseudomorphs of talc-tremolite after olivine have been preserved within the chromite grains (fig.149). Their border with the enclosing silicates is curved or rounded indicating the shape of olivine. The shape of many amphibole minerals and the schiller structure preserved in them in several sections of ultrabasic rocks, suggest that they are mainly derived from pyroxene minerals. Few pseudomorphs of the primary silicates are preserved,presumably due to breaking or pulling apart of fractured parts which destoryed the original shape of the primary silicates.

A brief account of the various minerals constituting the different assemblages are given below:

Talc. It occurs in the ground mass as aggregates of fine shreds, scales,flakes and fibres. Minute particles in aggregates give a mesh like appearance. Prisms and plates are seen randomly oriented in the groundmass. The talc is generally colourless. Rarely it gives pale green colour. The coloured varieties are pleochroic as X = pale green or pale yellow, Y = pale yellowish green Z = greenish yellow. Some of the prismatic and tabular sections are bent across their cleavages. Along the cleavages minute streaks of iron oxide are seen. In some sections talc exhibits a brown colour due to staining of iron oxide. Talc replaces tremolite-actinolite mainly along the cleavages,. Bigger plates of talc contain relict patches of tremolites (fig.143). Talc in its turn is replaced by chlorites.(fig.145).

Tremolite - Actinolite. Tremolite is colourless to pale green. Basal sections show greenish & yellowish green shades. Prismatic grains of various sizes are randomly oriented, crisscrossing each other (fig.144). Extinction angles vary upto 22°; few prisms show simple twinning. Fractures and cracks have developed across the cleavages. Many tremolite pseudomorphs after pyroxenes are often observed. Schiller structure is exhibited by many tabular and prismatic grains. Granules and specks of opaque mineral (magnetite) are oriented parallel to the cleavages and sometimes oblique to them. In some sections it appears that the magnetite is a released product during the alteration, while in other sections, particularly where the iron oxides are also oriented across the cleavages, the schiller structure seems to have been inherited from primary pyroxenes.

Pale olive green, prismatic, and columnar aggregates of actinolite are randomly oriented in some sections. These are pleochroic as X = pale olive green, Z = pale green. Their extinction angle varies upto 25°. Some of the prisms show closely spaced cross-fractures. Cleavages and fractures generally show fillings of iron oxide. Many bigger grains exhibit schiller structure. In some of the sections small idiomorphic grains of magnetite are associated with the actinolites. These actinolites also contain small granules of sphene.

Anthophyllite. In some sections it forms long columnar aggregates and prisms. These are at places of fibrous nature. Generally it is colourless, but some sections show shades of pale green and pale brown colours. Extinction is parallel. Cracks and fractures are filled with iron oxide. Anthophyllite is generally replaced by talc.

Chlorites. Chlorites are common constituents in most of the assemblages. They appear to be the last mineral to form amongst the silicates. They also occur in veins cutting across the chromitites. Chlorites occur in the following form: laths, flakes, scaly and fibrous aggregates. Generally, the flakes are seen as clusters and the fibres radiate. In many chromitites and other ultrabasic assemblages clusters of chlorite flakes are observed around ragged or corroded chromite grains(fig.147). They show different shades of green and yellow. Some chlorite sections are colourless. The coloured varieties are faintly to moderately pleochroic. The absorption scheme is as: X = pale green and greenish white, Y = pale green, Z=yellowish green and cream colour. Some of the colourless flakes show yellow tint due to staining of iron oxide. Fine dust of iron oxide is found along the cleavages of chlorite. Penninite is the predominant member of the chlorites. It shows parallel extinction and bluish grey to anomalous blue polarisation colours. Clinochlore observed in many sections has an extinction angle upto 8° and generally exhibits low first order interference colours. Bent flakes of chlorite display wavy extinction.

The chrome bearing variety-kammererite is easily identified megascopically from its pale violet colour and flaky nature. It is found along many shear planes of chromitites and also as a vein mineral. However, in thin sections, it is difficult to distinguish them from penninite and they appear to be chrome bearing variety of the same.

Serpentine - Serpentine (antigorite) occurs as a mesh formed of aggregates of fine fibres in random orientation. It is difficult to discern the individual part. It is colourless and shows low first order interference colours. In few assemblages it is isotropic or shows feeble anisotropism. Chrysotile occurs as fibrolamellar aggregates in some sections. Bending of the cleavages and wavy extinctions are observed in them.

Though, on the basis of mineral paragenesis serpentine appears to be the first hydrothermal mineral to form; it is of very limited distribution in space. Assemblages with serpentine as a predominant constituent are of minor occurrence and in many rock types serpentine has been largely replaced by later hydrothermal minerals.

Phlogopite - Phlogopite has been identified in some chromitites and in a few other assemblages. The flakes are colourless to pale green or pale yellow and rarely pale brown colour. The coloured varieties are pleochroic: X = colourless, Y = pale green, Z = pale yellow to pale bronze yellow. It shows an inclined extinction of 4-7°. Bent flakes show wavy extinction. The interference colour is of high first order. Multiple twinning is observed in many flakes. Bigger flakes show criss crossing bents or kinks across their cleavages(fig.146). Fractures and cleavages contain some fine dust of iron oxide.

Chromite - In many assemblages small grains of chromite with corroded borders are observed enveloped by silicate minerals. Many of these are relict fragments of the original grains,and partly preserved idiomorphic outlines could be reconstructed (fig.148). The chromite grains are black or brownish black with a red tint. Rarely grains show two or three sets of cleavages or partings filled with secondary silicates at angles between 70-80°.Some chlorite flakes contain small irregular relict grains of chromite. The detailed features of chromitites have been discussed later(refer chapter VII).

Vermiculite - Vermiculite shows various shades of brown and is highly flaky and laminated in nature. The individual flakes are rather small in size and exhibit silky sheen under normal light. Small grains of quartz are found embedded within the laminae. The dark brown colour of the mineral could be attributed to the high amount of ferruginous matter present in them or to coating of iron oxide which has obscured their optical characters. Certain unaffected portions show pale yellow tint with a bluish grey interference colour. All the lath shaped fragments exhibit parallel extinction.

A sample of the mineral was treated in a furnace to a temperature above 800°C and the characteristic exfoliation phenomenon was noticed. The exfoliated flakes were found to be much lighter in weight compared to that of original material. During this treatment, development of golden, bronzy, and silvery lustre on the flakes was observed, which is an outstanding characteristic of vermiculities (Nair and Singh, 1966).

Chalcedony (Chert) - Thin sections of chertified ultrabasic show colloform structure or a mosaic texture consisting of smaller quartz grains having islands of talc, tremolite, chlorite etc. In partially chertified rocks veins of chalcedony have filled in the fractures and weak planes of chromite and the silicate minerals. Some of the chromite fragments have rims of chalcedony. Colloform and spherulitic textures are common. From the cross cutting relations of the veins, two phases of chertification are discernible. The earlier one is more crystalline compared to the later phase.

In the chertified chromitites the unusual association of chromite and quartz is seen. The fractures and cracks of chromite are filled up with chalcedony. The gangue minerals have been completely chertified. While all silicate minerals were replaced by chert, chromite was left unaffected.

6.5. HYDROTHERMAL ALTERATIONS IN THE ULTRABASIC ROCKS

The ferro-magnesian minerals like olivine and pyroxenes forming the main constituents of dunites and peridotites, become unstable in

TABLE - 26

PARAGENESIS OF THE MINERALS OF THE ULTRABASIC ROCKS

MINERALS	MAGMATIC	HYDROTHERMAL	SUPERGENE
CHROMITE	———		
(Olivine and Pyroxenes)*	—?—		
SERPENTINE		——	
AMPHIBOLES		———	
TALC		———	
PHLOGOPITE		—	
CHLORITES		———	
CHERT (Chalcedony)		— —	—
VERMICULITE			——
LIMONITE			—

* Olivine and pyroxenes are only represented by pseudomorphs of secondary silicates.

the presence of chemical solutions. When hydrothermal solutions get accessto these rocks through fractures and joints, large scale alterations of the primary minerals take place, producing hydrous minerals of low temperature origin, like serpentines, talc, amphiboles and chlorites. Alterations also take place as a result of autometasomatism or autohydration in the late magmatic stage. If the hydrothermal solutions carry enough CO_2, carbonate minerals like dolomite and magnesite are also formed.

As mentioned earlier the ultrabasic rocks of Pauni have been completely altered due to hydrothermal activities. On the basis of field and laboratory evidences these processes can be broadly classified into the following types in the order of their paragenetic succession:

I. First stage (hydrothermal) (i) serpentinization, (ii) amphibolization, (iii) steatitization, (iv) phlogopitization, (v) chloritization, and (vi) chertification (Table 26).

II. Second stage (supergene) (i) vermiculitization and (ii) lateritization.

Though serpentinization was the first of the hydrothermal changes to take place, the low percentage of serpentine minerals occurring in the various assemblages, suggests that either this process was not extensive or that most of the serpentine rich rocks were affected by later processes. Steatitization, amphibolization and chloritization have caused widespread changes. Phlogopitization has taken place on a very minor scale. Chertification is a localised phenomenon. The above mentioned processes took place during hydrothermal stage. Vermiculitization and lateritization took place much later due to supergene processes.

The alteration in the chromiferous ultrabasic rocks of the present area is much similar to that of Norway and North Carolina where hydrothermal amphiboles, chlorite and talc are well developed and serpentine is developed only in minor amounts (Fisher, 1929). Similarly the chromiferous ultrabasic rocks of Ratnagiri district, Maharashtra are represented by a suite of hydrothermal mineral assemblages, as actinolite, tremolite schist, talc-tremolite schist, serpentine-talc-tremolite schist etc. (Konala, 1966). In the following pages an account of the physical, chemical and mineralogical changes involved in different processes of alterations is given.

6.5-1. SERPENTINIZATION

Field and laboratory evidences indicate that serpentinization is the first hydrothermal change to take place in the ultrabasic rocks of Pauni. Pure serpentinites are rare in the area presumably due to subsequent processes of alterations. The restricted occurrence of serpentine rich rocks may be also due to that serpentinization was not very widespread and affected only certain parts of the ultrabasic bodies.

Two stages of serpentinization have been established. The first stage is represented by the massive type mainly antigorite having replaced the magmatic silicate minerals. The second stage, mainly represented by the chrysotile, was probably connected with the later deformational activities since they were formed in veins and bands along weak planes.

The process of serpentinization of ultrabasics has been a much debated topic. That serpentinization is a deep seated phenomenon has been proved erroneous by recent workers. Graham(1917) and Benson(1918) regarded it as a late magmatic process. Hess (1932,38) thinks that serpentinization is either late magmatic or deuteric (autometasomatic) process and peridotite magmas are hydrous magnesian melts possibly approaching serpentine in composition. Haapala(1936) and Schurenberg(1954) support the view of Hess that serpentinization is due to autometamorphism. Bowen and Tuttle(1947) have proved that serpentines cannot be formed at temperatures above 500°C and that formation of serpentine by the action of water on forsterite can occur only below 400°C. They deduced that serpentines cannot be formed by the intrusion of a magma of serpentine composition at comparatively low temperatures. Hess (1946) has later accepted the views of Bowen and Tuttle with certain reservations.

It was also concluded that the serpentines are unlikely to occur through the transformation of olivine and pyroxene crystals by their acqueous mother liquor (autometamorphism).

$$Mg_2SiO_4 + MgSiO_3 + 2H_2O \rightarrow Mg_3Si_2O_5(OH)_4$$

forsterite enstatite serpentine

Bowen and Tuttle (op. cit.) further suggest that olivine and pyroxenes are introduced in the crystalline state(mush form) without water and are subsequently serpentinized below 550°C by water vapour acquired through contact with wet country rocks. If the rock contains only olivine then water vapour will yield serpentine and brucite below 400°C.

$$2\ Mg_2SiO_4 + 3\ H_2O \rightarrow Mg_3Si_2O_5(OH)_2 + Mg\ (OH)_2$$

forsterite serpentine brucite

If CO_2 were present to remove excess magnesia as soluble carbonate then serpentine could still be formed upto 500°C.Another reaction by which serpentinization of olivine could occur involve the addition of silica.

$$3\ Mg_2SiO_4 + SiO_2 + 4\ H_2O \rightarrow 2\ Mg_3Si_2O_5(OH)_4$$

forsterite serpentine

but this would involve consisdderable increase in volume for which there is not much substantial evidence,

Turner and Verhoogen (1960) accepted as a working hypothesis the duel concept of intrusion of peridotite magma in a largely crystalline condition,with simultaneous or subsequent serpentinization of its constituent minerals through the activity of acqueous solution of vapours derived for the greater part from the surrounding rocks.

One of the chief problems in serpentinization is the question of volume changes. Calculations by Graham(1917) indicate an increase of 40 - 64% in dunites and 34 to 38% in peridotites.Hess argued that if the ultrabasic magma had a serpentine composition,on emplacement there would have been 5% decrease, but as his basic hypothesis was proved erroneous by Bowen and Tuttle,other alternatives have since been sought. Olsen(1963) and Grubb(1962) believe that serpentinization is largely determined by former stresses in each ultrabasic body. In areas where folding,faulting and fracturing are at an optimum, intensive serpentinization and corresponding volume increases would be almost unrestricted. At the same time any fractures or low pressure zones would soon be filled by liquids of serpentine and/or carbonate composition, these having diffused in from the surrounding ultrabasic mass. On solidifying these formed serpentine and magnesite veins-(alternatively under higher stress/temperature conditions,chrysotile veins and replacement veins were formed). Recently it has been proved that serpentinization does not involve any change in volume(Thayer,1966).

In some circumstances peridotites reheated by extraneous solutions may be serpentinised during the cooling cycle,as for example when talc occurs as pseudomorphs after enstatite(Deer,et.al.1962).

$$6\,MgSiO_3 + 3\,H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + Mg_3Si_4O_{10}(OH)_2$$

enstatite → Serpentine talc

Serpentinization can take place chemically by the following reactions as well:

$$Mg_2SiO_4 + MgSiO_3 + 2H_2O \longrightarrow Mg_3Si_2O_5(OH)_4$$
forsterite enstatite serpentine

$$2\,Mg_2SiO_4 + 2H_2O + CO_2 \longrightarrow Mg_3Si_2O_5(OH)_4 + MgCO_3$$
forsterite serpentine magnesite

The process of serpentinization requires large amount of water. The source of water has been a subject of controversy. Three main sources have been suggested(Benson 1918;Turner and Verhoogen 1960).

(1) Water derived from the ultrabasic magma itself,during the last stage of its consolidation.

(2) Water of magmatic nature derived from other intrusives(mainly granites) into or near the ultrabasic mass.

(3) Water contributed by the enclosing water charged geosynclinal sediments or by the upward system of juvenile water not connected with any magmatic source.

Some primary serpentinization may occur during the last magmatic stages by auto-hydration especially in the dunite or pyroxenite. Granite intrusives no doubt cause serpentinization and other hydrothermal alterations on varying scale. As mentioned earlier,peridotites under some circumstances reheated by extraneous solutions may be serpentinized during the cooling cycle. Some workers (Du Reitz 1935,Keep 1929,Bowen and Tuttle 1949) have attributed serpentinization to the extraneously introduced magmatic water derived from nearly intrusive granites.

According to most of the modern authors - Betekhtin(1962), Den Ted(1959),Nerbert(1959),Kaaden(1960),Ross et al (1954) and Borchert(1958,1960), the mass serpentinization must be ascribed to secondary tectonics and the infiltration of extra magmatic water.

This water may originate in the wet geosynclinal sediments.

The degree of serpentinization of an ultrabasic province is controlled by(a) the amount of water available(b) the permeability of the rocks and (c) degree of fracturing and fissuring. Peridotite bodies of the same mineral composition may be more serpentinized in certain parts than others,and the reason for this,is probably the varying amount of fissuring and difference in grain size and texture. Serpentinization,as a hydrothermal process,is controlled by the zones of weakness and fractures etc. among which is also the zones with largest mechanical anisotropy i.e. contacts between massive ores and peridotites or dunites.

In the Great Dyke of Southern Rhodesia,serpentinization is observed to be a comparatively late process in the history of the dyke. It commenced probably after the consolidation of the dyke and is still in progress where conditions are favourable such as sufficient water supply,high rock permeability,and planes of movement which act as venues for water circulation(Worst,1960). Here the process of serpentinization is a surface phenomenon progressing downwards. Serpentinization extends to greater depths only along fault planes.

In the Nausahi ultrabasic belt of Orissa,serpentinization does not proceed very far to the depth,which has been proved by drilling. Fresh dunites and peridotites were touched at depths of 20 to 22 m. The absence of serpentinization in deeper zones has cast some doubts on the contention that serpentinization is a deep seated phenomenon.

In the Matherson ultrabasic belt N.Ontario, two different phases of serpentinization has been noticed, an initial relatively minor phase of autometasomatism assisted by acqueous solutions derived from the country rocks during emplacement, and a second intense stage of hydrothermal alterations connected with the later igneous activity (Grubb 1962). The chief serpentinizing solutions were acqueous solutions with dissolved CO_2 which moved up along fault planes effecting intense carbonatization, serpentinization and eventual steatitization in the ultrabasics. The source of serpentinizing solutions is considered to be deep seated.

In the Pauni ultrabasics CO_2 does not seem to have played any part in the reactions which resulted in serpentinization, as carbonate rocks have not been observed in the altered varieties. According to the drilling reports of the Orissa Cements Ltd.(1961), unaltered ultrabasic rocks were encountered in the deeper parts. This evidence rules out the probability of automatasomatism or silica rich acqueous solutions derived from geosynclinal sediments as causes of serpentinization. As evidences of mass serpentinization are lacking in these ultrabasics, it is presumed that the serpentine minerals were formed as a result of the reaction of silica rich solutions provided by the granites and pegmatites with the ultrabasics.

6.5-2. AMPHIBOLIZATION

The hydrothermal alteration of more calcium rich ultrabasic rocks, as well as, the effects of calcium rich solutions on normal ultrabasic rocks, results in the formation of tremolite and chlorite, instead of serpentine, if sufficient aluminium is available(Turner and Verhoogen,1960). In the Pauni area, the absence of carbonate minerals in the altered ultrabasics, suggests that the tremolite rich rocks have been derived from the primary ultrabasics rich in CaO.

The development of tremolite-actinolite in the ultrabasics, as secondary minerals, has been reported from many areas. The ultrabasic rocks of Unst, Shetlands islands, have been altered into tremolite actinolite, tremolite-talc, and tremolite-carbonate-antigorite schists. However, Read(1934) considers these assemblages to be products of low grade regional metamorphism. Formation of tremolite, by the hydrothermal alteration of olivine and pyroxenes of the ultrabasics, has been reported from Norway and North Carolina (Fisher, 1929), Macdonald(1941) has described zones of talc- actinolite, and of actinolite, around nodules of serpentine enclosed in mica schists, adjacent to quartz diorites in the Sierra Nevada region. The talc and actinolite are considered to have formed by the metasomatism of the serpentines.

In the present area, the formation of anthopyllites appears to be related to the pegmatite intrusives as the rocks rich in anthophyllite occur quite near the pegmatite bodies. Similar occurrences have been reported elsewhere. Thus in Yancy County, N.Carolina the action of pegmatitic liquid on dunites has produced a zoned reaction sequence from unaltered cores of granular olivine through talc, anthophyllite to phlogopite rock (Kulp and Brobst,1954). A similar occurrence of anthopyllites associated with serpentine has been described from Hafafit,Egypt(Amin and Afia 1954).The formation anthophyllites in rocks of bronzitic composition in the Sukkar-toppen dirstrict,West Greenland is related to the intrusion of pegmatites during the retrograde ~~fm~~ transformation of ultrabasic rocks associated with a period of active deformation (Sorensen 1952). In the ultrabasic rocks of Eastern Sierra Leone anthophyllites, though post date serpentine, have been found to replace olivine (Dunham et.al. 1958).

Since it appears from the petrographical evidences that talc formed at the expense of anthophyllite and not vice-versa,it is reasonable to conclude that higher temperature prevailed during pegmatitic stage. Talc can form upto 800°C at pressures of 30,000 lb/in^2 . Although in the experimental studies of Bowen and Tuttle (1949) anthophyllite appears in the hydrous phase as a passing phenomenon,they envisage the possibility of its formation as a primary mineral. In the peridotites of Manpur,Singhbhum district,India anthophyllites of primary origin have been reported where the alteration of anthophyllites has given rise to serpentine,talc and chlorite.

6.5 -3. STEATITIZATION

Talc is the predominant product of hydrothermal alterations of the ultrabasics in the present area. Talcose rocks are found at several places having varying amount of chlorite and tremolite. In these rocks serpentine is either absent or present only in minor quantities. Field and microscopic evidences indicate that talc has formed either directly replacing the primary silicate minerals or developed after the formation of earlier serpentine and amphibole minerals.

Steatitization is commonly but not always associated with serpentinization. Steatitization of ultrabasic rocks has been defined by Hess(1933) "as that process of hydrothermal alteration of an ultrabasic which in its final stages results in the formation of talcose rocks". In some circumstances peridotites reheated by extraneous solutions may be altered during the cooling cycle, as for example when talc occurs as pseudomorphs after enstatite along with serpentine (Deer et al, 1962).

$$\underset{\text{enstatite}}{Mg\,SiO_3} + 3\,H_2O \longrightarrow \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{talc}}{Mg_3Si_4O_{10}(OH)_2}$$

Turner (1948) has shown that formation of talc rich bodies may arise by silicification, carbonation or by the addition of CaO. The conversion of serpentine to talc by the addition of silica and the removal of magnesia without change in volume may be illustrated by the following equations:

$$\underset{\text{serpentine}}{(OH)_4Mg_3Si_2O_5} + SiO_2 \rightarrow \underset{\text{talc}}{(OH)_2Mg_3Si_4O_{10}} + MgO + H_2O$$

Another equation:

$$3\,\underset{\text{enstatite}}{Mg_1SiO_3} + SiO_2 + 2H_2O \longrightarrow \underset{\text{talc}}{(OH)_2Mg_3Si_4O_{10}}$$

In the Matheson ultrabasic belt of N.Ontario secondary steatitization with carbonatization form a distinct keeled envelop to most serpentinite bodies (Grubb 1962). These zones grade from pure talc to talc-chlorite to magnesite rocks. Along sheared or fractured zones where movement of solution was less restricted the resulting intensive carbonatization of the serpentinite reduced the CO_2 and increased the SiO_2 contents so that when temporarily blocked either by impervious dikes or country rocks or regions of higher compression, these new siliceous solutions reacted with the enclosing serpentinite to form talc and lesser chlorite.

$$\underset{\text{Serpentinite}}{Mg_3Si_2O_5(OH)_4} + 4\ SiO_2 + H_2O \longrightarrow \underset{\text{Talc}}{Mg_3Si_4O_{10}(OH)_2} + 2O_2$$

In the ultrabasic rocks of the eastern Sierra Leone talc occurs separately and as pseudomorphs after anthophyllites (Dunham et.al. 1958). Jayaraman(1940) has described talc pseudomorphs after tremolite in the dolomite marbles of Yellandu, Warangal district. He has shown the progressive changes in the chemical composition of the tremolites, during the formation of talc.

In the present area the silica rich solutions provided by the pegmatitic intrusives seem to have played an important role in bringing about large scale steatitization.

6.5.4. PHLOGOPITIZATION

Phlogopite is formed by a metasomatic replacement of peridotite associated with the introduction of F,P,Ti and Co_2 (Deer et.al 1962). In the Day Book dunites of Yancy county, the development of phlogopite is related to pegmatite intrusives (Kulp and Brobst 1954). Here, the reaction between the pegmatitic fluid and the olivine of the dunite, produced an impure talc zone next to the unaltered olivine,anthophyllite asbestos next to the talc and ferrous phlogopite adjacent to the desilicated pegmatite. In the Pauni ultrabasics such zoning of the altered minerals has not been observed. The phlogopite occurs as a minor constituent in some of the assemblages associated with talc and chlorite. The phlogopite appears to have been derived from the talc,probably due to the addition of K,Fe^{+2}, Al and F from the pegmatitic fluids.

6.5-5. CHLORITIZATION

Chlorite minerals are present in varying amounts in most of the rock types,suggesting that chloritization has taken place widely on considerable scale. The predominant variety is penninite with subordinate amount of clinochlore. The chromium bearing variety kammererite occurs mainly associated with the chromitites. Field and laboratory evidences indicate that chlorite was the last mineral to form among the secondary silicates. It is quite reasonable to assume that the formation of chlorite has served to stabilize the Al_2O_3 and FeO released during the formation of earlier minerals.

In the ultrabasic rocks of Twin sister mountains,Washington, occurrence of chlorite has been explained by reorganisation of serpentine formed in through going fractures in the fresh dunites by the action of silica rich adsorbed water or water vapours(Gaudette-1964). The conversion of the serpentine to chlorite through reorganisation may be accomplished by only a slight increase in the activation energy of the serpentine. This could result from slight temperature increase, small changes in the pressure of the environment, or merely from the extended duration of geologic time during which such reorganisation might be accomplished.

The greatest amount of alteration of the ultrabasics, associated with the chromite deposits of North Carolina,has been caused by chloritization. The chromite masses are invariably associated with penninite and talc.Some chromite grains are completely enclosed in penninite.

In the bronzite peridotite at Nunyle,Western Australia,chlorite is common to most of the rocks affected by hydrothermal activity, particularly those containing serpentine. Here chlorite is considered to be derived entirely from the reaction of aluminous minerals with serpentine,or as a result of the introduction of alumina along veins into serpentinites(Elkington;1963). In this area chlorite was also formed by the hydrothermal alteration of pyroxene and probably olivine.

In the present area chrome-bearing chlorite (Kammererite) denotes that small quantities of chromium were dissolved in the hydrothermal solutions. However, the quantities of such redissolved chromium ordinarily seem to be rather small corresponding to the resorption of chromite grains contemporaneously with the formation of several reaction minerals. This phenomenon,however does not have any great quantitative importance.

6.5-6. CHERTIFICATION

The silicate mineral assemblages and the chromitites of the Pauni ultrabasics have been chertified at certain places. Field and laboratory evidences show that the chertification was the last of the hydrothermal alteration processes. It probably took place in successive phases as evidenced by the cutting across relations of the silica veins and their different stages of crystallization as observed in thin sections. The silica rich solutions responsible for the chertification appears to have been derived from three sources, (i) released product of earlier hydrothermal alterations,(2) residual pegmatitic liquids and (3),from the country rocks.

6.6. SUPERGENE ALTERATION

6.6-1. VERMICULITIZATION

Bassett(1961) has summarised the occurrence of vermiculites in ultramafic rocks, and concluded that they are exclusively to be in close association with pegmatites,or if in fractures away from the pegmatites these are apparently genetically related to pegmatitic activity. However, Basatt indicates that evidences are such that a supergene alteration from biotite or phlogopite now appears to be the most feasible explanation for the genesis of vermiculites. During vermiculitization alkalies are removed and much hydration takes place.

Problems associated with vermiculites have been investigated by Barshad(1948) who concluded that they were essentially micas with the K replaced by Mg or Ca. He recognized four types:(i) vermiculite as an alteration product of chlorite during the hydrothermal stage. (ii) vermiculite-biotite mixture (iii) vermiculite-chlorite mixture and (iv) biotite-chlorite mixtures. By utilizing the base exchange capacity he could convert three of these types in to biotite. The vermiculite-chlorite mixtures, however,while otherwise similar,were not so in this respect.

Gaudette(1964) advocates that the vermiculites associated with the dunites of Twin Sister Mountains, Washington seems to have been formed as a result of secondary alteration of chlorite or serpentine by sub-aerial weathering processes. The processes of alteration is summarised below:

$(Mg,Fe)\,SiO_4 + SiO_2 + 4H_2O$ (olivine)
↓
$(Fe,Mg)_5Si_4O_{10}(OH)_8$ (serpentine)
↓
$(Mg,Fe)\,Si_4O_{10}(OH)\;\;Mg_3(OH)_6$ (chlorite)

$6\,MgSiO_3 + 4\,H_2O$ (enstatite)
↓
$Mg_3Si_4O_{10}(OH)_2\;Mg_3(OH)_6$ (chlorite)

↘ Weathering ↙

$(Mg,Fe)_3Si_4O_{10}(OH)_2\text{-}(Mg)$
vermiculites

Dunham et al (1958) have reported that the vermiculites,in the chromiferous ultrabasic rocks of Eastern Sierra Leone is exposed in the surface pits,associated with the pegmatites,down to over 40 m.

below the laterite horizon.It is absent in deeper levels. Vermiculites of this area are ascribed to surface weathering of phlogopite and biotite. The Day Book Vermiculite deposits,Yancy County in N.Carolina occur in altered dunites intruded by pegmatites(Kulp and Brobst, 1954). These are considered to be a weathered product of phlogopite formed by hydrothermal changes.

According to Elkington (1963) the occurrence of vermiculite in the altered Bronzite peridotite at Nunyle,W.Australia,near two pegmatites indicates that hydrothermal action was involved in its genesis. An alternate view given by him is that the hydrothermal action gave rise to chlorite which on weathering was converted to vermiculite.

The vermiculite deposits of Hafafit,Egypt occurring near the contacts of pegmatite and serpentinites are considered to be of hydrothermal origin by Amin and Afia(1954).Similarly for the vermiculite occurrences at Phalabarwa,Africa,Gevers(1949) envisages the possibility of a hydrothermal origin for the mineral. The vermiculites associted with the ultrabasic rocks traversed by pegmatites at Kwekira,Tanganyika have also been attributed to a hydrothermal origin (Williams and Skerl,1940).

The vermiculites of the present area show similar mode of occurrence and association as in the above mentioned areas. The ultrabasic rocks have been intruded by a large number of pegmatites and granites;and vermiculites are generally associated near the weathered contacts. From the nature of occurrences and association it appears that the vermiculites of Pauni area are the products of supergene alteration of some chlorite rich portions of the hydrothermally altered ultrabasics.

6.6-2. LATERITIZATION

In the present area, the ultrabasics have been lateritized at places. It is of supergene alteration and is confined to the zone of oxidation. All the silicate minerals have been converted into limonite during this process.

6.7. GENESIS OF THE ULTRABASICS

Two main categories of ultrabasic rocks are recognized by geologists: (1) Stratiform ultrabasic complexes or Bushveld type (Daly 1928 ,Hall 1932,Peoples and Holland , 1940) (2) Alpine-type of ultrabasic intrusion of the primary peridotite suite occurring along orogenic belts(Benson,1926;Hess 1937,1938;Thayer, 1960).

A third group, intermediate between the above two, known as pseudostratiform-alpine type complexes, has been recognized recently (Smith, 1958;Thayer,1960).

Based mainly on the criteria suggested by Thayer(1960) the ultrabasic rocks of Pauni area have been compared with the alpine type and stratiform type in table 25. It is quite evident from this comparison that the ultrabasic rocks of the present area show much similarity to that of alpine type in respect of mode of occurrence, shape and size, structure and common hydrothermal alteration.

6.7-1. STRATIFORM TYPE

Wager and Deer (1939), Cameron and Emerson(1960), Hess(1960) Jackson (1961), and many others have described stratiform ultrabasic complexes which have been formed by crystallization differentiation of a magma of basic composition. Other workers believethat many of the stratiform complexes were formed due to multiple injections of magmas drawn at intervals from a concealed reservoir. Differentiation in place can account for some of the large scale oscillations observed in the stratified lopolith of the Bushveld igneous complex (Lombard,1934). Similarly in the Great dyke of S.Rhodesia, Worst(1958) believes that the magma of the dyke was emplaced in many surges of inflows. The variations in the rock types of the Union Bay Complex, Alaska, have been explained by Ruckmic and Noble(1959) as due to intrusion of successive gabbroic, pyroxenic and dunitic magmas.

According to Kennedy(1955) a basaltic magma, crystallizing under different conditions such as variation in the partial pressure of oxygen, could be made to follow different trends in the differentiation giving igneous complexes.

6.7-2. ALPINE TYPE

The genesis of alpine type of ultrabasic rocks(as established earlier the Pauni ultrabasics belong to this category) is a debatable problem. In this regard, there are three main schools of thought

(i) Ultrabasic intrusions as magma.

(ii) Emplacement of peridotite material in the form of crystal mush.

(iii) Intrusion or even extrusion of basaltic material and their differentiation.

(i) Ultrabasic intrusions as magma

It was first advocated by Durpac(1920) and supported by Benson (1926). Later Hess (1938,1948,1955) elaborated the theory. He believed that the ultrabasic bodies were formed by magmatic intrusions (hydrous peridotite magma-serpentine magma).He has described parallel belts of serpentine intrusion which are concentrically zoned and are freeof chromite. Wilkinson(1953) in his study of alpine type of serpentinites of Queensland,has supported Hess and has produced evidences in favour of the fluidity of the ultrabasic magma. Watson(1951) has proposed the intrusion of peridotite magma in the Blashkel Islands complex. The concept has also been supported by Little(1949) Heissleitner (1957), Wijkerslooth(1954) Schmidt(1954 and Noble and Taylor (1960).

The lack of contact metamorphism around the alpine type of ultrabasic rocks,seems incompatible with any hypothesis involving intrusion of largely liquid magma.Rapid cooling also cannot explain this phenomenon because petrological evidences show overwhelmingly that cooling conditions were slow. This is expressed by the grain size of chromite and the silicates,which is in general much coarser than that of the layered complexes showing high temperature contact metamorphism.Rapidly cooled rocks and chilled margins are lacking near the contacts of alpine type ultrabasic rocks.

An alternative suggestion has been given by Turner and Verhoogen (1960) for the absence of contact metamorphism which might reflect inward flow of water from the country rock into the hot intrusion of ultrabasic magma.

(II) Emplacement of peridotite material in the form of crystal mush.

On the basis of observations on experimental studies of the mineral assemblages akin to ultrabasic minerals, Bowen and Tuttle (1949) concluded that the ultrabasics can intrude only in a solid state, since a magma of peridotite composition cannot exist below 1000°C, a temperature certainly not in accord with observations of metamorphism at the ultrabasic contacts. The system $MgO-SiO_2-H_2O$ has been studied by them at pressures well above, 2,000 atm and at temperatures upto 1,000°C but no liquid was formed at any composition, indicating that the fluxing of water is unable to effect melting of any mixture of magnesium silicates upto 1,000°C and that there is no likelihood of a natural magma. Bowen and Tuttle think that there is no escape from the conclusion that ultrabasics (alpine type) can be intruded only in a solid state.

Ross, et.al, (1954) came to the conclusion that diverse approaches to the problem of the origin of dunite and related rocks, seem to present convincing evidence that the rocks were formed by the intrusion of a largely mush like material and that this material was made up essentially of olivine. The relationship indicates that the peridotite substratum is the source of such unusual material. But they also state that some dunites and related rocks show relationships with basaltic rocks and evidently had a different genetic history, as for instance, in the case of Stillwater Complex.

The concept of crystal mush intrusion explains better the observed world wide phenomenon of the absence of metamorphic effects of even large bodies of peridotites of the alpine type. The lack of contact metamorphism on the country rocks is explained, if it is assumed that the fluid constituted only a few percent of the total peridotite mass. The energy set free by crystallization would then be very small and in that case the borders of the emplaced mass would be rapidly cooled into the temperature stability ranges of serpentine and any significant inflow of water from the country rock would inhibit or prevent contact metamorphism(Thayer,1960). The concept has been further supported by Flint et.al.(1948), Wells et.al.(1949) and Stoll (1958).

The structural and textural features of chromite deposits are in favour of this concept. Chromite bodies were brought up in solid conditions along with the silicate crystal mush. Intrusion in semi-solid condition is evidenced by extreme deformation by folding, rupture and shearing inside the body and shearing and thrusting along the borders as for example the Singhbhum ultrabasics(Singh,1966). Similar evidences have also been noted in the present area (Table 25).

(III) Intrusion or even extrusion of basaltic material and their differentiation.

This concept envisages intrusion or even extrusion of basaltic material originating below the Mohorovicic discontinuity and differentiation in laccolithic bodies. They are similar to the layered complexes where gravitation fractional crystallization took place in situ with an eventual effusive character of ophiolite magmas. Supporters of this concept are Bailey and McCallien(1963)Kundig (1954) and Borchert (1960,1961) and Challis and Launder (1966).

If the original magma was basaltic a large portion of acidic components should be associated with the ultrabasic differentiates as is observed in the stratiform complexes. This is not so in the case of alpine types. In the case of extrusion of basaltic magma, cooling would be too quick to allow any differentiation. Moreover, the structural and textural features of the ultrabasics along with the chromite ore bodies do not support this concept.

There are other concepts which however, have not gained much support such as(a) Emplacement of solid peridotite material from the peridotite substratum. Emplacement of the rocks took place in crystalline state without any fluid medium. Deformations took place in depth by metamorphic processes and flowage(Ross 1959,1961:Rost 1959).
(b) Intrusion of basaltic magma forming stratiform complexes in depth. In a much later geological epoch they involved in alpine tectonic movements (Helke,1962;Donath 1962).

(c) Ultramafic complexes were formed as the effect of a local basification and rheomorphic mobilisation of rocks in the basement complex of a rising front of acidification and anatexis. This is supported by Van Bemmelen (1960). He believes that it is also possible that tensional rifting in the geosynclinal area promoted the ascent of basic to ultrabasic magma from deeper levels in the substratum.

(d) The formation of ultrabasic rocks by metasomatism has been advocated by French workers. Perrin, Roubault and Ariens(1953) and Avias (in Sorensen 1967)have interpreted the concordant peridotites of New Caledonia as products of metasomatic transformation of basaltic lavas. The ultrabasic rocks are considered by Avias to have been formed by progressive concentration of Mg,Fe,Ni and Cr possibly as a result of high stress. Si,Al,Ca and Na were expelled to the adjacent rocks.

(e) Ultrabasic rocks as a product of metamorphic differentiation possibly caused by tectonic over pressure,has been advocated by several workers like Barth(1947),Ramberg(1952),Sorensen(1953,1967), Mikkola(1955),Bennington(1956) and Oen(1962). Bennington from a study of equilibrium conditions of serpentine mineral assemblages has opined that the ultrabasic rocks are the residual product of extreme metamorphic differentiation under high pressure and strong shearing stress. According to Reitam and Oen(in Sorensen,1967), the peridotites from Caledonides of N.Norway,were formed under special physico-chemical conditions in zones of high pressure,where the formation of minerals with small mol volumes such as forsterite and enstatite,is favoured.

The above views on metasomatic and metamorphic origin of ultrabasic rocks have gained acceptance only with regard to local occurrences in particular environments. Evidences in support of metasomatic and metamorphic origin for the ultrabasics of the present area are entirely lacking.

6.7-3. PSEUDOSTRATIFORM ALPINE TYPE COMPLEXES

These are intermediate in character between the stratiform and alpine type complexes discussed earlier. Thayer(1960) regards the Bay of Islands and Camaguey complexes as examples of these as they resemble the stratiform in distribution of gabbro and peridotite,but have all the fundamental characteristics of the alpine types.Smith(1958) considers the Bay of Islands complex to be of this type due to the following reasons:

"(1) although, layered gabbroic rocks overlie peridotite,in many places they are not conformable and there is no cryptic layering;(2) gabbroic chill rocks are lacking but the country rocks show moderate thermal metamorphism; (3) the ultrabasic rocks exceed the gabbros in volume; (4) flowage phenomena are prominent in places;(5) the plutons are wedge-shaped instead of lopolithic in form".

6.8 THE PAUNI ULTRABASICS

On the basis of above discussions and the field and laboratory evidences, the following conclusions have been drawn for the genesis and emplacement of the Pauni ultrabasics.

(i) Though the primary structures, textures and mineralogy of the ultrabasics have been largely obliterated by later deformations, igneous activities, and hydrothermal alterations, they show characteristics of alpine type (Table 25).

(ii) The ultrabasic bodies were derived from a deep seated primary peridotite magma which crystallized and partly differentiated by fractional crystallization at depth into chromitites and other olivine and pyroxene bearing bodies (The composition of this magma cannot be deciphered due to various stages of hydrothermal alterations).

(iii) The differentiates intruded the country rocks in a semi-solid conditions as evidenced by folding,x rupture and shearing inside the body. Lack of contact effects supports that the bodies intruded at a low temperature.

(iv) The bodies were emplaced during the earlier stages of first fold movements (F_1) and the localisation was controlled by the axis of a major fold (The major ultrabasic zone occupies the axial region of a synform fold).

(v) The ultrabasics intruded mostly as small discontinuous, lenticular concordant plutons along the weak zones of the country rocks.

(vi) Later deformations and hydrothermal activities have been responsible for the present shape, form, size and composition of the Pauni ultrabasics.

CHAPTER - VII

CHROMITE DEPOSITS

7.-. INTRODUCTION

Chromite has a unique position in the wide range of ore minerals because of its occurrence as the only kind of ore mineral of chromium, and further the ore in its turn is restricted genetically to the ultrabasic rocks. In the Pauni area chromite grains have concentrated to form deposits in several small ultrabasic bodies. The degree of concentration of chromite grains varies widely from few disseminated grains as accessory constituents to massive ore composed almost entirely of chromite. Bodies forming rich concentration of chromite have been termed as chromitites,being one of the rock units of ultrabasics.

7.2. LOCALISATION OF ORE BODIES

The chromite deposits of Pauni occur in the ultrabasic zone lying 1 Km. northwest of the town. The chromite bodies,proved and exploited so far, are concentrated in a belt at three places,about 800 m. apart from each other. This chromite belt trends ENE-WSW from Nilkanteswar temple on the bank of the Wainganga in east to Nimgaon in west. There are four main quarries which lie along this strike (Map 2). The chromite belt occupies roughly the central part of the area covered by the ultrabasic bodies. Field evidences indicate that this chrome bearing horizon lies along the axis of a major synform fold of the country rocks. Towards north and south of this central belt the ultrabasic lenses are smaller in size and occur at wide intervals containing occasionally very small uneconomic chromite lenses.

As all the primary silicate minerals have been altered in the ultrabasics, it is not possible to associate the chromite bodies with any particular rock types. However, it has been observed that the chromite deposits are dominantly associated with the steatitised ultrabasics.

It has been found that the ore bodies are invariably associated with the isolated ultrabasic lenses and broadly conform with the disposition of the parent rocks. Though the emplacement of the ultrabasic bodies has been controlled by the major fold axis there does not appear to be any structural control in the localisation of chromite bodies. Some deformations of the chromite bodies like splitting, dissemination, pinching and minor discordance with the parent rocks appear to be due to flowage of magma during their emplacement. Further, they were deformed by shearing, faults, and folds and later intrusives after their emplacement. At a later period the hydrothermal alterations have affected the entire ultrabasic mass, and thus the alteration does not bear any relationship with the localisation of the chromite deposits. Hence it has been concluded that the chromite deposits are of pre-tectonic and pre-hydrothermal changes.

7.3. STRUCTURE, SHAPE, SIZE AND NATURE OF THE BODIES

Broadly, the chromite bodies of Pauni area can be classified as lenticular bands. These can be further subdivided as (i) banded, including the schlieren and gneissic banded types, (ii) lenticular

PLATE No.XVI

Field Diagrams

Fig.No.56 Section - Discontinuous chromite lenses in the ultrabasics. Lenses of the ultrabasics are observed in the chlorite-schists. Location - Pit 3, Quarry 2.

Fig.No.57 Section - Small chromite lenses in the ultrabasics.Location - Pit 3, Quarry 4 (Modern Plastic's claim).

Fig.No.58 Plan - Chromite lens showing bifurcating, enclosing talc tremolite schist. Location - Pit 2 , Quarry 3.

Fig.No.59 Chromite lenses showing pinching out character. A folded chromite layer in the upper portion. Location - Pit 2, Quarry 3.

Fig.No.60 Plan - Several thin chromite bands and stringers adjacent to a chromite lens. Location - Pit 3, Quarry GCS(Modern Plastic's claim)

Fig.No.61 Section - Thin folded bands of chromite and associated ultrabasics. Location - Pit 6, Quarry 1.

Fig.No.62 Section - Fault displacing the ultrabasics, chromite body and other associated rocks. Location - Pit 3, Quarry GCS(Modern Plastic's claim).

Fig.No.63 Plan - Pinch and swell structure of a chromite lens -Location- Pit 5, Quarry 4(Modern Plastic's claim).

Fig.No.64 Section - Stringers of chromite in the ultrabasics. Location Pit 1, Quarry 3.

Fig.No.65 Section - Chromite lenses extending into the residual soil cover. Location - Pit 3, Quarry GCS (Modern Plastic's claim).

Fig.No.66 Section - Pegmatites intruding the chromite bodies. Location- Pit 6,Quarry 1.

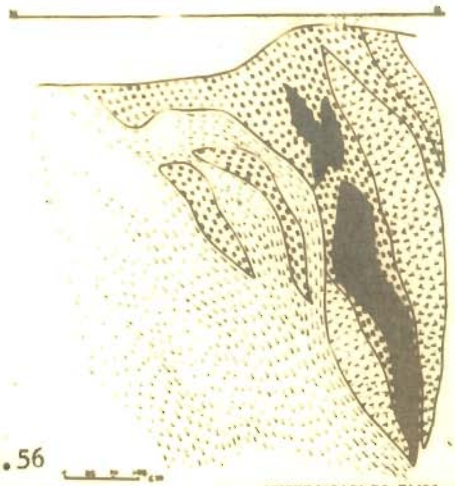
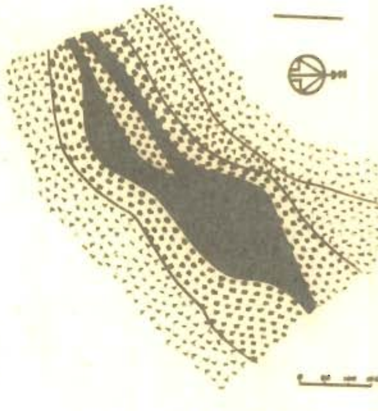


Fig.No.56

Fig.No.57



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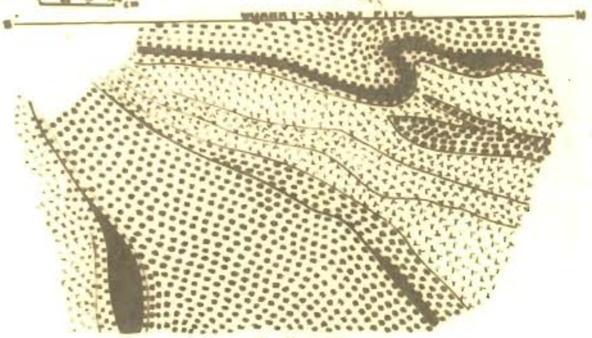

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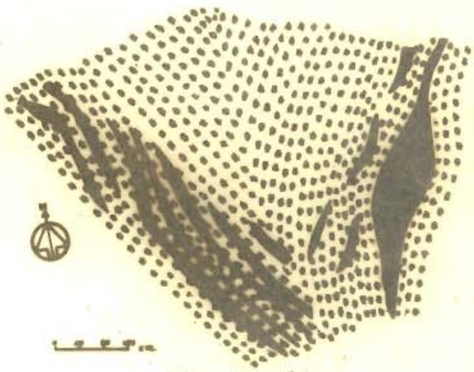

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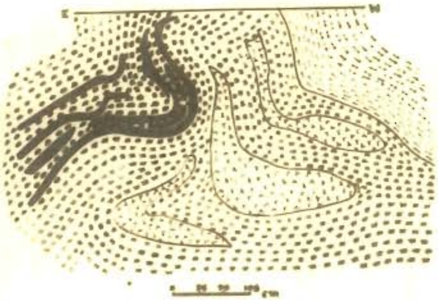

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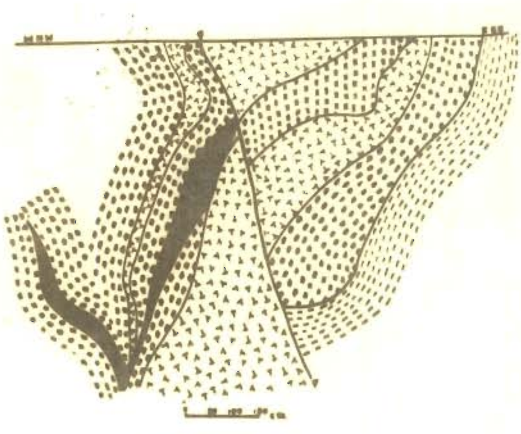

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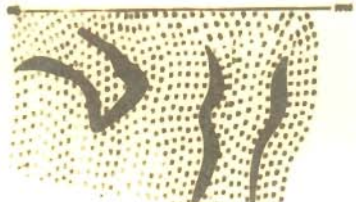

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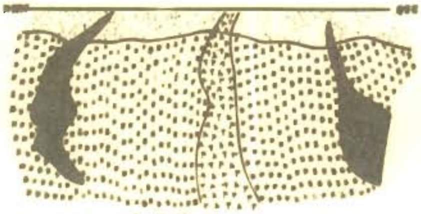


Fig.No.65

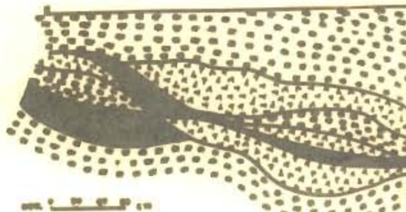


Fig.No.66

types and (iii) disseminated types . The ore bodies generally vary in length from 0.30 m. to over 50 m. and in width 0.5 m. to as much as 2 m. Minor occurrences of pockets,pods and stringers are also found. All these types of deposits together fall under the group described as 'podiform type' by Thayer (1963,1964). Podiform chromite deposits are defined as fundamentally lenticular concentrations of chromite ranging from massive to disseminated type. Further this type of chromite ore bodies is characteristic of the alpine-type of'ultrabasics. In the Pauni area the massive lenticular type is most common and important from economic point of view.

The ore bodies are irregularly disposed along both their strike and dip and show pinch and swell structure. Irregular folding and displacement due to faulting of the ore bodies are often observed (Figs.61 ,62). Repetition of the chromite bodies due to folding and faulting has taken place at close intervals. The bodies have been subjected to much shearing stresses. Four to five major sets of joints are noticed in the majority of the ore bodies (Fig. 97). The joint planes generally show a thin coating of secondary silicate minerals like talc or silvery grey micaceous chlorites. These planes generally show striations indicating movements along them .Many of these joints are closely spaced at 5 to 10 cm. intervals. Small pieces of ore in geometrical shapes as rectangular and pyramidal blocks come off easily on gentle breaking (Fig.109). The ore is easily separable along the joint planes,hence the exploitation of ore does not involve blasting or heavy tools. In some of the ore bodies shear planes are curviplanar. Small blocks separated

PLATE No.XVII

BLOCK DIAGRAMS

Fig.No.67 Discontinuous lenticular bodies of chromite. These lenses are parallel to the enclosing ultrabasics. Location-Pit 1,Quarry 2.

Fig.No.68 Chromite lens showing variable thickness. An 'island' of ultrabasics seen in the chromite body. Location - Pit 2, Quarry 3.

Fig.No.69 Abrupt pinching of a chromite lens. Location- Pit 6,Quarry 1.

Fig.No.70 Vertical and oblique sections of a chromite body intruded by pegmatites. Location- Pit 6, Quarry 1.

Fig.No.71 Cylindrical chromite body. Location- Pit 5, Quarry 4. (Modern Plastics claim)

PLATE No.XVII

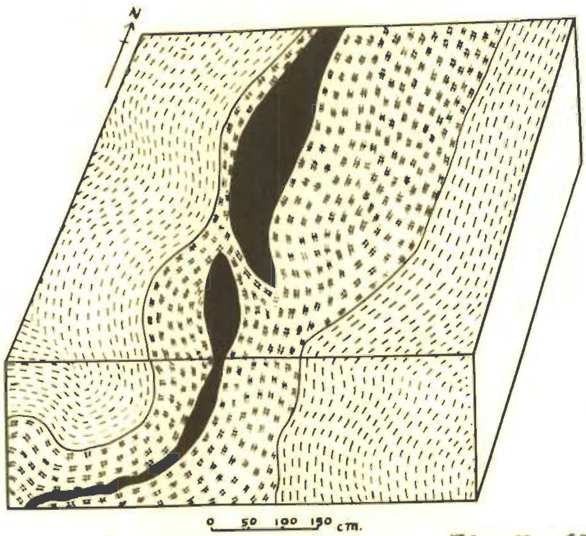


Fig.No.67

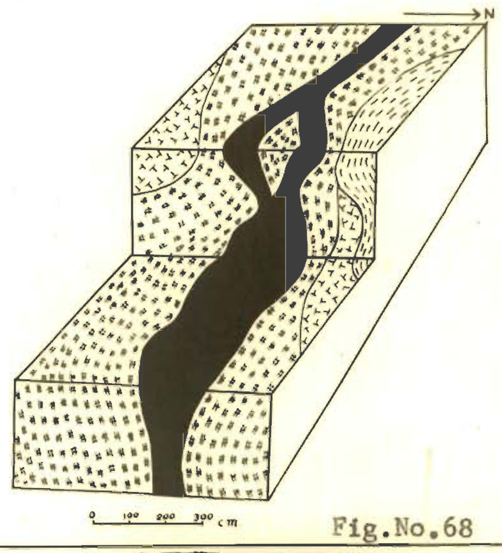


Fig.No.68

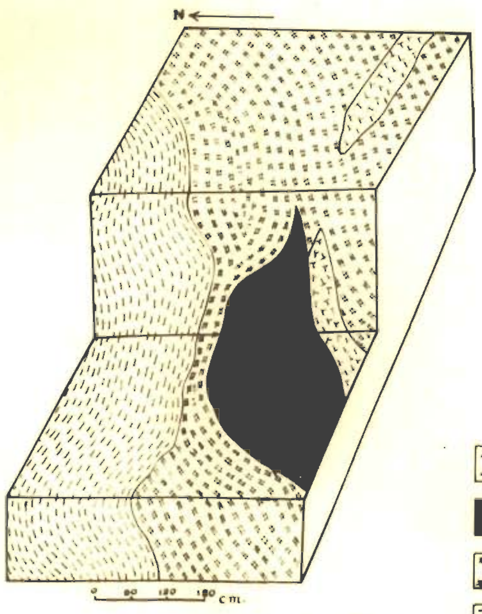


Fig.No.69

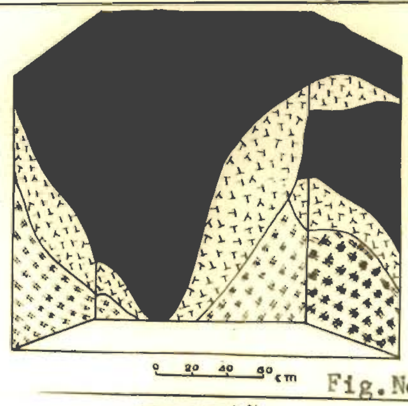


Fig.No.70

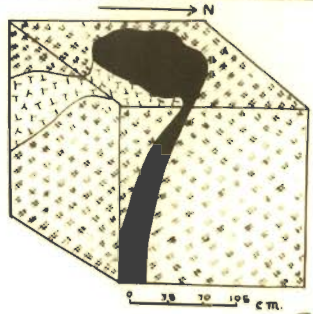
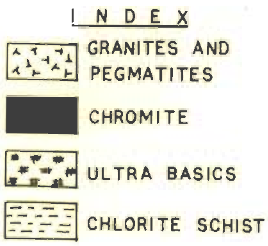


Fig.No.71



from such bodies give semirounded to rounded surface devoid of angular edges. Less commonly spheroidal pieces with a coating of silicates occur, which have been termed as "chromite balls"(fig.111).

Some of the ore bodies bifurcate or split and after some distance again join, enclosing pockets or lenses of gangue minerals (figs.58,68). Although bounded sharply on the sides, deposits grade out laterally into stringers or may end abruptly (figs.69,96). Some ore bodies may grade from massive high grade ore on one side to low grade disseminated type on the other side. However, no consistent pattern on top and bottom or on hanging wall and foot wall is seen.

Chromite lenses occur in the ultrabasics as disconnected bodies similar to the occurrence of its parent rock in the chlorite-schists. Wherever the lenses are less disturbed tectonically, the long axis of one lens may indicate the presence of another lens along the strike direction. The distance between the lenses may vary. The lenses, though pinch out after some distances along their strike, are sometimes connected by trails of small concentrations of chromite grains. Some of the chromite bodies gradually merge with the enclosing ultrabasics.

7.4. TYPE OF ORE

The following types of chromite are found in the area:

(i) Massive granular type (non-banded); (ii) Banded (including schlieren banded) type; (iii) Disseminated type; (iv) Miscellaneous types including float ore, lateritised ore and chertified ore.

TABLE -27

MODAL ANALYSIS OF CHROME ORE SAMPLES

Serial No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Specimen No.	1/621	1/614	1/610	1/670	1/620	1/606	1/586	1/591	1/540	1/13	1/59	1/11	1/15	1/618
Chromite %	83.65	80.21	87.13	84.54	86.62	90.75	86.09	82.48	92.39	91.21	88.78	88.56	89.06	84.48
Gangue %	16.35	12.95	12.87	15.46	13.38	9.25	13.91	17.52	7.61	8.79	11.12	11.44	10.04	15.52
Gangue minerals	CHL. TA.	CHL. TA.	TA. SERP. QUA.	CHL.	TA. SERP.	SERP. TA.	SERP.	TA. SERP.	TA. SERP.	SERP TAL.	TA CHL.	SERP	TA	TA CHL.

Serial No.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Specimen No.	1/2	1/533	1/604	1/581	1/569	1/121	1/53	1/6	1/85	1/699	1/86	1/668	1/561	1/599
Chromite %	97.08	86.25	88.62	90.66	74.77	76.78	60.69	51.31	72.48	54.42	68.21	69.96	75.04	68.43
Gangue %	2.92	13.75	11.38	9.34	25.23	23.22	39.31	42.60	27.52	45.58	31.79	30.04	24.96	31.57
Gangue minerals	CHL.	CHL. TAL.	TA. QUA.	TA. SERP.	TRE. TA.	TRE. CHL.	CHL. TA.	CHL. TA.	TA. CHL.	TA. TRE.	TA. CHL.	TA. SERP.	CHL.	TA. CHL.

Serial No.	29	30	31	32	33	34	35	36	37	38	39	40	41
Specimen No.	1/52	1/8	1/59	1/76	1/7	1/62	1/58	1/652	1/495	1/54	1/608	1/61	1/12
Chromite %	73.96	51.27	77.59	59.44	67.36	75.77	50.19	75.69	53	50.32	49.70	31.25	71.33
Gangue %	26.04	48.73	22.41	40.56	32.64	24.23	49.81	24.31	47.	49.68	50.30	68.75	28.67
Gangue minerals	TRE.	TA. CHL.	TA. CHL.	TA. CHL.	CHL. TRE.	TA.	TA. QUA.	TA. CHL.	TA. CHL.	CHL.	TA.	TA.	TRE. TA.

CHL. - Chlorites TA - Talc SERP - Serpentine TRE - Tremolite QUA - Quartz-chalcedony

Further the chromite ores can also be classified on the basis of their minerals into the following types of chromitites:

(i) Talc-chromitite (ii) Chlorite-chromitite. (iii) Tremolite-chromitite. (iv) Serpentine-chromitite. (v) Talc-chlorite-chromitite. (vi) Talc-tremolite-chromitite. (vii) Talc-serpentine-chromitite. (viii) Tremolite-chlorite-chromitite. (ix) Chlorite-phlogopite-chromitite (x) Chert (chalcedony) chromitite.

Table 27 shows the modal analyses of some of the representative ore samples with their respective percentages of chromite and gangue minerals. The character of gangue minerals associated with the ores has already been described in chapter VI.

Massive or granular type - Close aggregates of chromite grains with minor interstitial gangue has given rise to massive ore. There are several grades of ore depending upon the ratio of the ore-mineral and the gangue. Generally the amount of gangue varies between 15 to 25% (Table 27). Massive ore with less than 3 percent gangue (by volume) has been occasionally found in the quarries. The ore generally shows a dull black or dull greyish black colour. Some ores with minor gangue exhibit a shining black or pitch black colour. The specific gravity of the massive ores varies between 3.3 to 4.25. Megascopically the chromite ores are fine to medium grained. As mentioned in a later part of this chapter the original coarse grains appear to be smaller due to fracturing and fracture filling by the gangue minerals. Few small ore bodies give a compact massive appearence. At places due to shearing the ore has been mylonitised and the crushed particles are closely packed together along the shear planes. Some of the ores are soft and easily disintegrate due to the higher amount of weathered gangue minerals.

In thin sections, the ore shows fractured fragments of anhedral and polygonal chromite grains (fig.1,156). The fractured fragments together show 'pull apart' texture (refer page196). The interspace between the fractures has been pushed aside and filled with silicates. The opposite walls are mutual and match well if joined together (fig.154). Many fragments of the chromites show embayed borders and effects of resorption (fig.158). In the ordinary light the chromite grains are dark opaque, or masked by blood-red or brownish red colour. Many grains show transluscent fringes of dark brown colour. Rarely the grains are transluscent with yellow to brown colours. Under reflected light in thin section the grains exhibit grey colour with a red tint and sub-metallic lusture. Dull black patches are often observed.

<u>Banded type</u> - Banded type of ore is of restricted occurrence. It includes the normal banded types with continuous layers, lenticular banded and schlieren banded types. In the normal banded types the bands of segregated chromite are separated by silicate bands with disseminated chromite or by barren silicate layers. The banding is planar and rhythmic (fig.115-117). Generally the chromite bands are between 0.5 to 2 cm. thick. Less commonly it reaches upto 5 cm. These chromite bands contain 20 to 30 percent gangue by volume. The alternating silicate bands vary from 0.2 to 2 cm. in thickness. In few of these banded types the alternate chromite layers or silicate layers converge at some points. In some of the banded types, the silicate layers appear to be of secondary

origin as these layers are not persistent and are devoid of chromite grains.(fig.118).

In the schlieren banded types, the bands are very thin and their boundaries are transitional and ill-marked (Fig.119). They are generally persistent for short distances and at times are contorted (fig.120). It is difficult to separate the individual bands. The percentage of gangue minerals is quite high (30-40%). The schlieren banded type is of minor occurrence in the present area, and is generally found associated with normal banded types.

Many closely spaced lenticles and streaks of chromite are found in the ultrabasics as impersistent bands (fig.121).Small parallel to sub-parallel lenticles containing 40-50% chromite grains, are observed in the silicate mass. Many of these lenticles show contortions. Their thickness varies from 0.5 to 2.0 cm. and laterally the individual lenticles range between 5 to 10 cm.

In thin section the bands of chromite consist of fractured fragments with corroded and embayed borders enclosed in the secondary silicates. The fragments show incipient fractures. In the ordinary light chromite grains show dull black colour with a reddish tint. The gangue minerals around the chromite grains exhibit a yellowish brown staining. Under reflected light in thin section the chromite grains are greyish black with sub metallic lustre.

(iii) Disseminated type. The chromite grains are disseminated in the ultrabasics in various proportions from a few scattered grains to as much as 30 percent. In some specimens the chromite grains form incipient parallel banding. This type of ore grades into schlieren and normal banded types.

In thin section the chromite is generally fine grained (0.5 -1 mm) and many of them exhibit euhedral outlines (fig.148). Due to resorption their borders are ragged. As compared to other types, fracturing of the individual grains is much less in this type of ores. This is presumably due to abundance of soft silicates making the ore comparatively incompetent. Many chromite grains in the form of relict patches are surrounded by clusters of chlorite flakes (fig.147). Other properties are similar to the chromite already described in massive ores.

(iv) Miscellaneous types

(a) Chertified ores - These ores are confined to certain pockets in quarry No.1 and 2 (S.C. Shukla's claim). Generally the amount of chromite is less than 50% in these ores. Some of the chertified ores have several cavities containing cryptocrystalline silica (chalcedony) on the walls.

In thin sections, separated fragments of chromite grains are observed in a ground mass formed mostly of cryptocrystalline silica with relict talc and few flakes of chlorite. Some of the fragments show rims of chalcedony showing colloform texture. Silica has replaced partly or wholly the silicate minerals occupying the fractures of chromite. In ordinary light the chromite fragments are dark opaque and under reflected light brownish black colour. Rims and fringes of the fragments exhibit orange red or reddish yellow colour.

(b) Float and lateritised ore - This type of ore is found in the zone of oxidation particularly in the soil cover either as stray pebbles and boulders or as thin laterite cover in the weathered part of the deeper chromite lenses. Broken faces of the ore show a reddish brown coating. Microscopic study has shown that while the gangue minerals were limonitised the chromite grains remained unaffected.

7.5. TEXTURE OF THE ORES

The following paragraphs deal with the texture, grain size, shape, fracture and the interrelations among the chromite grains and the interstitial silicates, as observed in polished sections under reflected light.

7.5-1. PRIMARY TEXTURES

Primary textures in most of the Pauni chromite ores have been completely obliterated. Many of the crystal fragments show embayed borders with the interstitial silicates (fig.158). Some of the fragments exhibit corroded or ragged outlines while many others retain sharp outlines. In a few unfractured or less fractured ores the original polygonal outlines are still well preserved, showing hypautomorphic granular texture. Primary banded texture is also noted in some ores, Some chromite grains show exsolution intergrowth with hematite(fig.159)

Hypautomorphic granular texture   Coarse grained, polygonal hypautomorphic and subrounded chromite are clustered together with thin films of silicates along their interspaces. The grain boundaries are mutual (fig.156).

Banded texture is observed in thinly banded ores. Thin bands of chromite grains are separated by silicates. The contacts between silicates and chromites are irregular, showing corrosion and embayments by silicates.

Exsolution texture - In some ores chromite grains show parallel streaks and lamellae of hematite along octahedral planes (discussed later in page 99).

7.5-2. SECONDARY TEXTURES

Pull apart texture

The massive ore consists of fractured fragments of original polygonal to anhedral grains of chromite. The chromite grains in these ores are angular to subangular fragments rather than crystals. Since the texture seems to have been formed by pulling the chromite grains apart it is referred as pull apart texture (Thayer, 1963). The walls of the fracture have been pushed aside and the interspaces have been filled with secondary silicates (fig.154). The opposite walls are mutual and match well if joined together. For similar texture Fisher (1929) has given the name mitred structure, and related it with the hydrothermal changes in the gangue minerals.

Cataclasm and resorption

The microscopic examination reveals that the ores show in common two facts: cataclasm and resorption. The cracks and fissures originated by these forces are filled with secondary silicates. Two different stages of resorption are distinguished. The first stage is related to the formation of the ores during magmatic stage (magmatic corrosion) and the second resorption is related to hydrothermal changes accompanied by the crystallization of new minerals. Although the first resorption is not uncommon in the Pauni ores, the second type is more remarkable and ubiquitous. Generally the second resorption has obscured the features of the first resorption.

Nearly all the grains have been separated into fragments due to cataclasm and fracture filling (fig.152). As the chromite grains are highly fractured and the fractures have been filled by silica and silicates, it is difficult to delimit the boundary of the original grains. In many ores smaller fragments are close together, separated from each other by thin film of silicates. In such cases it is difficult to infer whether these are fractured fragments of bigger grains or they represent independent smaller grains. The grains (fragments) of chromite vary in size from 0.3 mm. to 3 mm.

Cataclastic texture is the most prevalent texture exhibited by the chrome ores of Pauni. Many of the massive ores which have been subjected to intense stresses show cataclastic or brecciated texture (fig.153). This represents an aggregate of several small angular fragments separated by the gangue minerals. In the disseminated ores the grains are less fractured than in massive ores.

Fracture patterns

As mentioned earlier, the chromite grains were subjected to stretching (tensional forces) during the time of emplacement, causing systematic fracturing normal to the direction of maximum tension. This gave rise to pull-apart texture. Later, due to post-emplacement tectonic activities the chromite was subjected to different degree of fracturing. Variations from unfractured or less fractured ores to highly brecciated or mylonitised ore are observed (figs.150-153). Photomicrographs show the different degree of fracturing suffered by the chromite ores. Different stages of fracturing are discerned, as the later fractures have affected the earlier ones by displacement or by cross-fracturing (fig.151). Curved patterns, warping and bending of the fractures are common. These patterns of fracture have probably resulted due to rotational movements during deformations (fig.152).

Irregular fractures are more common than regular fractures i.e. they are not parallel or straight and continuous. Triangular pits are observed along certain fractures. However, they are not as systematic or distinct as often noted in galena.

Two major sets of fractures are observed in less disturbed ores, while one set is prominent and have affected all the grains, the other set cross or oblique fractures, is impersistent and extends for short distances (fig.151).

Fracturing of the individual grains have been partly controlled and conditioned by the shape and the size of the chromite grains and partly by the shape, size and amount of the gangue minerals around the chromite grains. Some smaller unfractured or less fractured grains are found associated with the highly fractured grains. The former might be the original (primary) smaller grains; while the latter representing the surrounding coarser grains suffered much fracturing. The amount of gangue present affecting the brittleness and toughness of the ore body is also an important factor in the degree of fracturing suffered by the chromite grains eg. in the disseminated chromite ores where the gangue minerals are more abundant the fracturing is less, and in the massive ores where the gangue is in minor amount the fracturing is intense.

In some of the ore sections thin irregular bands or veins showing intense granulation and brecciation are observed in the coarser fractured grains. These intensely crushed portions probably represent microfault planes or shear zones. Mitra(1967) has mentioned similar observations in the chromite ores of Sukinda,Orissa.

7.6. OTHER ORE MINERALS

Hematite

Some of the chromite grains show thin parallel streaks of hematite which is white in colour and of high reflectivity with strong anisotropism (fig.159). This appears to have developed along the octahedral cleavage planes of chromite. The streaks or lamellae of hematite are confined to certain grains and are of variable length. The lamellae are seen mostly in one direction; less commonly in two directions and rarely along three directions. The acute angles subtended by different exsolution lamellae of hematite show wide variation between 22° to 90°.

In some of the ores stringers and patches of secondary hematite have developed along the streaks of the primary hematite. They have grown on either side partly replacing the chromite (fig.159). Ragged borders and their irregular width strongly suggest that these are of replacement origin.

The replacement of the exsolution lamellae probably took place during the hydrothermal stage. The hematite lamellae of the chromite is considered to be of high temperature origin and the secondary hematite replacing this ore is a low temperature variety. Chromite-hematite exsolution intergrowth has been observed in the ores of Kankauli and Vagda Ratnagiri district, Maharashtra (Chakravarty and Guha, 1961).

Minor amounts of secondary magnetite, pyrite and goethite are associated with the gangue minerals in chromite ores. These are considered secondary because of their close association with the secondary minerals. They are distinctly observable under high magnification.

Magnetite- occurs as specks, irregular grains and streaks along the cleavages of some of the gangue minerals.

Pyrite is observed as several tiny idiomorphic grains, specks, and granules in individual and aggregate forms, in the gangue minerals.

Goethite is observed in a few ore sections. It occurs as fracture fillings in the silicates and as rims and veins along the contacts of chromite and the gangue minerals. It appears to be of supergene origin.

CHAPTER - VIII

CHEMISTRY OF THE CHROMITES

8.1. INTRODUCTION

The chemical composition including the major and the trace elements of Pauni chromites was investigated for the following objectives:(i) to determine whether these chromites exhibit the characteristics of true spinels over a wide range of composition; (ii) to find out whether there is any marked variation in their constituents in different orebodies and in different types of ores; (iii) to examine the effects of hydrothermal changes in the ore bodies.

The chemistry of chromite is often not well understood, especially with regard to the variations of FeO,Fe_2O_3 and the ratio of RO to R_2O_3. Based on studies of the chemical constituents of chromite and their structure many workers have given different views on these variations. The present investigator felt it imperative to pool these views together and present the chemistry of chromite in a proper perspective. Further, this would help in the correct interpretation of the chemical data of the chromite from the Pauni area and to correlate these with the genetic history of the deposits.

8.2. CHEMISTRY OF CHROMITE

Chromium occurs as a concentrated constituent in abundance in the ultrabasic rocks such as dunites,peridotites,and pyroxenites.

The concentration of chromium in igneous rocks decreases progressively as the basicity of the host decreases. In the ultrabasic and basic rocks the bulk of the chromium along with some alumina, iron and, magnesium form chromite and other chrome spinels. In other rock types, chromium occurs as a minor constituent of magnetites, and silicates like uvarovite (chrome-garnet), chrome diopside, tawamanite (chrome-epidote), fuchsite and mariposite (chrome-micas), kammererite and Kotschubeite (chrome-chlorites). Other silicates like olivine, amphiboles, pyroxenes and mica may contain quantities of chromium in excess of 1,000 ppm.

Chromite belongs to the spinel group and like most of its members is an isomorphous mixture of different oxide end members, with varying chemical composition. Bragg (1915) and Nishikawa (1915) analysed the structure of spinel ($MgO\ Al_2O_3$). The basic structure consists of layers of oxygen atoms approximately in cubic close packing, with tetrahedral and octahedral positions between the large oxygen anions. R^{2+} cations occupy tetrahedral sites and R^{3+} cations occupy octahedral sites. There are 8 tetrahedral, and 16 octahedral positions in the spinel unit cell. Substitution among the R^{2+} and among the R^{3+} ions which have differing ionic radii, changes the dimension of the unit cell, the refractive index and the colour. The above parameters represent the chemical composition of the chrome spinel itself. The chrome spinels may be expressed in terms of the theoretical end members.

Spinel - MgO Al_2O_3; Picrochromite - MgO.Cr_2O_3 ; Magnesia ferrite MgO.Fe_2O_3; Hercynite-FeO.Al_2O_3; Chromite FeO . Cr_2O_3; Magnetite - FeO.Fe_2O_3.

8.2-1. CHROMITE FORMULAE

The theoretical formula of chromite is Fe Cr_2O_4 with Cr_2O_3 percentage 67.9. However, in nature, such a purity is never obtained. Fisher (1929) has pointed out that pure chromite with FeO.Cr_2O_3 composition occurs only in meteorites. Generally in the chromite composition, the ferrous iron gets replaced in part by magnesium and the chromium by aluminium and ferric iron.Hence the composition of chromite is expressed by the formula (Mg,Fe) $(Al, Fe, Cr)_2O_4$. The wide range in the chemical composition of chromite, due to variation in ratios of FeO to MgO and Cr_2O_3 to Al_2O_3 and Fe_2O_3 can be adequately shown on a triangular diagram devised by W.D.Johnston and described by Stevens(1944). Stevens has used a simple diagram with FeO Fe_2O_3, (Mg, Fe) O Cr_2O_3 and (Mg Fe) O Al_2O_3 occupying the three corners of the triangle (fig. 72). By joining the apices of the triangle with the centre of the opposite sides the triangle is divided into six fields. The field in which Cr_2O_3 is the major constituent is the field of chromite,and this has been subdivided into two fields viz. those of ferric chromite and alumina chromite,depending upon the second major constituent. The other four fields are chromium magnetite,chromium spinel,alumina magnetite,and ferrian spinel. Thus the composition of chromite may be arbitrarily expressed as a solid solution of six end members, $Mg\ Al_2O_4$, $Mg\ Cr_2O_4$, $MgFe_2O_4$, $Fe\ Cr_2O_4$, $Fe\ Al_2O_4$ and $Fe^{2+}Fe_2^{2+3}$ 04.

8.2.2 MINOR CONSTITUENTS

Manganese, nickel, titanium and vanadium are the important minor constituents in chromite. MnO and NiO fit in the RO of the chromite whereas V_2O_3 and TiO_2 come in the R_2O_3. Stevens(op. cit.) Rait(1946) Baskind (in de Wet and Van Niekerk 1952) and Vander Walt(1941) do not consider titanium to be present in the lattice of chromite crystal. Stevens substitutes an equal amount of ferrous oxide from the total, assuming the titanium to be present as ilmenite. De Wet and Van Nickerk(1952) consider that titanium admittedly plays a minor part in the lattice, as trivalent or octahedrally coordinated constituent. The amount of titanium is generally more in iron rich chromites. Vanadium is generally not very highly concentrated and does not exeed 0.1% in chromites(Goldschmidt, 1937). Vanadium occurs in direct proportion to the amount of Fe^{+++} and inverse proportion to that of chromium (de Wet 1952). Most chromites contain from a few hundredth to a few tenths percent MnO. NiO is a very persistent constituent of chromites of commercial ore ranging from 0.1 to 0.5 percent.

8.2-3. RO : R_2O_3

The ratio of RO/R_2O_3 (RO=Fe'' Mg'': R_2O_3=Cr''' Al''' Fe''') is one or very near to the same. It differs from unity if the chromite is oxidized or the ferric oxide is incorrectly reported (Baskind, op cit).

The abnormal ratio may also be due to secondary iron oxides contained in the samples, or defect structures in spinel or even due to solid solution of oxides within spinels. Baskind has called attention to the difficulties in interpreting the composition of naturally occurring chrome spinels in terms of their difference in physical properties reflecting their chemical composition. In this regard he has produced some evidences by means of infra-red photographs of chrome-grain sections. It is perfectly feasible to expect chromite crystals, separating as a solid solution from magma to exhibit changes in composition from crystal to crystal or within the same crystal. In such cases the chemical analyses give only average values.

According to de Wet and Van Niekerk (op. cit) the excess of trivalent ions need not be due to foreign matter in the chromite, but is likely to be due to defect structures. They point out that the excess of ferric oxide reported by Stevens in some samples may be due to defect spinles, with γ-Fe_2O_3 as end member. They caution about the representation of chrome spinel composition in terms of simple end members.

According to Jackson (1963) oxidation or reduction of iron in chromite destroys the charge balance of the mineral and cannot be accomplished without large gains or losses in other major cations by diffusion or without the generation of another oxide phase. Alteration of chromite has been described by a number of authors and is evidenced in the following three ways:

(i) Exsolution of a α (R_2O_3) phase(Wijkersslooth,1942)

(ii) Presence of a secondary spinel phase (Miller,1953)

(iii) Development of γ(defect) structures in chromite (Rait,1946).

From a study of several chromite analyses Fisher (1929) has indicated that the ratio of 1:1 between bivalent and trivalent oxides is not the general rule in chromite. Based on this ratio, Fisher has classified chromites as follows:

	Ratio of R_2O_3 to R'' O (molal amounts)
Low ratio	1:0.53
"Sub-normal" (less than 1:0.90)	1:0774
"Normal"(Between 1:0.90)	1: 0.998 and 1:1.00
"Abnormal"(Greater than 1:1.00)	1:1.34
Higher ratio	1:3.69

According to Fisher, chromite is not a definite mineral and cannot be regarded as a member of a definite isomorphous series, although the three, four five or six spinellids which make up chromite are interrelated.

8.2-4. CHROMITE COMPOSITION IN RELATION TO PARENT ROCKS

In the crystallization of basaltic magmas the minerals to crystallize first are rich in magnesium and low in iron. Chromite is generally regarded as an early crystallization product. With the continued crystallization the magma becomes richer in iron and poorer in chromium and magnesium.

Thayer (1946) has discussed in detail the various factors that might influence the chemical composition of chromites. According to him the composition of chromite formed in a peridotite magma may be expected to reflect the overall composition of the magma, and the ratio MgO to FeO should be related to the composition of olivine and orthopyroxene. High magnesia chromite should result in a forsterite dunite. Thayer further points out that FeO/Fe_2O_3 ratio in chromite is a function of the state of the iron in magma. Since only small amounts of Fe_2O_3 are readily taken into olivine and enstatite structure and the total chromite in the magma is in minor amounts, slight variations in Fe_2O_3 content of the magma will be greatly magnified in FeO/Fe_2O_3 ratio in chromite. It is apparent from this suggestion that chromites rich in Fe_2O_3 content were formed under oxidizing conditions. Thayer has also pointed out that the chromites rich in Cr_2O_3 occur in feldspar free peridotite low in alumina. According to Jackson (op. cit.) variations in chromite compositions are due to differences in magmatic conditions during the crystallization of chromite. The lateral variation in chemical composition of the Stillwater complex reflects a persistent oxygen partial pressure gradient across the intrusion. The iron end members of the spinel solid solution series have the lowest melting points and should increase in chromite with time as heat is extracted from the crystallizing system.

Thayer (1960) has made some distinctions in chemical features of the alpine type and stratiform type chromite deposits (cf. Table 25).

The salient features of the alpine type chromite deposits are FeO:MgO about 1:2, Cr:Fe about 2:1 to 4:1 Cr_2O_3 ranges about 15-65%. In the stratiform type chromites FeO:MgO are about 1:1; Cr:Fe about 1.5:1; Cr_2O_3 average ranges 38-50%. Although Jackson has shown that the composition of chromite may differ substantially in stratiform layers only a few centimetres apart stratigraphically similar variations within layered podiform deposits have not been reported.

8.3. CHEMICAL ANALYSIS OF THE PAUNI CHROMITE

Thirteen chromite samples of Pauni area representing different ore bodies and different types of ores (Table 29) were chemically analysed. Further, their important trace-elements were determined by spectrograph methods. The locations of these samples have been shown in Map 2

With reference to the Table 29 the location and characters of the analysed chromite samples are given below:

(1) Fine grained disseminated type; limonitised gangue. Gangue more than 60%. Collected from Pit SCS Quarry 1. (Sp.No.1/55).

(2) Fine grained disseminated type, gangue over 50%, chlorite and serpentine; collected from Pit No.6. SCS Quarry 1. (Sp.No.1/560)

(3) Coarse grained; gangue 35%, mostly talc; collected from an isolated chromite occurrence near the Upashya nullah about 1½ Km, north of the main chromite belt (Sp.No.1/561);

(4) Fine grained chertified ore; chromite 60%. Collected from Pit No.3 SCS Quarry 1 (Sp.No.1/58).

(5) Very coarse grained; chromite over 95%,with serpentine chlorite· gangue. Collected from Pit No.1 SCS Quarry No.2 (Sp.1/2).

(6) Coarse grained; chromite over 80%. Talc forms the predominant gangue. Collected from Pit No.6 SCS quarry Noll (Sp.No.1/498).

(7) Coarse grained; chromite over 85%. Talc forms the predominant gangue mineral. Collected from pit No.3 GCS Quarry(Sp.No.1/585).

(8) Coarse grained; chromite over 85%. Talc represents bulk of the gangue. Collected from Pit.No.4 GCS Quarry Sp.No. 1/613.

(9) Corase grained; chromite over 70%. Chlorite is the predominant constituent of the gangue. Collected from pit No.5. SCS Quarry 2. (Sp.No.1/586).

(10)Coarse grained,chromite over 85%. Chlorite is the predominant gangue. Collected from Pit No.2 SCS Quarry 3(Sp.No.1/605).

(11)Coarse grained; chromite over 80%. Talc forms the predominant constituent.Collected from about 300 metres north of SCS Quarry (Sp.No.1/86).

(12) Coarse grained silicified ore, chromite over 65%.Collected from Pit No.1 SCS Quarry 1(Sp.No.1/443).

(13) Coarse grained; chromite over 75%. Tremolite is the major gangue mineral. Collected from pit No.3 GCS Quarry (Sp.No.1/561).

8.3-1. SEPARATION OF THE CHROMITE FROM GANGUE MINERALS

About a kg. each of the sample was crushed in a steel mortar,and was passed through 120 mesh sieve. The crushed particles were subjected to repeated panning in water to remove the lighter gangue.

The powder was heated for sometime in water containing dilute hydrochloric acid. The powder was dried and subsequently treated with bromoform. Inspite of the above treatment, a considerable amount of gangue containing minute fragments of chromite was still present. The concentrate was repeatedly run through a Frantz isodynamic separator. The samples were examined under a binocular microscope to find their purity. It was found that the samples were over 98% pure. Further purification was difficult as specks of gangue remained in the fractures of many chromite grains. It was verified with a powerful magnet that the samples do not contain any magnetite. This final concentrate was coned and quartered. The sample was further ground in an agate mortar for final analysis.

8.3-2. SCHEME OF ANALYSIS

The scheme of analysis followed by the present worker is a combination of the methods of Dinnin(1959), Bilgrami and Ingamels (1960), Shapiro and Brannock (1956) and Goswami(1957) with certain modifications. The scheme is as follows: 0.4 gm. chromite sample (-300 mesh) moistened with 3 drops of HNO_3 and digested in 25 ml. of 60% perchloric acid. Filter and wash with 2% perchloric acid and reserve the filtrate. Burn the filter paper with residue and weigh. Hydroflourize the silica and the silica percent determined from loss in weight. Fuse rest of the residue with Na_2CO_3 and the cake dissolved in Hcl and added to the filtrate reserved and the volume made to one litre. The rest of the procedure is given in Table 28.

TABLE -28

SCHEME OF CHROMITE ANALYSIS

Filtrate (one litre)

Cr_2O_3

500 ml for determination of Cr_2O_3. Titrate with $K_2Cr_2O_7$ by Fe Ammon. sulphate method using diphenylamine sulphate as indicator.

CaO and MgO

200 ml filtrate. SO_2 passed to reduce and then R_2O_3 precipitated and filtered out. Filtrate made to volume 500 ml.

Fe_2O_3 (Total)

After removing interference, colour complex is developed using orthophenanthroline, citrate buffer and hydroxylamine hydrochloride. Measure the density at .510 μ

MgO (200 ml.)

CaO precipitated with Na WO_4 using NH_4Cl NH_4OH buffer; solution decanted. Volume made to 250 ml. 50 ml. of this solution is titrated against versene using erichrome black T as indicator.

Combined CaO + MgO

Determined by titrating this solution against erichrome black T as indicator Ca is determined indirectly from results obtained for total MgO+CaO and for MgO alone.

MnO

25 ml solution formed with a mixture of HNO_3+ H_2SO_4 to remove chlorides before the colour complex is developed. The density of the colour is measured at 550 μ .

TiO_2

100 ml of the solution precipitated with NaCl. Ppt washed and dissolved in dil H_2SO_4. Yellow colour of Ti ion is developed using H_2O_2. H_3PO_4 is added to eliminate the colour of ferric iron. Density of the colours measured at 430 μ

R_2O_3

100 ml. R_2O_3 (including some Cr_2O_3) precipitated with ammonia. Precipitate filtered, washed, ignited and weighed. Ignited precipitate is fused with Na_2O_3 and Cr_2O_3% is determined volumetrically. Percentage total of iron as Fe_2O_3, FeO and TiO_2 (found) subtracted from R_2O_3 to give Al_2O_3%.

FeO

0.25 gm.chromite sample digested in acid mixture($H_3PO_4:H_2SO_4=4:1$) containing known amount of Cerric sulphate at 240°C for 3 to 3½ hrs. The Cerric sulphate consumed by the ferrous iron of the sample is determined against ferrous ammonium sulphate using diphenylamine sulphonate as indicator. FeO constituent of the sample is calculated from the amount of Cerric sulphate found consumed.

Analytical data

The analytical data(major elements)of the 13 chromite samples of the area are given in Table 29 . The trace element data of the samples is given in Table 30Table 31 contains data of the complete analyses of two samples and partial analysis of one sample of Pauni chrome ores. For purposes of comparison complete analyses and chemical formulae of chromites of different occurrences of India are given in Table36.

TABLE-31

ANALYSIS OF CHROME ORES

Constituents	1	2	3
Cr_2O_3	40.67	41.71	48.31
Al_2O_3	21.63	17.99	6.21
Fe_2O_3	13.60	13.80	12.17
FeO	12.23	12.41	8.43
MgO	15.09	16.57	--
CaO	0.40	0.50	--
SiO_2	9.05	9.63	9.16
L.O.I.	1.18	1.53	
Total	101.62	101.73	

Samples 1 & 2 - Prospecting Report of M/S S.C.Shukla's chromite Mine at Pauni (unpublished 1961) No.3. Paithankar,1960.

TABLE - 29

ANALYTICAL DATA OF CHROMITE FROM PAUNI AREA

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Cr_2O_3	50.74	49.34	51.12	44.66	48.72	44.54	42.06	48.78	48.40	50.17	50.2	49.47	51.82
Al_2O_3	23.08	18.13	14.74	22.35	17.06	16.86	23.42	19.58	13.56	13.62	15.74	14.01	15.07
Fe_2O_3	5.74	14.65	-	-	2.54	11.44	6.91	6.69	10.41	14.91	12.11	10.19	7.06
FeO	7.51	5.95	22.63	21.31	19.20	21.14	15.10	7.39	14.30	5.44	6.45	18.81	15.16
MgO	9.87	9.73	10.70	10.68	8.60	2.31	11.20	10.24	8.60	11.00	10.92	5.04	8.63
MnO	0.36	0.52	0.48	0.52	0.46	0.74	0.40	0.51	0.60	0.56	0.32	0.92	0.56
TiO_2	1.22	1.21	1.04	1.42	0.89	0.99	0.91	0.85	0.90	0.74	1.05	0.44	0.91
CaO	0.08	0.03	-	-	-	-	-	0.61	-	-	0.62	0.01	0.50
SiO_2	2.40	2.30	0.70	0.75	2.57	3.64	0.55	2.87	3.25	1.75	0.63	2.10	1.62
Total	101.00	100.65	101.41	101.69	99.04	100.66	100.55	100.52	99.42	98.19	98.99	100.89	100.33
Cr	34.71	33.75	34.97	30.59	33.32	30.47	28.77	33.37	33.10	34.32	35.70	33.84	35.44
Fe	9.84	14.86	17.58	16.56	16.69	24.42	16.56	12.51	18.39	14.65	13.47	21.74	16.71
*Cr/Fe	3.538	2.271	1.989	1.847	1.996	1.247	1.737	2.667	1.799	2.342	2.650	1.556	2.120
RO/R_2O_3	0.5722	0.4975	1.230	1.108	0.9813	0.6448	0.9064	0.6100	0.6912	0.5826	0.6777	0.7706	0.8196
Sp.Gr.	4.352	5.053	4.579	4.649	4.959	4.279	-	4.159	-	-	4.605	-	4.641
Impurity	Oxdized gangue	Chlo-rite	Talc	Silica	Serpentine chlorite	Talc	Talc	Talc	Chlorite	Chlorite	Silica	Silica	Tremolite

* Iron atoms were not adjusted between RO and R_2O_3 group so as to give an ideal RO/R_2O_3 ratio of 1:1

Analysts: N.G.K.Nair & A.P.Mall

TABLE-30

TRACE ELEMENTS OF CHROMITE FROM PAUNI

Element	Wave length used - A°	Concentration in ppm.											
		Sample No.											
		1	2	3	4	5	6	8	9	10	11	12	13
Ni	3414.765	225	2100	265	390	210	1400	1130	2100	490	600	900	265
Co	3453.505	210	335	145	127	450	1750	1750	1750	390	450	670	145
V	3185.396	88	180	32	54	53	1525	720	1000	390	112	182	60
Cu	3247.540	<10	75	<10	<10	<10	190	30	10	10	<10	70	< 10
Pb	3683.471	<10	20.5	12.5	16.5	300	375	2050	375	55	20.5	20.5	375

Elements like W, Mo, Zn, Ag Be, Ba, Sr are either absent or are present below their sensitivity level

Analysists: A.P.Mall & N.G.K.Nair

8.4. COMPOSITION OF THE PAUNI CHROMITES

The composition of all the thirteen analysed chromite samples can be expressed in terms of molecular ratio(mols or mol fractions) of R'' O and R_2''' O_3 constituents after the method of Thayer(1946) As all the samples were found to contain some SiO_2 due to the presence of gangue impurities like serpentine,tremolite,talc etc., SiO_2 was deducted with an equivalent amount of MgO in the case of talc and serpentine and an equivalent percentage of CaO where tremolite is present.

The oxide percentages divided by their respective molecular weights give the molecular ratio. The moles of Cr_2O_3,Al_2O_3,Fe_2O_3 and TiO_2 were recalculated to 100. Similarly the mols of MgO,FeO,MnO and CaO were recalculated to 100. The formulae of the 13 chromite samples derived from the mols and mol percentages of their constituents are given in Table 32. The norm percentages in terms of chromite,spinel and magnetite,and MgO/FeO ratio of the analyses have been given in Table 33.

8.5. CHEMICAL CHARACTERISTICS OF THE CHROMITES

From the data given in Table 29 , it is apparent that the chromites of this area show considerable variation in regard to their FeO,Fe_2O_3 constituents. However,the average formulae of the Pauni chromites can be expressed as $(Cr_{59}Al_3Fe_{10})$ $(Fe_{46}Mg_{49}Mn_2Ti_3)$. Analyses 1 and 2 representing fine grained chromites with the formulae $(Cr_{56}Al_{38}Fe_6)$ $(Fe_{31}Mg_{63}Mn_2Ti_4)$ and $(Cr_{56}Al_{29}Fe_{15})$

PLATE No.XVIII

Fig.No.72 Triangular diagram showing composition of the chromites of the area - Analyses plotted on the projection normal to the top of the spinel prism (Cf. Stevens, 1944).

Fig.No.73 Graphical representation of ratio of RO - R_2O_3 radicals of the 13 analysed chromites of the area.

Fig.No.74 MgO - FeO ratio of the chromites (analysed) of the area.

Fig.No.75 Al_2O_3 -Fe_2O_3ratio of the chromites.

PLATE No.XVIII

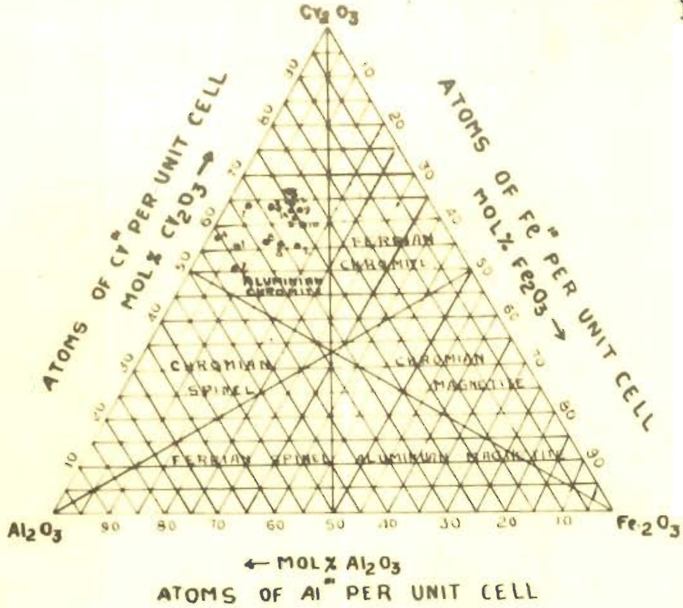


Fig.No.72

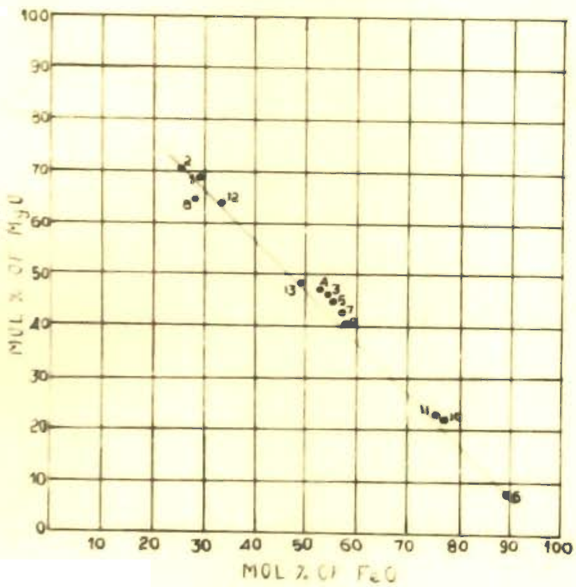


Fig.No.74

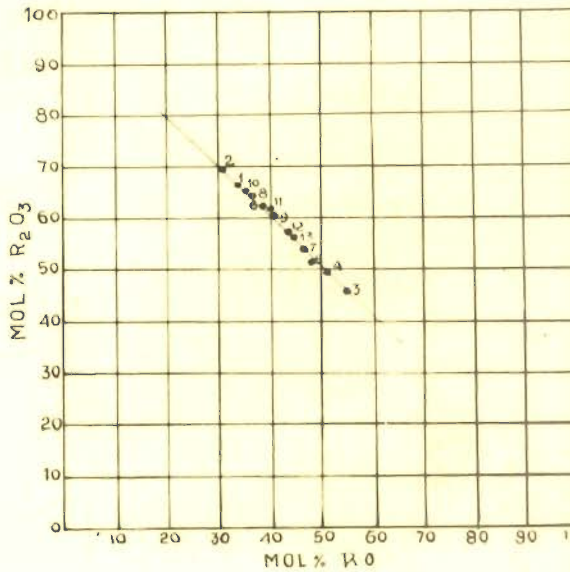


Fig.No.73

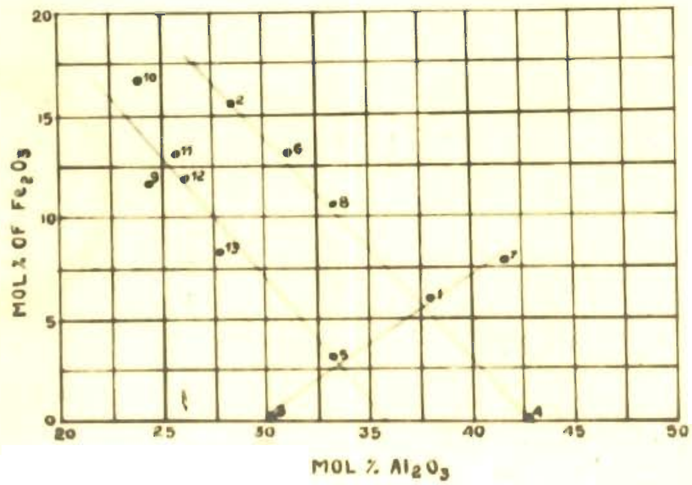


Fig.No.75

($Fe_{29}Mg_{63}Mn_3Ti_5$) show close resemblance. Analysis No.3 ($Cr_{70}Al_{30}$) ($Fe_{53}Mg_{43}Mn_{-}Ti_2$) and No.4 ($Cr_{57}Al_{43}$) ($Fe_{52}Mg_{43}Mn_{.}Ti_3$) are similar in that they are devoid of Fe_2O_3. Substitution of chromium by alumina is eivdent in analysis No.4. In most of the other analyses substitution of chromium by alumina and ferric iron, and magnesia by ferrous iron is apparent. Samples No.6 and 12 show a low percentage of magnesium with a corresponding increase in the total iron content.

Triangular diagram shown in fig. 72is projection normal to the top of the spinel prism of composition showing variations in the mol percentages in the R_2O_3 constituents of the chromites analysed. The nature of the six segments of this triangular diagram has been discussed earlier. The data of the analysed chromite was plotted in the diagram and they fall within the segment of aluminium chromites.

The relation between R_2O_3 and RO radicals of the chromites have been plotted in fig.73 which shows that the ratio of RO to R_2O_3 varies widely. It exceeds 1.10 in analyses 3 and 4. In the rest of the analyses it falls short of one ranging from 0.49 to 0.98.

The relations between MgO and FeO radicals have been plotted in fig.74 .It shows a linear variation within the wide range of 8 to 72 mol percent, However, six of these analyses(3,4,5,7,9 & 13) fall within the narrow range of 40 to 50 mol percent. The ratio MgO/FeO as shown in Table 33 shows variation between 0.80 to 3.06.

Similarly the relations between Fe_2O_3 and Al_2O_3 radicals have been plotted in fig.75. Two main groups of chromites showing linear variations are deciphered. Analyses 5,10,11,12 & 13 form one group and 1 2,4,6 & 8 form another group.

8.5-1. END MEMBERS

The end member system devised by Stevens(1944) to express the chemical composition of chromites is spinel ($MgO.Al_2O_3$),magnesiachromite ($MgO.Cr_2O_3$),ferro chromite($FeO.Cr_2O_3$) and magnetite ($FeO.Fe_2O_3$),and is determined as follows:

8.5-2. DETERMINATION OF IONIC CONTENT OF CHROMITE UNIT CELLS.

The unit cells of spinel structure are assumed to contain 8 ($R''O\ R'''_2O_3$). The number of ions of each constituent present in the unit cell has been calculated from Table35, taking the above as unit cell for chromite. In all the analyses except 4,RO: R_2O_3 ratio show marked deviation from normal. As mentioned in the introductory part of this chapter, no attempt was made to adjust the Fe atoms between FeO and Fe_2O_3 so as to give the ratio of RO to R_2O_3 equal to one. The molecular ratios were then recalculated to atoms per unit cell,assuming 8 bivalent and 16 trivalent atoms in each unit cell. The number of trivalent and bivalent metallic ions per unit cell of thechromites is given in Table35.

8.5-3. DETERMINATION OF END MEMBERS

The end member formulae per unit cell are obtained by the following equations (Stevens,1944).

$$\text{Spinel} = Al/2\ ;\ \text{Magnesio chromite} = \frac{Mg - Al}{2}$$

$$\text{Ferrochromite} = \left(\frac{Cr + Al}{2}\right) - Mg$$

$$\text{Magnetite} = 8-(\text{Spinel} + \text{Magnesiochromite}+\text{Ferrochromite})$$

Where each element is given in atoms per unit cell.

TABLE - 33

NORM OF THE CHROMITES

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Chromite	55.98	55.74	69.93	57.26	63.62	55.34	50.33	55.92	62.70	59.24	60.96	61.76	63.97
Spinel	37.98	28.50	30.06	42.74	33.21	31.24	41.78	33.49	24.45	23.98	25.58	26.11	27.73
Magnetite	6.03	15.74	-	-	3.15	13.41	7.87	10.58	12.83	16.76	13.45	12.12	8.29
MgO/FeO	2.055	0.220	0.815	0.832	0.783	0.083	1.289	2.121	0.664	3.060	2.931	0.477	0.936

TABLE - 34

END MEMBER PERCENTAGES (FORMULA) OF THE CHROMITE

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Spinel	37.97	28.50	30.06	42.73	33.21	28.21	41.77	33.49	24.45	23.98	25.58	26.10	27.73
Magnesio-chromite	25.00	34.97	13.35	0.68	9.15	-	12.63	28.90	13.21	47.40	43.36	4.73	17.49
Ferro-chromite	30.97	20.77	56.58	56.57	54.48	71.79	36.58	27.41	49.49	11.85	17.60	47.04	46.47
Magnetite	6.05	15.75	-	-	3.16	-	9.02	10.20	12.85	16.77	13.46	12.13	8.31

T A B L E -35

ATOMS/UNIT CELL IN THE CHROMITES

Unit cell content taken as 8 (RO R_2O_3) Total R''' = 16 & Total R'' = 8

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Cr'''	8.956	8.919	11.189	9.162	10.180	8.855	7.871	9.011	10.032	9.479	9.753	9.882	10.235
Al'''	6.076	4.561	4.811	6.838	5.314	4.998	6.685	5.358	3.913	3.837	4.093	4.177	4.436
Fe'''	0.968	2.520	-	-	0.506	2.147	1.444	1.631	2.055	2.684	2.154	1.941	1.329
Fe''	2.451	2.286	4.260	4.173	4.326	6.896	3.375	2.353	4.538	1.886	1.882	5.165	3.864
Mg''	5.038	5.078	3.473	3.474	3.389	0.569	4.352	4.991	3.013	5.710	5.515	2.466	3.617
Mn''	0.120	0.202	0.093	0.103	0.105	0.244	0.090	0.165	0.191	0.195	0.093	0.256	0.146
Ti''	0.358	0.420	0.156	0.250	0.180	0.291	0.183	0.242	0.258	0.229	0.277	0.109	0.209
Ca''	0.033	6.014	-	-	-	-	-	0.249	-	-	0.233	0.004	0.165

Formulae percentages are obtained by multiplying the formulae per unit cell by 100 by dividing by 8. Table 34 contains the formulae percentages of end members of the chromites of Pauni area. Samples 1,8,10 & 11 show fairly high amount of magnesia chromite. Sample No.6 shows absence of magnesio chromite. Sample 3,4,5,6,7,9,12 & 13 contain a high amount of ferrochromite. In samples 3,4,5,6,9,12 & 13 iron is more than the overall total magnesium including the metal in the spinel. Samples 2,7,8,9,10,11,12 & 13 show appreciable amount of magnetite.

8.4-4. TRACE ELEMENTS

Important trace elements Ni,Co,V, Cu and Pb of all the samples except No.7 were determined by spectrograph methods. Other elements like W,Mo,Zn,Ag,Be,Ba and Sr are either absent or are present below the sensitivity level. Table 30 contains the analytical data of the trace elements of 12 samples. The trace-element content shows wide variation in the Pauni chromites. Ni varies from 210 ppm to 2100 ppm, Co from 127 ppm. to 1750 ppm. and V from 32 ppm. to 1525 ppm, Cu 10 ppm. to 190 ppm. and Pb 10 to 2050 ppm. None of the trace elements mentioned above shows any definite and persistent relation with any of the major elements. However, the amount of V,Ni and Co is fairly high in samples having a higher percentage of total iron and correspondingly low content of chromium. This is evident from the trace element data of samples 6,8 and 9.

8.6. CONCLUSIONS

Based on the foregoing discussions,the following conclusions have been drawn: (1) The chromites of Pauni area present a wide variation in their chemical composition particularly with regard to Fe_2O_3, FeO and Al_2O_3. These variations may be attributed partly to the varying oxidizing conditions prevalent during the crystallization of chromite and partly due to the effect of intense hydrothermal activities. Cr_2O_3 and MgO show a fairly uniform percentage with an average of 50 and 10 respectively. (2) Following Fisher(1929) on the basis of RO,R_2O_3 ratio the Pauni chromite has been classified as follows: (i) Low ratio samples No.2. (ii) Sub-normal chromites,sample are 1,6,8,9,10,11,12 & 13 (iii) Normal chromites sample No.4,5,& 7. (iv) Abrnormal chromite sample No.3. (3) The average chemical composition of the Pauni chromites can be expressed by the formula $(Cr_{59}Al_{31}Fe_{10})$ $(Fe_{46}Mg_{49}Mn_2Ti_3)$. (4) In the triangular diagram(fig.72) the chromites of Pauni area are restricted to a narrow field of aluminium chromites,like the other Indian chromites. (5) Many of the analysed samples have a fairly high ferric oxide content which suggests that they have formed in an oxidizing environment.(6) In the R_2O_3 radicals the mol percentage of chromium oxide varies from Cr_{50} to Cr_{69},alumina from Al_{24} to Al_{42},and ferric oxide from Fe_2 to Fe_{16}. In the RO radicals,the mol percentages of FeO varies from Fe_{23} to Fe_{64},and magnesia from Mg_7 to Mg_{71}. (7) The ratio between Cr:Fe varies from 1.25:1 to 3.5:1 and RO to R_2O_3 from 0.5:1 to 1.2:1 (8) In the end member composition spinel shows variation from

24% to 42%. In 9 of the 13 samples analysed, the ferrochromite is more than the magnesio chromite. Normative magnetite is present in appreciable amount. However, it is absent in samples 3,4 and 6. (9) Due to complete alterations of the parent ultrabasic rocks it was not possible to correlate their composition with that of the chromite. (10) The important trace elements present in these chromites are V, Co and Ni. They show considerable variation in amount. There does not seem to be any regular correlation between these and the major elements. However, some of the iron rich chromite samples contain fairly high content of V, Co and Ni.

MAP No.6

PLATE No.XIX

CHAPTER - IX

GENESIS OF THE CHROMITE DEPOSITS

9.1. A REVIEW

Concentration of chromite crystals during the crystallization of a magma of ultrabasic composition gives rise to chromite deposits. The quantity of these concentrations will depend upon the amount of chromium content in the magma. When chromium concentration is very insufficient in the magma, chromite forms only as an accessory mineral.

There are different views regarding the period of crystallization of chromite with respect to the associated pyrogenic silicate minerals like olivine, ortho-and clino-pyroxenes, and calcium plagioclase. Three distinct periods of crystallization of chromite have been recognized by Fisher(1929) and Sampson(1931):

(1) Chromite of the early magmatic period - chromite formed earlier than olivine or contemporaneously with it. An overlap in the period of crystallization of the two minerals may be noticed.

(2) Chromite of the late magmatic period - later than most of the silicates and crystallizing with the last truly magmatic silicate, commonly either bronzite or plagioclase. This chromite could be observed in the cleavages or fractures of the earlier minerals.

(3) Chromite of the hydrothermal period - definitely later than the pyrogenic silicates and is associated with the hydrothermal minerals. This is mostly preceding or contemporaneous with intense serpentinization.

The most important point to establish is the quantitative aspect of the chromite crystallisation during the above three periods. While chromite might occur in minor amounts in any of the three periods,big concentration forming economic deposits is mainly confined to a particular period. According to Ross(1931) the following theories of formation of chromite must be taken into account while considering their genesis: (a) Crystal settling in a magma chamber and subsequent intrusion as a mush of crystals.(b) Crystal settling after intrusion. (c) Intrusion as a single magma and segregation in situ of the early products of crystallization.(d) Intrusion as melts of olivine and chromite that segregated in a parent magma chamber. (e) Introduction of chromite by hydrothermal solutions.

Several workers have considered chromite as an earlier constituent to crystallize(Vogt,1921,1926; Hall,1932-Johnston 1946, Thayer,1963) while others (Sampson,1929,1931 and 1932 Diller 1920, Ross 1929, 1931,Bateman 1951) have put forward evidences in favour of its late crystallization and of its formation even in the hydrothermal stage. Betekhtin(1937,1940) and Grafeneur(1948) have advocated that chromite deposits may be of 'histeromagmatic' origin referring to both late magmatic and hydrothermal stages formed by injections of ore rich residual melts into cooled dunite peridotite masses. Among the Indian workers, Deb and Chakrobarty (1961) consider many of the Indian chromites to have formed due to injection of residual solutions rich in chromium.While Verma(1964) advocates a hydrothermal origin for the chromite deposits of Nausahi, Orissa, Singh(1959) and Mukherjee(1962) consider chromite deposits in general as segregations during the magmatic period.

A brief account of the nature and genesis of the important Indian chromite deposits have been given in Table 37.

The divergence of opinion on the genesis of chromite is mainly pertaining to the alpine type of deposits. Regarding the stratiform type of deposits, the problem of injection of a residual magma or a chromite rich hydrothermal solution does not arise, as the chromite layers have formed in them due to the in situ differentiation of the magma. In the alpine type ultrabasics the irregular lenticular type of orebodies and their general discordant relationship with the parent rocks and their association with the shear zones and zones of serpentinization have posed many questions on their genesis. The disposition, external form, internal structure and the association of the alpine type of chromite (podiform type of Thayer, 1963) are governed by two sets of independent factors: (1) movement during the magmatic stage and (2) post-magmatic deformations and hydrothermal alterations.

Without going into details of the above factors, many workers have been easily led to conclude that such deposits have formed due to injection of chromite rich solutions during the late magmatic period or during the hydrothermal stage. In the 'histeromagmatic' theory (late magmatic or hydrothermal) chromite is supposed to have injected as a residual liquid or as hydrothermal solutions along pre-existing weak planes. The successive stages assumed are as follows:

(1) Crystallization of the silicate minerals and gravitative separation of a chromite rich residual liquid.

(2) Consolidation of dunites and peridotites and subsequent development of shear planes.

(3) Injection of residual liquid along shear planes(late magmatic) followed by serpentinization of dunites and peridotites.

(4) Injection of chrome bearing hydrothermal solutions along the shear planes (hydrothermal) with concomitant serpentinization of the dunites and peridotites.

9.1-1. CHROMITE- A PRIMARY DIFFERENTIATE

The evidences of many stratiform complexes agree completely with the crystal chemistry theory that Cr and Mg crystallize together early in any melt. In these complexes the layered rocks including the chromitites,were formed in situ by fractional crystallization of a fluid magma and settling of the crystals to the floor. The chromite crystallized simultaneously with olivine or bronzite and where the magma was entrapped between the settled grains,clino-pyroxenes and felspars were the last minerals to crystallize. Evidences of magmatic liquid approaching the composition of chromite are totally lacking in these complexes (Cameron and Emerson,1959;Jackson 1961;Worst 1958). Cameron and Emerson(1959) cite many laboratory evidences to suggest that chromite settling occurred during the magmatic stage of development. Thayer(1963) raises the significant question, why should chromite be injected into dunites and peridotites and never into gabbros, a differentiate of many alpine type of ultrabasics. In electrometallurgy, it has been found that melts containing more than 25 or 30% Cr_2O_3 are too viscous to handle. It is difficult to conceive how a melt containing 50-60% Cr_2O_3 attains mobility for injection.

The temperature of dry fusion of both olivine and chromite is excessively high. Chromite melts at 2000°C or over (Ross, 1931). Experiments conducted at the Bureau of Standards give temperature of fusion of chromite as 2180°C. Melts of such excessively high temperature cannot fail to show marked contact metamorphic effects on the enclosing rocks during their injection. Further under such high temperature the rock forming minerals would melt. Such high temperature contact metamorphic effects are entirely lacking near chromite deposits. In chromite bodies chilled borders characteristic of hot intrusive solutions are absent. Considering the formation of a chromium rich hydrothermal solution, it is difficult to assume the presence of water in a chrome melt in amounts sufficient to reduce the temperature of fusion from about 2000°C to well below 870°C.

The association of shear zones along the contacts of ultrabasics and chromite bodies, has led many workers to believe that these zones controlled the localisation of ore bodies during the injection of their melts. Evidences are in favour to suggest that the shear planes along the contacts of chromite and ultrabasics followed the formation of chromite. The contact zones of the massive orebodies with the enclosing dunites and peridotites are zones of largest mechanical anisotropy. These are extremely favourable sites for shearing and fracturing to take place as a result of tectonic stresses. The high degree of fracturing and brecciation of the chromite grains near such zones, supports the idea that shearing has developed after the formation of chromite deposits.

The high degree of serpentinization, largely confined to the proximity of many chromite bodies, has been put as an argument in favour of a hydrothermal origin for the deposits. The present worker believes that this coincidence is only a a consequence of preferred serpentinization. Serpentinization as a hydrothermal process was controlled by zones of weakness. It was natural that the fracture and the shear planes formed in and around the chromite bodies, acted as channelways for the hydrothermal solutions, as consequence of which serpentinization largely affected the chromite bodies and the enclosing rocks. Further, during shearing the chromite bodies were subjected to more brecciation in contrast to the surrounding wall rocks, and the numerous fractures thus formed in the former aggravated their serpentinization.

In many chromite districts ore bodies have been found associated with both serpentinized and unserpentinized zones, which amply support the fact that serpentinization was unrelated to the formation of chromite. Singh(1959) has cited such an evidence in support of a magmatic origin for the chromite deposits of Jojohatu(Singhbhum).

Based on the above discussions and from the evidences collected from the Bauni area, the present worker finds it difficult to accept that chromite could form as a result of the injection of a residual liquid or by hyrothermal solution. It can be finally concluded that chromite deposits form right within the magmatic stage as a product of segregation.

9.2. GENESIS OF THE PAUNI CHROMITES

Due to the complete alteration of primary silicates of the chromites and other parent ultrabasic rocks and consequent obliteration of the primary textures, it has not been quite possible to establish the direct paragenetic relationship of the chromite with the pyrogenic silicates.

Based on the following field features, mode of occurrence, petromineralogic, paragenetic and chemical studies of the various chromite ores of Pauni, the present worker is of the view that the orebodies represent the primary differentiate and they crystallized within the magmatic period.

9.2-1, FIELD CHARACTERS

(1) The ore bodies are strictly confined within the numerous linear detached ultrabasic exposures.

(2) Bigger deposits forming long lenticular bodies are generally parallel to the strike of the enclosing ultrabasics. (fig.67,68).

Minor discordant relation of many small ore bodies with the trend of the ultrabasics could be attributed to the flowage of the semi-solid magma during their emplacement. The occurrence of small stringers, pods and pockets represents either minor form of magmatic segregations, or these are broken off parts during the magmatic flowage (fig.57,64).

(3) In the banded ore bodies thin layers of chromite alternate with barren silicate layers or disseminated chromite layers in a rhythmic

order (fg.115)indicating a primary origin of these ores due to gravitational differentiation under magmatic conditions. The periodic changes of physico-chemical conditions added by the differing power of crystal nucleation from a supersaturated magma give rise to rhythmic banding in the ores(Wager 1939). The disappearance of these bands or their merger with massive ores at certain intervals is possibly due to the flowage of magma.

(4) Schlieren or gneissic banding as observed in certain ores is the result from crystal settling (Betektin 1937,1940). Further Sampson(1942) advocates that schlieren banding forms due to crystal settling of the disseminated ores,especially by the flowage of the magma during consolidation (figs.119,120).

(5) The chromite lenses have been subjected to tectonic effects like folding,faulting,jointing and shearing along with the enclosing ultrabasic bodies(fig.59,62)It is quite apparent that the localisation of the chromite in the ultrabasics was not guided by any pre-existing weak zones. The chromite bodies were emplaced simultaneously with the ultrabasics as 'autoliths' in them and all the evidences point to the fact that the ore bodies are pre-tectonic in age.

(6) The gradation of the massive ore to disseminated ore suggests that the chromite bodies have formed due to magmatic segregation as observed in the typical magmatic ores in Bushweld complex or other stratiform types. Further,the disseminated ore generally suggests simultaneous crystallization of the silicates and chromites.

(7) The chromite bodies of the present area do not exhibit any chilled borders or criss-crossing veinlets - the typical features of injected melts in already consolidated rocks.

9.2-2. MICROSCOPIC FEATURES

As the relationship of the primary silicate minerals and the chromite has been mostly obliterated due to cataclastic effects and hydrothermal alterations, it is rather difficult to deduce much about the primary textures. Nevertheless certain characters observed in thin sections and polished ores support a magmatic origin of the chromite.

(1) Generally the chromite shows corrosion and resorption effects. (fig.158). These have been largely caused by the residual liquids during the magmatic stage and partly by the later hydrothermal solution. The effect of the latter was less due to its low temperature. Magmatic corrosion of chromite indicates that chromite must have concentrated in earlier differentiate. The predominantly anhedral and embayed grains of chromite in most of the ores suggest that magmatic fluid was sufficiently active to corrode the early formed chromite crystals.

(2) Mutual moulding of the borders (mutual boundary textures) between chromite and pseudomorphs of secondary minerals after olivine and pyroxene indicates their simultaneous crystallisation (fig.149).

(3) Exsolution intergrowth of chromite and hematite (fig.159) indicates unmixing of the solid solution at a high temperature during the

magmatic stage.

(4) Most of the ores show a high degree cataclastic effects like fracturing and brecciation(figs.151-153). These have been partially caused by flowage of the magma (pull-apart texture) and to a large extent due to later tectonic deformations. The fractures are occupied by secondary silicate minerals like chlorite,serpentine,amphiboles,talc and chert. Such features have been cited by Fisher (1929) in favour of magmatic origin of chromite. According to him "fracturing of chromite grains is more pronounced in the hydrothermally altered ultrabasic rocks than in the fresh varieties. Incipient fractures serve as solution channels and the force of crystallization of later minerals within these channels may split off peripheral portions of the grains or pass completely through the chromite."

(5) The veins of hydrothermal minerals,cutting across the chromite ores, do not contain chromite, though they include chrome bearing chlorites. This indicates that the hydrothermal solution did not have any bearing on the formation of the chromite. The formation of hydrothermal minerals took place much after the emplacement of the ultrabasics and the enclosed chromite bodies.

(6) The disseminated chromite grains are smaller in size and are generally idiomorphic,(fig.155)while in the massive chromite ores the grains are coarse and are anhedral to polygonal showing mutual boundary texture (figs. 1, 156). It is quite possible that the disseminated crystals formed a little earlier compared to the massive type. Many workers have stressed the fact that fine grained euhedral

chromite generally crystallised earlier than the coarse grained chromite during the magmatic stage(Fisher 1929,Sampson 1932,Singh 1959).

9.2-3. GENETIC HISTORY OF THE CHROMITE ORES

Based on the above evidences and discussion, the following paragenetic history of the chromite ores has been concluded.

(1) The Pauni ultrabasics are the products of crystallization differentiation of a primary peridotite magma under plutonic conditions. The magma differentiated at depth to form different ultrabasic types including the chromite ore bodies (chromitites).

(2) In the magmatic chamber the chromitites formed as layers or bands of more or less uniform thickness.

(3) During the initial phases of the first stage (F_1) orogenic movements the primary differentiates of the ultrabasics were split up into smaller fractions in a semi-solid condition which were emplaced into the weaker zones of the country rocks at a low temperature (below 500°C).

(4) During their upward movement the chromite layers were disrupted as a result of the flowage of the 'mush', and lenticular bodies with pinch and swell structures were formed. Bifurcation and splitting of the ore bodies and development of stringers took place during this period The elongation suffered by the crystal mush due to flowage developed primary fractures in the chromite ores giving rise to pull-apart texture.

(5) After their emplacement the ultrabasic differentiates including the chromite bodies suffered severe tectonic movements when folding, faulting, shearing and brecciation took place. This was accompanied by intrusion of basic rocks and followed by intrusion of granites and pegmatites.

(6) During and following these activities, intense hydrothermal processes caused and obliteration of primary textures and structures and replacement of primary pyrogenic minerals except the chromite by secondary minerals like serpentine, talc, chlorite, tremolite and chalcedony. Thus new suites of secondary rocks were formed. Supergene alteration and weathering gave rise to surficial lateritic and float ores.

The time and space relationship of the chromite with the gangue minerals has been presented in the paragentic Table 26.

Table 37 contains the genetic aspects of the important chromite occurrences of India, in a nutshell.

CHAPTER - X

MINING AND ECONOMIC ASPECTS OF THE CHROMITE DEPOSITS

10.1. INTRODUCTION

The occurrence of chromite in the present area was first noticed in the year 1955. The alluvial cover of the area concealed the deposits for a long time, and it was from the float ores the presence of chromite was discovered. Subsequently the geological Survey of India investigated the potentialities of these deposits during the year 1956 and 1959. Later, geophysical survey was carried out by the same organisation during the field seasons 1962 to 1964. Regular exploitation of the deposits started in 1958 and since then the mining activity is in progress.

10.2. MINING METHODS

In this area the chromite ore is won by open cast mining methods. The irregular nature of the ore deposits, their structural deformations and the soft nature of the parent rocks and the country rocks, present limitations for underground mining methods even on a small scale. Generally pits and trenches are made at certain intervals, and if any ore body is encountered the pits are developed along the probable strike and dip directions. Quarrying is done by shovels, crossbars and pick axes. Blasting is not involved as the rocks are very soft. The ore is easily separated in small blocks due to closely spaced joints. The removal of the ore and the debris is done by manual labour.

As the water table is fairly shallow(about 12 m.)diesel pumps are used to remove the water from the quarries. Mining operations are closed during rainy seasons. The quarry near the bank of Wainganga river faces additional water seepage problems. The pits are generally abandoned after a depth of about 20 m. due to heavy water flowage and the higher cost of production. When an orebody pinches out along its strike direction excavation is generally stopped. The present worker has observed that proper benching methods are not followed in the quarries and the whole mining operation is carried out on a very irregular pattern. This is probably due to the lack of proper understanding by the miners regarding the nature and behaviour of the ore bodies and their parent rocks. Many of the prominent ore bodies in the main chromite belt have already been wholly or partially exploited to a depth of 20 to 25 m. from the surface. It is quite probable that the ore bodies still extend in depth in most of the quarries and a proper mining method may yield fruitful results.

10.3. PROSPECTING AND EXPLORATION

Exploration and exploitation of the stratiform type of chromite do not pose any problem because of their occurrence as continuous layers and their consistent relations with the parent rocks; but the alpine type chromite deposits raise several hazards for the geologists and the miners. Greev(1963) says "it is considered that the exploration of chromite ore bodies of alpine type ultramafics is a task with a low possibility for success especially when it deals with exploration of ore bodies which do not outcrop". In the Pauni area, because of the irregular nature of the ore bodies and the structural deformations like folding and faulting, it is difficult to anticipate the size, shape and continuity of the ore bodies. Hence normal mining methods are difficult to apply. Generally by the time a proper understanding of the ore body has been formed a large part of the orebody would be mined. It has to be properly borne in mind that several lenticular ore bodies parrallel or subparallel to each other form ore bearing zones, similar to the occurrence of parent ultrabasic rocks in the country rocks. Later deformations have caused further breaking up of these bodies into smaller ones causing discontinuity, reappearance and repetition along their strike and dip directions. During mining if an ore body pinches out either in its strike or dip direction, excavations should not cease as continued work may prove a new ore body in these directions. Sometimes trails of disseminated ore or stringers may connect adjacent ore bodies and this will act as a guide for the development of the quarries. Before extending the quarrying, trenches with deep pits should be put at intervals to follow the continuity of the parent rocks and chromite lenses. Thus the most important point in mining and prospecting in the present area is to recognize the ore bearing zones. Such zones would contain several ore bodies at close intervals.

Before the more expensive methods like pitting, trenching and drilling are resorted, geochemical soil surveys may be carried out. If the soil contains higher chromium content in relation to the chromium background values, presence of ore bodies may be indicated. However, chromite is one of the most unsuitable elements for geochemical prospecting because of its low solubility. Hydrogeochemical and biogeochemical prospecting for chromite have been employed with partial success in the Radusa district, Yugoslavia (Jankovic,1963). Hosking (1963) has discussed the geochemical prospecting carried out for chromite in Mindanao,Phillipines and for the Great Dyke of S.Rhodesia. However, these have limitations in an area like Pauni,because, weathering of chromiferous silicates(chrome-chlorite) releases more chromium than the decomposition of chromite ores.

Geophysical exploration may be carried out to delineate probable chrome bearing zones. In the geophysical prospecting of chrome ores the density contrast of the chromite bodies with the associated rocks plays an important role. The following geophysical methods have been adopted successfully in some chromite districts;

(i) Gravimetric methods - Gravimetric methods can be successfully applied in locating massive chromite bodies if there is much variation in the density of the ore bodies and the surrounding rocks. Large deposits of chromite have been explored successfully by gravity methods in the Camaguuey district, Cuba (Hammer,et.al.1948;Davis et.al.1957). In the Golan Mine, E.Turkey,gravity survey has led to large ore bodies (Yungul,1956). Gravity surveys have proved to be very useful in Cuttack district,Orissa (Bose and Banerjee,1966). At Pauni, due to the hydrothermal alterations, the density of the parent ultrabasics has been reduced compared to that of chromite.

However, this density contrast has been mullified by the presence of amphibolite bodies in the proximity of chromite bodies.

(ii) Magnetic prospecting-Magnetic prospecting will be useful if the magnetic susceptibilities of the chromite and the country rocks are much variable Magnetic surveys at Zimparalik Mines, Turkey, led directly to the discovery of buried ore (Ergin, 1954). Chromite is normally feebly magnetic. It has been observed in some areas that some of the serpentinized periodotites are more magnetic than the associated chromites, due to the presence of released magnetite content in the former. In such cases chromite gives negative magnetic anomalies. The Kemi area, Finland, provides the example of the above condition (Thayer, 1960).

Accordingly magnetic surveys combined with gravimetric surveys may serve useful in chromite prospecting.

(iii) Electrical prospecting methods - Electrical prospecting methods do not generally apply to chromites because of its chemical inertness and similarity in conductivity to associated rocks like dunites and peridotites. However, in areas like Pauni where the ultrabasics have been highly altered, there appears to be much contrast in the conductivity of chromite and the associated rocks, hence it is quite possible that the resistivity method may prove successful . Resistivity methods and induced polarisation methods have been used in chromite prospecting with success in central and north Sweden (Parasnis, 1963).

Bhanu Murthy and Jagannadham(1966) have carried out geophysical surveys in the Pauni area and have shown that magnetic and resistivity surveys have fairly helped in delineating the zones of ultramafics from the surrounding rocks.

Drilling - Drilling has proved a very expensive method for the exploration of chromite deposits at Pauni due to the smaller dimensions of the ore bodies and their irregular nature. However, shallow bore holes will be useful in the alluvium covered terrain in NE and SW of the main zone, to ascertain the strikewise extension of the ultrabasics. Inclined bore holes may help to discover ore bearing zones.

Drilling operations were conducted in the Pauni area during 1960-1962 by the Orissa Cements Ltd. on behalf of M/S S.C.Shukla. In all 49 inclined holes were drilled. The average depth of these bore holes was 17m. and maximum depth reached was 30 m. (fig. 77).

Pitting and trenching. In the zones delineated by the above surveys, cross trenches and pits are made to confirm the presence of ore bodies and to assess the extension of the ore bearing zone. Pitting and trenching have been a common procedure for prospecting of chromite in the preliminary stages before starting a quarry in this area.

10.4. MINES AND PROSPECTS

In Pauni the ore-bearing area consists of leased out claims owned by M/S S.C.Shukla, Mine Owners and Modern Plastics Ltd., Nagpur (Maharashtra) who have been producing chromite by open cast mining methods. The Modern Plastic Ltd. have been working

PLATE No.XX

LOCATION MAP OF QUARRIES AND PITS (S.C. SHUKLA'S CLAIM) PAUNI AREA

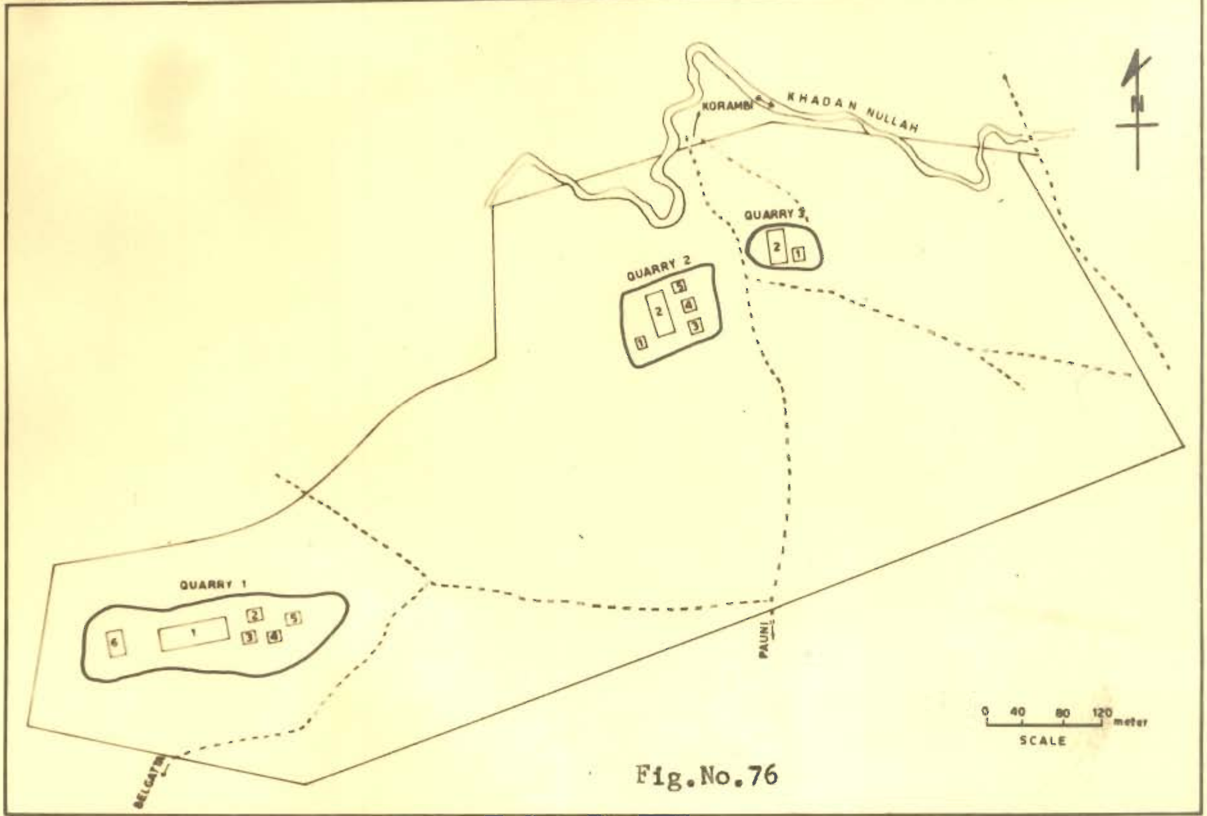


Fig.No.76

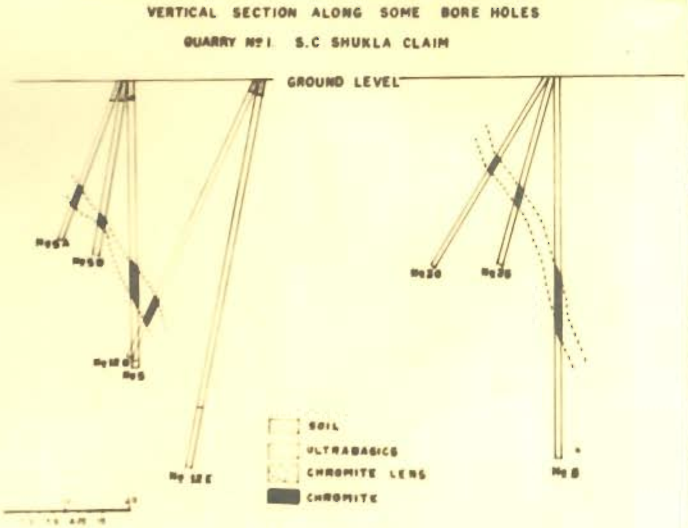


Fig.No.77

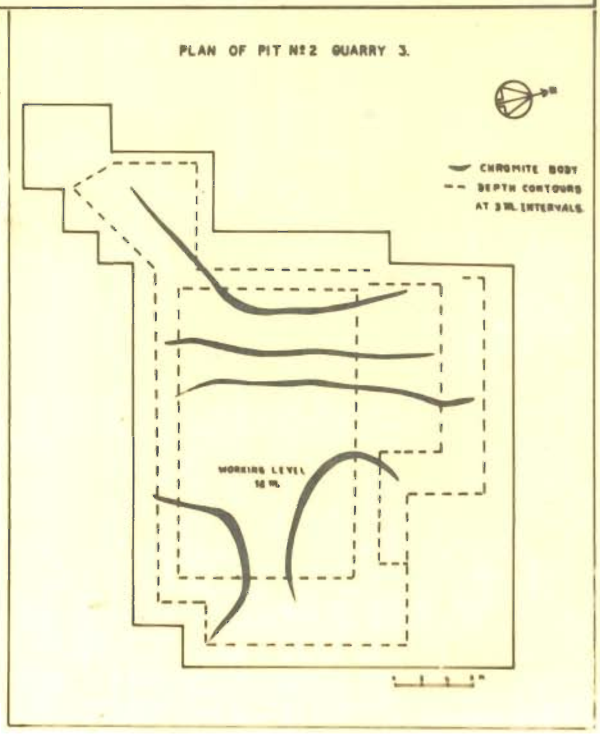


Fig.No. 78

intermittently whereas M/S S.C.Shukla have been active in mining during the period 1959 to 1966. Since 1967 there is a lull in the chromite production in the area presumably due to the higher cost of production and competition from the chromite mines of Orissa. Lately the Hindustan Steel Ltd., Bhilai, has taken lease of some of the area lying west of M/S S.C.Shukla's claim for exploration purposes.

A brief description of the ore bodies in some of the pits of the quarries (fig.76) as observed by the present worker is given below:

S.C.SHUKLA'S CLAIM

QUARRY NO.1 - This is located near south-western border of the exposed ultrabasic belt, and north of the Pauni-Khapri road. The quarry is elliptical in shape and extends for about 2000m. in length and 40 m. in width. In all six pits (No.1 to 6) were opened by the end of 1965. This is the oldest quarry of the area, started during 1958 and was exploited continuously for nearly four years. During this period about 2000 tons of ore were produced from this quarry. Except for pit No.6 and part of pit No.1 other pits were filled up with water and muck. Certain informations have been provided by the mines manager and labourers regarding the ore bodies in these pits.

Pit No.1 - This pit is over 120 m. in length and about 30m. wide and 20m. deep. The disposition of the main ore body in the western end of the pit is NW-SE dipping 70° due SW and on the eastern end it is along NNW-SSE dipping 80° towards west. From west to east there is an increase in the average width of the orebody from 0.3m. to about 1.2m. The orebody at places has assumed a thickness upto 3m. The ore is of massive type with varying amounts of gangue minerals. Thin lenses of banded and schlieren banded ores in the southern side of the pit strike SE-NW and dip about 30° towards southwest.

Pit No.6 - This pit lies west-southwest of pit No.1 and near to the Pauni-Khapri road. Three parallel chromite lenses are observed in the pit at intervals of about 1.5m. striking roughly north-south. The western body dips steeply towards east, while the other two are almost vertical. The vertical lenses are about 0.3m. in width while the former shows a thickness between 0.5 to 1.7 m. At one place the western orebody splits up into two parts and join again along the strike, enclosing an ultrabasic pocket(fig. 68). Towards norththis body with a thickness of 1.5m. abruptly pinches out upwards in the vertical section (fig.69).

On the western side of the pit several thin parallel bands of chromite varying between 2.5 to 8 cm. in width and spaced at about 15 cm. intervals, with sharp borders, occur within the ultrabasics. These bands have been folded along with the enclsoing ultrabasics (fig. 61). Another ore body of average thickness in the northeastern side of 0.3 m. trends ENE-WSW dipping 70° towards south. In the vertical section it pinches out and reappears after an interval of one metre. Most of the larger orebodies contain massive ore while the smaller ones are of disseminated type.

QUARRY NO.2

It is located to the NE. of Quarry No.1, between the tank and the Pauni-Korambi road (fig 70). The quarry is of rectangular shape; about 150 m. in length and 50 m. in width. It consists of five pits (No.1-5) and the major orebodies were quarried during the years 1963 and 1964.

Pit No.1 - Three chromite bodies have been observed in this pit. The main body is between 0.7 to 1 m. thick. On the western end the orebody ESE-WNW with a dip of 65° towards south-west and at the eastern end it strikes NNW-SSE dipping towards northeast. These appear to be the limbs of a plunging anticlinal fold. Two other thin parallel bodies occur in this pit, having a strike between N-S and NNW-SSE with steep dips. The main body is of massive type while the smaller ores show banded and disseminated ores.

Pit No.2 - Two bands of chromite with 15 to 20 cm. of average thickness were exposed in the pit. The trend of the orebody on the eastern side is ENE-WSW with a dip of 55° toward south and the ore on the western side strikes ESE-WNW dipping 65° towards south. The ore is of banded nature.

Pit No.3 - A laterally pinching orebody with a maximum thickness of 1.5 m. trending north-south is exposed. The dip is variable in amount from 15° to 70° towards west.

Pit No.4 - A chromite body of average 0.5 m. thick striking ESE-WNW with a dip of 50° towards south is exposed.

Pit No.5 - The chromite body has an average width of less than one metre and strike SE-NW with a dip of 70° towards south-west. Part of the ore is chertified along with the surrounding ultrabasics.

QUARRY No. 3

This quarry is located about 100 m. northeast of Quarry No.2 and on the eastern side of the Pauni-Korambi road (fig.76). The quarry is of rectangular shape and is about 150m.long. Exploitation of the ore bodies was active during 1965 and 1966. It consists of two major pits (No. 1 & 2).

Pit No.1 - Three thin parallel lenticular bands of chromite are observed in this pit,which vary in thickness from 5 to 15 cm. They strike between NE SW and ENE-WSW with a steep dip towards northwest (fig. 64). A fourth lenticular band varying in width from 10 to 20 cm. trends NE-SE and dips 45° towards NW. The ores contain a fairly high amount of gangue and are of disseminated type.

Pit No.2 - Several ore bodies have been encountered in this pit,which are probably limbs of a complexly folded single or two ore bodies. The average thickness of the ore bodies is between 0.5 to 1m. The disposition of the three prominent ore bodies(from east to west) is given below:

1. Strike of the orebody varies between NNE-SSW and ENE-WSW with an average dip of 50° towards NW.

2. The strike of the second ore body is between N-S and NNE-SSW dipping 50° towards west.

3. The ore body trends NNW-SSE with a dip of 60° towards WSW.

The ore in the above bodies is of massive type containing little gangue and is of high grade.

MODERN PLASTICS CLAIM

There is only one quarry with several pits in this claim. The quarry is located adjacent to the left bank of the Wainganga river within the 750' contour lines. Exploitation of the ore in this sector started in 1960. The quarry is over 500m. long and 40 m. wide. Pit No.3 and 5 were the main working pits during the present worker's visits.

Pit No.3 - The main orebody extends for over 75 m. along its strike. Its thickness ranges from 0.3 to 2m. The strike of the orebody in the northern end of the pit is nearly north-south dipping 60 towards west, and in the southern end it is NE-SW dipping steeply towards northwest. About 2 m. west of the main orebody few thin parallel to sub-parallel bands occur, having a thickness between 3 to 15 cm. (fig 60). They appear to coalesce in depth to form single orebody. The large body consists of massive ore whereas the stringers and thin bands form disseminated ore.

Pit No. 5 - The strike of the orebody ranges between N-S to ENE -WSW with an average dip of 50° towards west and northwest. They vary from 4 cm. to 0-7 m. in their thickness. Few lenticular bands (5-10 cm) are also observed with their strike along NNW-SSE dipping

60° - 70° towards SW. The ore contains high amount of gangue.

10.5 BENEFICIATION OF THE CHROMITE ORES

The Pauni area contains large amount of low grade chromite ores in the form of disseminated and banded types. Apart from this there are many chertified ore pockets. In the first few years of mining such low grade ore was discarded and no attention was paid towards their beneficiation. However, beneficiation processes were started in 1964. The low grade ores with Cr_2O_3 less than 35% are being upgraded to ores above 48 to 50% by means of crushing and jigging. The low grade lump ore is disintegrated by means of small power crushers. With the processes of washing,panning and jigging chromite grains are separated and concentrated. The Indian Bureau of Mines conducted beneficiation tests from low grade chromites of the area. They found that the ore containing 45.42% Cr_2O_3 could be upgraded to 53.5% Cr_2O_3 with a recovery of 90.5% Cr_2O_3,employing gravity method of concentration.

Experiments have been conducted by the National Metallurgical Laboratory on certain low grade chromites having Cr:Fe ratio less than 3:1 to upgrade them for the production of ferro-chrome. It has been found that by preferential reduction of FeO and its subsequent leaching by acid the Cr:Fe ratio of 3:1 could be obtained with almost 100% recovery (Indian Minerals year Book, 1960).

10.6 RESERVES

As the ore bodies are highly irregular in nature,both along their strike and dip,any estimation of their total reserves in the area will be far from correct. It is estimated that the reserves of chromite in the known ore bearing area are about 480,000 tons down to a depth of 15 m. Reserves are likely to increase if the adjoining alluvium covered areas are properly explored and further increase is expected if the ore is proved at greater depth in the present ore-bearing belt. The estimation of reserves of podiform chromite deposits is generally a matter of speculation, because of their unpredictable structural pattern. Hence the production capacity cannot be correctly estimated from the statement of reserves, unless it is based on strongly indicated ores.

10.7. PRODUCTION

TABLE - 38

PRODUCTION OF CHROMITE 1958-1966

Year	PAUNI (QUANTITY Tonnes)	BHANDARA * VALUE (Rs.'000)	ALL INDIA TOTAL QUANTITY (Tonnes)	VALUE (Rs.'000)
1958	229	9	63,957	3,186
1958	209	16	95,596	5,364
1960	1,228	107	100,112	5,733
1961	1,289	108	48,785	2,899
1962	591	50	66,648	4,259
1963	1,006	246	65,042	4,195
1964	730	64	33,424	2,045
1965	999	78	59,685	3,723
1966	1,490	122	77,656	5,197

* The production of chromite of Pauni area represents the total output from Maharashtra State.

The Pauni area has been constantly producing chromite every year (cf. table 38) since it started production in 1958. The average annual production is about 1000 tonnes. The total output in 9 years

PRODUCTION OF CHROMITE
PAUNI — BHANDARA

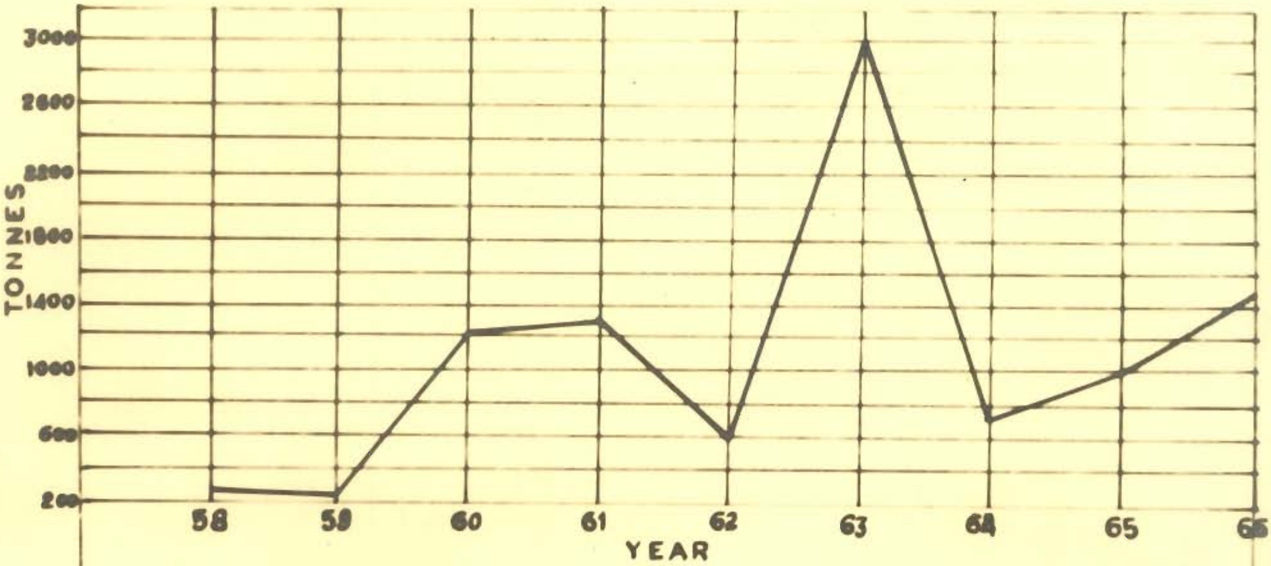


Fig.No.79

PRODUCTION OF CHROMITE
ALL INDIA TOTAL

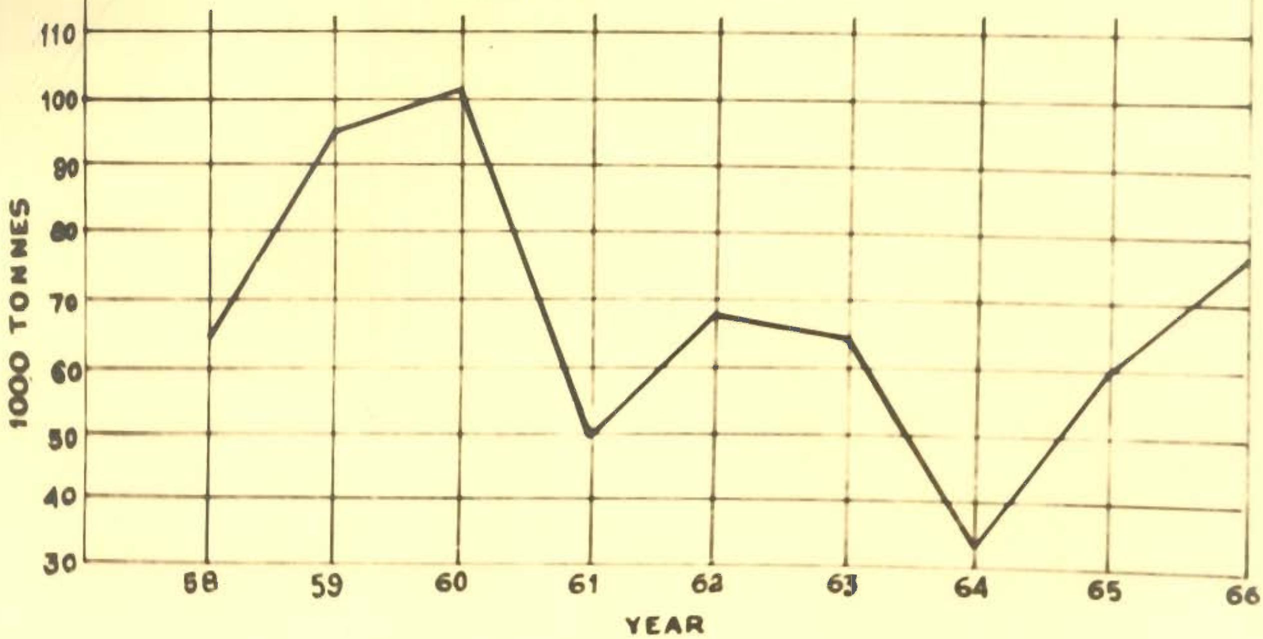


Fig.No.80

(1958 to 1966) was 9771 tonnes. In 1963 the output was very high i.e. 3,006 tonnes. The production is much subjected to the demand of the ore from the consumers. Fig. 79,80, show graphically a comparative statistics of chromite production from Pauni with that of the All India total production. It is well apparent that Pauni follows an independent course in the chromite production, as the ore is produced just to meet the demands of the Orissa Cements Ltd., Orissa.

10.8 SPECIFICATIONS, GRADE AND UTILIZATION

The principal uses of chromite are (i) metallurgical (ii) refractory and (iii) chemical, Chrome ores are generally classified on the basis of their suitability for the above uses. For metallurgical and refractory purposes hard lump ore is required, whereas for chemical purposes soft lump ore or concentrates can be utilized.

(i) Metallurgical grade - Chrome ore to be used for production of ferro-chrome should have a Cr_2O_3 content, not less than 47-48% and Cr:Fe ratio not less than 3:1, MgO and Al_2O_3 should not exceed 25%: sulphur should not exceed 0.5% and phosphorous should not exceed 0.5%.

In the ferro-alloy production only chromium and iron are extracted from the ore, while the other constituents are discarded. High amount of iron oxide is undesirable for metallurgical purposes, as iron is reduced to metal with Cr and lowers the grade of ferro-chrome. High contents of SiO_2 increase the processing costs.

In U.S.A. chrome-ores with an average Cr_2O_3 content of 46.9% and Cr/Fe ratio of 2.8 are being used for metallurgical purposes.

(ii) Refractory grade - Low grade ores with Cr_2O_3 content as low as 40% are used in the manufacture of refractory bricks. Silica and iron content should not exceed 5% and 15% respectively as both of these reduce refractoriness. High alumina is desired and Cr_2O_3 and Al_2O_3 should preferably exceed 60%.

In the refractory brick production the chrome ore as such is incorporated in the crude condition and no constituent is removed. Hence, the relative proportion of the various constituents, their texture and strength must be considered carefully for the refractory grade.

In U.S.A. chrome ores with an average Cr_2O_3 content of 34% are being used for refractory production.

(iii) Chemical grade - Chromite should have a Cr_2O_3 content of 44%; Cr:Fe ratio of 1.6:1; SiO_2 less than 8% and MgO should be as low as possible.

For the chemicals only chromium oxide from the ore is extracted. SiO_2 should be as low as possible as it increases the processing costs. Ores with high iron content is tolerated as it is eliminated without much extraction cost. In the United States ores with an average Cr_2O_3 content of 44% and Cr/Fe ratio of 1.5-1.6 are being used for chemical purposes.

The Pauni chromite is being used for refractory brick manufacturing by the Orissa Cements Ltd. Rajnandgaon, Orissa. As the silica content is fairly high (8-9%) the ore is blended with ores from other areas having low amount of silica to meet the required specification for refractory purposes. Lately the Hindustan Steel Ltd. Bhilai is being supplied with the beneficiated ore from this area.

10.9 FUTURE PROSPECTS

The present worker believes that the Pauni area possesses more potential in chromite reserves, than what has been assesed at present. Proper planning and systematic mining and dressing are imperative to avail a steady rate of production from the area and to avoid waste of low grade ore. Many old dumps contain huge amount of low grade ores which could be easily recovered and upgraded for commercial use. The abandoned pits could be further worked to win the ore bodies in deeper parts, using high power pumps to overcome the water problem. If systematic exploration is carried out along the strike of the belt, towards northeast in the Sindpuri area, more ore bodies may be proved. With planned development and exploitation of these deposits, it is hoped that Pauni area will be regularly supplying refractory chrome ores to the need of the country for years to come.

CHAPTER-XI

CONCLUSIONS

The thesis presents a concise account of the geological investigations(carried out between October 1963 to February 1968) on the structure, petrology and the chromite deposits of Pauni-Bhiwapur area of Maharashtra State. The area covering about 160 Sq.Km. is largely comprised of the Pre-Cambrian rock formations of the Sakoli Series. On the basis of the studies described in the preceeding chapters the major conclusions are being summarised in the following paragraphs.

Based on the lithology, metamorphism and structural features the rocks of the area have been grouped into the following five stratigraphic units.

(i) Pauni Formation (the oldest) - comprised of chlorite-schists (largely migmatitised) and quartz-magnetite-grunerite rocks with altered ultrabasics, amphibolites, and acid intrusives.

(ii) Parsori Formation (partly exposed in the area) is represented by the chloritoid-chlorite-muscovite-schists.

(iii) Bhiwapur Formation - consisting of phyllites, quartz-phyllites and iron ore bands.

(iv) Gaidongari Formation comprised of quartzites, slaty shales, meta-argillites, slates, variegated slates and conglomeratic slates.

(v) Younger Sedimentaries (Younger to above four formations of the Sakolis) formed of conglomerates, sandstones and shales.

Four major faults have been deciphered in the area which form the boundaries of the above stratigraphic units (Map 2).

The geologic succession established by the present worker is the first ex systematic attempt on the stratigraphy of the Sakoli Series of the southern Bhandara region. It was difficult, however, to correlate these formations with the Sakolis of the northern part. The Younger Sedimentaries have been tentatively correlated with the Lower Gondwanas.

The area under investigation falls in the southwestern part of the 'Sakoli Synclinorium' (Fig. 10). Based on the detailed geometric analyses of structural elements(largely foliation planes S_2) it has been concluded that in this region the Sakoli group of rocks have suffered at least three fold movements named as F_1, F_2 and F_3 producing complex fold patterns. The area covered by the Sakoli formations forms three distinct structural domains i.e. the Pauni block, the Gaidongari block and the Bhiwapur block. The Pauni block shows the imprints of the three episodes of folding whereas the Bhiwapur and the Gaidongari blocks were affected only by the later two deformations F_2 and F_3. Although the general trend of F_1(NE -SW) could be correlated with the regional trend of the 'Sakoli Synclinorium' the other two crossfold trends F_2(NNW-SSE) and F_3 (ENE-WSW) are rather difficult to compare with those of the Nandgaon and Khairagarh orogenies as described by Sarkar(1957,1958) in the northern region of the Sakolis.

F_1 fold movements confined within the Pauni block represent the earliest orogenic cycle in the area, which was associated with ultrabasic,basic and acid igneous activities. Though the general trends of F_2 and F_3 are nearly normal to each other, their variable intensity within a small region suggests that these movements represent successive phases of the same orogenic cycle. The superimposition of F_3 fold on F_2 has given rise to a 'depression' and' saddle 'structures in the Gaidongari block and a series of en-echelon folds in the Bhiwapur block. In general, plane non-cylindrical, non-plane- non-cylindrical, polygonal and disharmonious types of folds have developed at several places in the area. The pattern and styles of the folds have been conditioned and controlled by the pre-existing S surfaces. It has not been possible to unroll the fold patterns to their original positions.

The chlorite schists of the Pauni Formation are largely migmatitised. These schists and the few associated layers of quartz-grunerite-magnetite rocks represent regionally metamorphosed ferruginous clays and iron rich siliceous bands respectively. The amphibolites have been classified into four groups viz. normal amphibolites, quartz-free amphibolites, plagioclase amphibolites and hornblendites. These show enough evidences for their igneous origin. The granites, pegmatites, and quartz-felspathic veins forming migmatites, (a co-magmatic suite of rocks) appear to have formed from a magma or melt of deep seated origin.

During the early phase of the F_1 movements, emplacement of ultrabasics(including chromite bodies) took place, as linear parallel lenses, mostly concordant with the weak zones of the country rocks. In the later phase of the same fold movements acidiic intrusions(granites and pegmatites) and permeation of the country rocks by quartzo-felspathic solutions (migmatitisation) took place along the weak zones. In between these two phases basic rocks(now represented by amphibolites) were intruded mostly as concordant bodies.

The chlorite-muscovite schists of the Parsori Formation contain chloritoid and porphyroclasts, which are characteristic of shear zones. It has been concluded that these rocks have undergone two stages of metamorphism, the first is of low grade regional type, and the second is presumably due to dislocation metamorphism.

The phyllites, quartz-phyllites and iron ore bodies of the Bhiwapur Formation were originally deposited as pelitic to semi-pelitic sediments, with linear lenses of iron rich sediments. On regional metamorphism, these sediments were transformed to different rock assemblages of the green-schist facies. The biotite rich and garnet rich zones in the quartz-phyllites are due to the variation in the chemical composition, rather than to any change in pressure temperature conditions. The iron ores associated with the quartz-phyllites contain mostly martitised magnetite with garnet, grunerite and quartz as gangue minerals. It has been concluded that the magnetite in the iron ores was formed along with the silicates during the regional metamorphism,while the hematite is of later origin formed due to alteration of the magnetite and the iron rich silicates.

The Gaidongari Formation consists largely of low grade meta-pelitic rocks. A gradual increase in the amount and size of the rock fragments is observed in the upper portions, suggesting that in the early period of sedimentation the deposition was steady and the tectonic conditions stable. In the later period the tectonic environment became unstable causing rapid erosion,transportation, and deposition.

The Younger Sedimentaries are formed of gently dipping beds of conglomerates, shales, and sandstones. The grain size analyses of two horizons of sandstones indicate that they have different provenances, which has been corroborated by different suites of heavy minerals present in them.

The ultrabasic rocks exhibit characteristics of the alpine type. As mentioned earlier they were emplaced during the initial stages of the first fold movement F_1, as small discontinuous, lenticular, concordant plutones, in the weak-zones of the country rocks in a more or less semi-solid condition. They were derived from a deep seated primary peridotite magma which crystallized and partly differentiated by fractional crystallization at depth into chromite and olivine and pyroxene rich bodies. Later hydrothermal activities converted the primary silicates into serpentines, talc, tremolite, actinolite and chlorite minerals. Supergene alteration gave rise to vermiculites and chert at places.

The chromite deposits confined within the ultrabasics occur mostly as massive lenticular bodies belonging to the Podiform type of Thayer (1963). These are of irregular size and disposition. The chromite ores generally exhibit pull-apart and cataclastic textures with high degree of fracturing. Exsolution intergrowth of hematite with chromite is often observed in polished sections. The chemical analyses of 13 pure chromite samples have shown that they fall under the group-alumina chromites, in the triangular diagram. They exhibit wide variation in their chemical composition, particularly with regard to Fe_2O_3, FeO and Al_2O_3. The average chemical composition can be expressed by the formula $(Cr_{59}Al_{31}Fe_{10})$ $Fe_{46}Mg_{49}Mn_2Ti_3)$. The ratio of RO to R_3O_3 deviate much from the normal. The important trace elements present are Co, Ni, V, showing considerable variation in different samples.

The field and laboratory evidences have indicated that the Pauni chromites are primary differentiate of a peridotite magma. In the magmatic chamber the chromitites formed as layers or bands of more or less uniform thickness. During the upward movement of the ultrabasics, the chromitite layers were disrupted, as a result of the flowage of the 'mush' giving rise to lenticular bodies. Bifurcation and splitting of the ore bodies took place during this period. The elongation suffered by the crystal 'mush' due to flowage developed primary fractures in the chromite ores, producing pull-apart texture. After their emplacement the ultrabasic differentiates including the chromite bodies suffered folding, faulting, shearing and brecciation. During and following these activities intense hydrothermal processes caused the obliteration of primary textures and structures and the replacement of the primary silicates by secondary silicates. The later basic and acid intrusives were also much responsible for the above changes.

On the basis of field observations it has been inferred that the northeastern and southeastern part of the area along the ultrabasic belt, form a future prospect for the location of chromite deposits. Further, cheaper methods of mineral dressing will increase the potential source of a better grade chromite.

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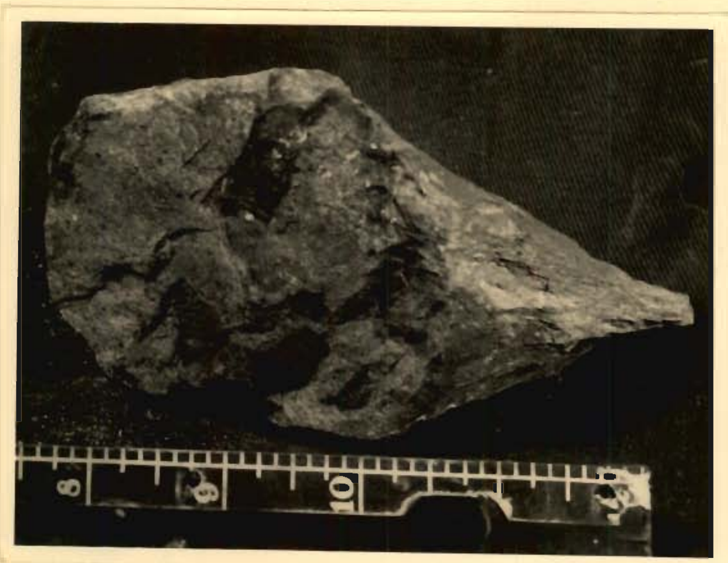
FIELD PHOTOGRAPHS

SPECIMEN PHOTOGRAPHS

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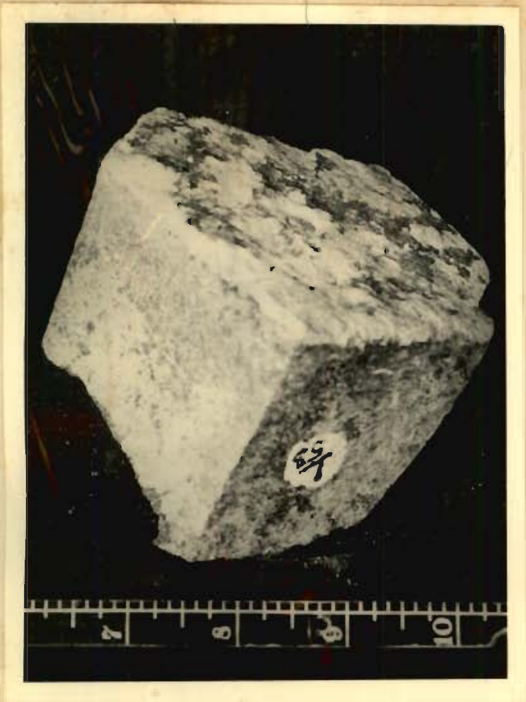


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