CONTRIBUTION TO GEOCHEMISTRY
of the
KHETRI COPPER BELT,
Dist. Jhunjhunu, RAJASTHAN (INDIA).

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Thesis Submitted for the Degree of
Doctor of Philosophy in Geology
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CONTRIBUTION TO GEOCHEMISTRY OF THE KHETRI COPPER BELT,
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ABSTRACT

The Khetri Copper Belt, which extends for about 80 km from Singhana (28°06' : 75°53') in the north to Raghunathgarh (27°39' : 75°21') in the south, falls in the Rajasthan State. Stratigraphically, it is a part of Delhi System, the subdivisions of which are known as Ajabgarh Series (predominately argillaceous group) and Alwar Series (predominately arenaceous group). There is a major strike fault running almost along the contact of these two series. There are intrusions of granites, pegmatites, dolerites, etc., into these metasedimentary rock series which have been intensely deformed into doubly plunging folds and affected by a number of secondary reverse and normal faults. The regional strike of both the rock series is NE-SW and dip varies from 30° to 70° towards north-west.

Mineralization of copper has largely been at or near the contact of lower Ajabgarh Series with the upper Alwar Series. Comparatively, the former rock series played a greater role as a host rock than the latter. The chief centres of ore deposition have been the innumerable fractures in the shear zone which runs parallel to the main fault. Field evidence indicates that some of the secondary faults served as the channels for ore fluids.

The important ore mineral of copper in the deposits is chalcopyrite which is also frequently associated with pyrite and pyrrohotite in varying proportions. The predominant host rock of the copper deposits in the Madhan-Kudhan and Kolihan copper mines is garnetiferous quartz-chlorite schist. The
wall rocks show some evidence of alteration due to sericitization, silicification, felspathization, biotitization and chloritization.

The present investigation is mainly concerned with the distribution, geochemical behaviour and significance of certain trace elements in rocks, some rock-forming minerals, ores, as well as residual soils of the outcropping rocks of the copper belt. Petromineralogical studies have been very helpful to confirm the identity and nomenclature of the various rock types.

About 250 selected samples have been analysed by Atomic Absorption Spectrophotometer in order to determine the traces of the metals like Cu, Pb, Zn, Ni, Co, Cd, Cr, Li and Ag in them. Additionally, five different samples of igneous rocks and four of metamorphic rocks are analysed following the conventional chemical methods for quantitative determination of all the fourteen major constituents.

The chemical evidence coupled with field and petromineralogical studies reveals that the granite, which occurs at Gotro, a village close to Madhan-Kudhan copper mine, is intrusive. Further, the original nature of the different metasedimentary rocks and also of the basic intrusive has been determined with the help of variation diagram and A C F diagram.

Lithologic or stratigraphic control over the ores has been ruled out for lack of any evidence. However, there are some positive evidence to believe that the ore deposits have been largely controlled by the structure of the host rocks.

The granites being poor in mafic minerals are generally depleted in copper content while the granite gneisses having a greater proportion of mafic minerals, record relatively higher values. This is an important indication that the concentration of copper in these rocks is directly related to the proportion in which the mafic minerals occur in them.

The schists generally have a higher concentration of trace elements than the other rock types of the area. The separated pyrrhotite from the ores is more nickeliferous than the coexisting chalcopyrite. Analytical results of the separated mineral fractions of granites and granitic rocks as well as of the host rocks show that the trace metals concerned are generally concentrated in the ferromagnesian phase. The felsic group (quartz plus feldspars) generally shows insignificant traces of these metals except Pb which is usually high in
the pink granite gneisses. Further, the trace metal distribution in the bulk rocks is compared with their separated mineral fractions and it has been pointed out whether the trace elements are associated with the silicate phase or the sulphide phase.

Dispersion aureole of the individual trace elements in a particular rock group and residual soil is shown with the help of geochemical variation diagram. Primary and secondary dispersion pattern of Cu, Pb and Zn have been compared and a scheme of their relative mobility has been proposed.

The isoconcentration maps of Cu, Pb, Zn, Ni and Cr have been prepared to show clearly the areas of low and high concentration of these elements in the rock samples of the belt. When the weight percentages of Cu, Pb, Zn and Ni in granites and the host rocks are plotted separately in triangular and rectangular diagrams, the concentration trends of the ratio of elements in the two rock groups show striking similarities. This is a valuable evidence in support of genetic relation between those trace elements which commonly occur in granites and the host rocks.

The nature of concentration trends of certain trace elements, as stated above, and the data showing general depletion of copper in the granites and enrichment of the same metal in the separated hornblende and biotite fractions also have some useful bearing on the geochemical relation between the productive copper deposits of Khetri and the neighbouring intrusive granite of Gotro.
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CONTENTS

CHAPTER I  INTRODUCTION  ...  1
  i) Location, extent and communication  1
  ii) Physiography, drainage, etc.  2
  iii) Scope of work and statement of problem  4
  iv) Brief history of the copper deposits  5
  v) Ancient mining  ...  6
  vi) Prospecting, mining and reserves  6
  vii) Sampling and preparation of samples  8
  viii) Acknowledgements  ...  10

CHAPTER II  PREVIOUS WORK AND GEOLOGY  ...  12
  i) Brief review of earlier investigations  12
  ii) Stratigraphic position  ...  22
  iii) Structural setup  ...  24
  iv) Metamorphism  ...  25
  v) Ore deposits  ...  27
    a) Occurrence  ...  27
    b) Mineralogy and composition  29
    c) Form and shape  ...  29
  iv) Control of ores  ...  30
    a) Lithological  ...  30
    b) Stratigraphical  ...  31
    c) Structural  ...  31

CHAPTER III  LABORATORY METHODS OF STUDY  ...  34
  i) Systematic analyses of rock samples for major elements by conventional chemical methods  ...  34
  ii) Separation of minerals from rock samples  37
  iii) Trace element analyses by Atomic Absorption Spectrophotometer  ...  40

CHAPTER IV  OCCURRENCE, LITHOLOGY, PETROMINERALOGY AND PETROCHEMISTRY OF ROCKS  ...  44
  i) Occurrence and lithology  ...  44
    1. Intrusives
      a) Granites and granitic rocks  44
      b) Pegmatites and quartz veins  47
      c) Basic dykes  ...  48
## 2. Metamorphics

- **a) Quartzites** ...
- **b) Schists and phyllites** ...
- **c) Carbonate rocks** ...

### ii) Petromineralogy ...
### iii) Petrochemistry ...

### CHAPTER V GEOCHEMISTRY AND DISTRIBUTION OF TRACE ELEMENTS IN ROCKS, MINERALS AND SOILS

- **i) General statement** ...
- **ii) Interpretation of results** ...

### CHAPTER VI GEOCHEMICAL DISPERSION OF TRACE ELEMENTS

- **i) Geochemical variation diagrams for primary and secondary dispersion aureoles** ...
- **ii) Comparative study of primary and secondary dispersion patterns of Cu, Pb and Zn** ...
- **iii) Trace element isoconcentration maps** ...

### CHAPTER VII SIGNIFICANCE OF TRACE ELEMENTS

- **i) Concentration trend of some trace elements** ...
- **ii) Geochemistry as applied to the Khetri copper ores** ...

### CHAPTER VIII SUMMARY AND CONCLUSIONS ...

### REFERENCES ...

### EXPLANATION OF PLATES ...

### APPENDIX
<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al SF diagram</td>
<td>68</td>
</tr>
<tr>
<td>2</td>
<td>Variation diagram</td>
<td>69</td>
</tr>
<tr>
<td>3</td>
<td>ACF diagram</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>Histograms of some trace elements in granites and granitic rocks, quartzites and schists and phyllites</td>
<td>80</td>
</tr>
<tr>
<td>5</td>
<td>Histograms of some trace elements in Khetri copper mines samples' and other rock types.</td>
<td>93</td>
</tr>
<tr>
<td>6</td>
<td>Histograms of some trace elements in the residual soils of granites and granitic rocks, quartzites, schists and phyllites and other rock types.</td>
<td>96</td>
</tr>
<tr>
<td>7</td>
<td>Histograms of some trace elements in the separated mineral fractions of granites and granitic rocks.</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>Histograms of some trace elements in the separated mineral fractions of host rocks.</td>
<td>102</td>
</tr>
<tr>
<td>9</td>
<td>Variation diagram showing relationship between Cu, Pb, Zn, Ni, Co and Cr contents of the bulk rocks and their separated mineral fractions in granites and granitic rocks.</td>
<td>105</td>
</tr>
<tr>
<td>10</td>
<td>Geochemical variation diagram for primary dispersion aureoles of various trace elements in granite and granitic rocks.</td>
<td>112</td>
</tr>
<tr>
<td>11</td>
<td>Geochemical variation diagram for primary dispersion aureoles of various trace elements in quartzites</td>
<td>115</td>
</tr>
<tr>
<td>12</td>
<td>Geochemical variation diagram for primary dispersion aureoles of various trace elements in schists and phyllites.</td>
<td>117</td>
</tr>
<tr>
<td>13</td>
<td>Geochemical variation diagram for primary dispersion aureoles of various trace elements in Khetri Copper mines samples.</td>
<td>120</td>
</tr>
</tbody>
</table>
14 Geochemical variation diagram for secondary dispersion aureoles of Cu, Pb and Zn in the residual soils of granites and granitic rocks, quartzites and schists and phyllites.

15 Variation diagram for primary and secondary dispersion pattern of Cu, Pb and Zn in granite and granitic rocks and their residual soil samples.

16 Variation diagram for primary and secondary dispersion pattern of Cu, Pb and Zn in quartzitic rocks and their residual soil samples.

17 Variation diagram for primary and secondary dispersion pattern of Cu, Pb and Zn in schists and phyllites and their residual soil samples.

18 Variation diagrams for Cu-Zn-Pb in granite and granitic rocks and host rocks with copper ores.

19 Variation diagrams for Ni-Cu-Zn in granite and granitic rocks and host rocks with copper ores.

20 Variation diagrams for Ni-Cu-Zn-Pb in granite and granitic rocks and host rocks with sulphide ores.
LIST OF TABLES

Table 1  Table of formations present in Delhi System (Heron, A.M., 1923), 14P.
Table 2  Stratigraphic succession of Khetri Copper Belt, Rajasthan, as proposed by Roy Chowdhury and Das Gupta (1965), 18P.
Table 3  Analyses of rocks from Khetri Copper Belt, Rajasthan.
Table 4  Analyses of residual soil samples from Khetri Copper Belt, Rajasthan.
Table 5  Analyses of the bulk rock and their separated mineral fractions of granite and granitic rocks, Khetri Copper Belt, Rajasthan.
Table 6  Analyses of the host rocks and their separated mineral fractions, Khetri Copper Belt, Rajasthan.
Table 7  Chemical analyses of rocks from Khetri Copper Belt, Rajasthan. (Major elements).

(Tables 1 and 2 are in the text and tables from 3 to 7 are in the appendix).
LIST OF MAPS

1 Location map

2 Trace element isoconcentration maps
   a) Copper
   b) Lead
   c) Zinc
   d) Nickel
   e) Chromium

3 Schematic geological map of the Khetri Copper Belt (Northern part), Rajasthan.

4 Schematic geological map of the Khetri Copper Belt (Southern part), Rajasthan.

(Map No. 1 - in the text, maps 2 to 4 - in the pocket).
Chapter - I

INTRODUCTION

Location, extent and communication

Some of the important localities of geological interest which lie on this belt are Singhana (28°06' : 75°53' ), Khetri Nagar (28°4'15" : 75°48'30" ), Khetri (28°0' : 75°47' ), and Babai (27°53' : 75°46' ) in the northern part and Satkui (27°49' : 79°35' ), Dhanaota (27°44'45" : 75°30' ), Chappoli (27°44' : 75°36' ) and Saladipura (27°36' : 75°31' ) in the southern part of the belt.

The area under investigation is included in toposheets Nos.44P/12, 16 and 45N/9, 10, 13. of the Survey of India and extends over a distance of about 80 km from Singhana in the north to Raghunathgarh in the south.

Khetri Nagar happens to be the present chief copper mining district. It is situated about 150 miles SW of Delhi and approachable through Gungaon and Narnaul by a good road.

Most of the above mentioned localities within the copper belt are interconnected by metalled roads and frequently buses ply through them. The copper workings of Madhan-Kudhan and those of Kolihan are separated from one another by a road distance of about 10 km.
Physiography, drainage, etc.

The Khetri copper belt is a part of the Delhi System which forms the northwestern extension of the Aravalli mountain range (see Heron, 1923). The Delhi System is composed of two series of rocks namely Alwar and Ajabgarh.

The Aravalli range occupies the north-western part of the Indian Peninsula. They "are now the remnants of once great mountain ranges of tectonic origin" (Krishnan, M.S., 1968, P. 6). According to Pascoe, E.H. (1950, p. 253) the range, which played the most important role in the history of Peninsular topography, was the Aravalli. Here the rocks are highly disturbed with the axes of disturbances more or less parallel to the direction of the chain.

The entire Aravalli range is characterised by a general NE-SW trend commencing from Champaner (22°33':73°24' ) in Gujarat at the head of the gulf of Cambay to near Delhi. It runs across Rajasthan placing Bikaner, Jodhpur and Jaisalmer on the west and Udaipur and Jaipur on the east of it. Auden, J.B. (1933) observed that the Aravalli rock formations appear to continue northeastwards into parts of sub-Himalayan zone of Tehri-Garhwal. Near Delhi, they form sub-surface ridges bordering the Punjab plains. The southeastern part of the Aravalli range bifurcates, one limb turns eastwards and merges into the Satpura range in Central India, the other limb probably continues southwestwards upto the islands of Laccadives and Maldives in the Arabian Sea. The prominent exposures in the north are high quartzitic ridges of Khetri, about 100 miles north of Jaipur.
The Alwar quartzites generally form high ridges while the Ajabgarh Series of rocks present a low lying topography. The high ridges are generally interrupted by sand dunes which are formed from the disintegrated material of the parent rocks, taken away by wind and deposited elsewhere. At places these ridges are found rising prominently from the plains of the region which is widely covered with sand. The elevation of the crest of the ridges sometimes attain 3,450 feet (Raghunathgarh). There are well developed ridges at Kho (3,212 feet) and at Khetri and Bagor where the elevation of the Alwar quartzite is over 2,000 feet from the mean sea level. The well known forts of Khetri and Bagor were constructed on these quartzites. At Babai and Gurha-Ponk, the quartzite ridges are very prominent and extend for several miles.

The Ajabgarh series of rocks are represented by a few rounded, low-lying outcrops often strewn with boulders of the same rocks.

There is no major river in the area. Only two seasonal rivers, viz., Kantli and Kharkhar serve as the drainage of the area in the rainy season. The rivers flow along the natural depression formed by the high ridges occurring on either side. The annual rainfall in the area is low and varies from 20 to 22 inches. The seasonal rains from the southwest monsoon wash the area from June to September. May and June are the hottest months in the region when the day temperature sometimes rises upto 116°F (46.6°C). In cooler months of December and January the thermometer records minimum temperature of about 47°F (8.3°C). Sometimes winters have occasional showers.

There are scattered bushes and shrubs in the area. The predominant
vegetation is Euphorbia plant which grows on the hilly terrain and slopes. Snake, scorpion and goira are common. Panthers are rare while deer are main inhabitant of the jungle.

**Scope of work and statement of problem**

For the last two decades a greater attention has been paid to the Khetri copper belt by the Geological Survey of India, Indian Bureau of Mines, National Mineral Development Corporation and other workers attached to several scientific institutions of India. Some of the investigations have been published and from which it is evident that many of the earlier workers have given considerable attention to the geology, lithology, structure, metamorphism, mineral paragenesis and economic potentialities of the belt. Attempts were also being made to throw some light on the genesis of the copper ores of the area.

A review of the published literature indicates that practically no attention was given to apply the knowledge of geochemistry in the earlier investigation of the area. Therefore, according to a plan worked out, the present project was undertaken with a view to study the geochemistry of the Khetri copper belt. Through trace element studies of rock, mineral and residual soil samples, aided by petromineralogical work, an attempt has been made to gather a knowledge of the geochemical dispersion of certain trace elements in the belt and also to bring out the geochemical relation between the various rock groups and the associated trace elements. Further, an attempt has also been made to trace the source of the copper deposits of the belt.
Brief history of the copper deposits

Certain localities in the Khetri copper belt had been the places of considerable interest to ancient miners who have left evidence of past mining and smelting activities in the form of many abandoned old working pits, cuts, trenches, huge slag heaps and mine dumps.

Nothing is known about the exact period of ancient mining activity. Ain-e-Akbari (p. 194, No. II), written in 1590 A.D., is perhaps the earliest record in which the existence of copper mines at Singhana, Udaipur and Babai was mentioned. Singhana and Udaipur are reported to have copper coinage mints also in those days. Two mints, one at Singhana and the other at Khetri existed upto 1869, which were later closed down by the British Government in India. Silver coins were minted once in the name of Mohammad Shah Alam (1759-1786, A.D.).

According to the Rajasthan Gazetteer (Vol. II, p. 160) and Imperial Gazette of India (Vol. XXII, p. 435), the copper mines in this area did not work regularly from 1872 to 1944. Some efforts were made by several private concerns to take up the mining work during 1923-1927. It was the Jaipur Mining Corporation which carried out some significant mining work during 1944-55.

In March 1957 the Indian Bureau of Mines carried out drilling and prospecting systematically and had submitted an Interim Report in August, 1958. Based on the recommendations of the above report, exploratory mining was taken up in February, 1959. In 1961 Western Knapp Engineering Company, SanFrancisco, U.S.A., were appointed as consultants.
Ancient mining

Ancient mining deserves appreciation of the skill which the old miners possessed. Although in those days there was no dynamite to blast the rocks yet they developed a technique to break them by alternate heating and sudden cooling. Fire wood used to be burnt for heating the rocks. On the third day the miner used to descend the mine with chisel and hammer, a small basket tied round his waist and resting on his knees and a 'diya' on his head. Probably rope ladders were used as conveyers. The workman was skilled enough to bring back only copper ore with him. Some old workings still have ancient wood plumbing arrangement in the form of a ladder to facilitate the movements of the worker during mining. The collected ore was then powdered to proper grain-size using 'Ghuns'. Later on the ore was reduced by mixing it with cowdung, followed by drying and roasting.

The roasted ore was then transferred to the smelting furnace which was made of fire-clay. The ore was mixed with charcoal and flux alternately and heated for about 12-14 hours. The flux was called 'Reet'. The molten copper was then transferred into suitable containers and allowed to cool. It was then ready for the market.

Prospecting, mining and reserves

The work of mineral exploration and prospecting in the area has received momentum in recent years. According to Chandra Chowdhury (1968), 93,111 meters of drilling and 11,800 meters of exploratory mining have already been done. The annual target of copper metal from Madhan-Kudhan mines is 21,000 tonnes and the daily output target of copper ore is 8,000 tonnes. The annual target of Kolihan mine is 10,000 tonnes of copper metal.

* 'diya' = An earthen oil lamp.
** 'Ghuns' = Big hammers
and daily output target of ore is 1,600 tonnes. The site selected for the smelter plant is near the Madhan-Kudhan mine. It is proposed to transfer the ores from Kolihan mine and nearby places to Madhan-Kudhan by an aerial ropeway which is under construction. The daily output of ore dressing and flotation mills at Madhan-Kudhan is expected to be 4,600 tonnes of concentrates per day. These two copper mines are now being developed by the Hindustan Copper Limited, a Government of India undertaking. It is expected that the mines would start production by 1972-73. Further exploratory work in the neighbouring areas is being carried out by the Geological Survey of India.

The exploratory work at Satkui is also being completed recently. A total of about 4,249 metres (Hore et al., 1968) have been drilled in Satkui with good prospects of copper ores. Prospecting is in progress near Saladipura area for pyrite deposits (see Muktinath et al., 1968).

Ore reserves

The proved reserves (Sikka et al. 1966) in the Madhan-Kudhan and Kolihan mine sections are 7,84,90,000 tonnes averaging 1% Cu, 0.02 OZ/tonne Au, 0.53 OZ/tonne Ag upto a depth of 800 meters, with an average width of 7.5 meters. The indicated reserves are 1,01,30,000 tonnes averaging 2.29% Cu, 0.032 OZ/tonne Au and 0.069 OZ/tonne Ag, 0.0165% Ni, 0.0157% Co upto an average depth of 400 meters.

The latest available determination of the grade and quality of copper ores (Chandra Chowdhury, 1968) are summarized here.

The average grade of copper from Madhan-Kudhan Mine is around 0.8 to 1% and Kolihan Mine, 1.5% initially (i.e., the first three years) followed
by 2.2 - 2.4% subsequently. The grades of ores are classified as follows:

- Very low grade ore: 0.5 - 0.65 % Cu
- Low grade ore: 0.7 - 1.2 % Cu
- Medium grade ore: 1.5 - 1.8 % Cu
- High grade ore: 2.9 - 3.2 % Cu

In the central block of Kolihan mine the grade goes up to 3.5 to 5% of Cu. The sulphur content varies from 3 to 8%. The concentrated ores gave a value of 25% copper and 31% of sulphur.

Pyrite-pyrrhotite deposits of Saladipura contain 22.5% to 40% sulphur and the estimated reserve of iron sulphides are 115 million tonnes (Muktinath et al. 1968). Sphalerite, which is commonly associated with pyrite and pyrrhotite, has no economic importance on account of its low zinc content (less than 1% Zn).

**Sampling and preparation of samples**

Samples were collected on a square grid pattern at one km intervals for rocks and the corresponding residual soils. The sample spacing was, however, reduced on the outcrops of granites and granitic rocks. Care was taken to follow the grid lines as far as possible. When more than one sample from an outcrop was collected (dykes, contact rocks, veins, etc.) other than that which falls on the grid points, they were properly numbered. As far as possible only the fresh and unweathered rock samples were collected. The residual soil samples were collected by scooping with a spoon after removing the cover layer completely from the soil.

About 2 kg of rock sample and 500 gms. of residual soil sample were collected from each grid point. Rock samples were stored in new cloth bags.
while soil samples, in plastic bags which were sealed in the field to avoid contamination.

Using 'R' for rock samples and 'S' for corresponding soil samples the collected samples were numbered similarly as $R_1/S_1$, $R_2/S_2$ and so on from the different grid intersections.

In the northern part of the area there is a metalled road (connecting Singhana in the north with Babai in the south) which was taken as the base and the grids were numbered in accordance with the position west and east of the road. In the southern part of the belt (i.e., from Satkui in the north to Saladipura in the south) numbering of samples was done locality-wise.

Preparation of samples

The rock samples were crushed in a Jaw Crusher to smaller pieces. After coning and quartering the chips were transferred to a porcelain mortar and pestle for coarse powdering. Coning and quartering was repeated. Final powdering was done in an agate mortar and pestle.

The powdered sample was then passed through a fine linen cloth stretched on a wooden frame. The oversize particles were again ground in an agate mortar and sieved until they all passed through the cloth and attained a size of 100 to 120 mesh.
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Chapter - II

PREVIOUS WORK AND GEOLOGY

Brief review of earlier investigations

Hacket, C.A. (1881), who first studied the geology of the Central and Eastern Aravalli region of Rajasthan, dealt in some detail the geology and structure of the presently known Khetri Copper Belt. He also briefly stated the occurrence of some economic minerals in the area.

He found that "between Khandela and Khetri, the range again expands and near Raghunathgarh attains to an elevation of 3,450 feet above sea level, but a few miles north of Khetri at Singhana, the range may be said to terminate, for north of that are only a few broken narrow ridges rising abruptly from the plain, and which terminate near Dadri, about 40 miles north of Singhana". He further stated "the Aravalli range, becomes more important both in elevation and breadth", in the Khetri area. He correlated the rock groups of the area with the rest of the Aravalli system and observed that comparatively these rocks have very few granitic intrusives. The main rock types reported by him are gneisses, schists, limestones and the Alwar quartzites forming the peaks of the hills in the area. He found that in the north, near Singhana, the Aravalli hill range was connected with the Alwar hills by the hills in Torawati. In the southern end, the hills extend up to Jaipur and further beyond. The highest peak in the
Khetri area reported by him is located in the range of Alwar quartzite on which the old Khetri fort was built.

He also mentioned in his report that the famous old copper mines at Khetri and Singhana are situated in this portion of the range, the former occurring in the schists and the latter in the quartzites.

The credit of the first systematic geological survey of the Aravalli region goes to another pioneer worker, viz., Heron, A.M. (1923). Earlier it was Bose, P.N. (1906) who made some casual remarks on the geology and mineralisation of this area. Heron (1923) made a more detailed study of the geology, structure and lithology of western Jaipur including the Khetri Copper Belt and also studied the copper deposits of the area (Khetri Copper Belt) from the economic viewpoint. Further he suggested a classification of the rock types known in the region (Table 1).

Heron (1923) at places found it difficult to clearly demarcate between the Alwar and Ajabgarh Series because of the close resemblance of their structural and lithological characters. Generally, the Alwar group of rocks formed higher ridges while the Ajabgarh group occupied low lying and irregular hills. The anticlinal structure is very clear at the south-western end near Babai and extends from Gurha-Ponk (27°50' : 75°41') for about 26 miles south-westwards upto Sangrua (27°25' : 75°22'), Gurha-Ponk happens to be the highest point (3,350') in the belt.

Heron (1923) described the Alwars as a group of largely thin-bedded quartzite with micaceous laminae, some broader zones rich in mica and a
<table>
<thead>
<tr>
<th>TABLE - 1: TABLE OF FORMATIONS PRESENT</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Jaipur and Alwar</th>
<th>W. Jaipur and Jodhpur</th>
<th>S.E. Jaipur and Karauli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent and sub-recent ... Aluvium, blown sand etc.</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>(Vindhyan System ...)</td>
<td>Vindhyan System</td>
<td>Upper Vindhyan System</td>
</tr>
<tr>
<td>(Purana)</td>
<td>(Delhi System)</td>
<td>Lower Vindhyan System</td>
</tr>
<tr>
<td>(Ajabgarh Series)</td>
<td>Intrusive epidiorites, granite and pegmatite</td>
<td>Malani rhyolites</td>
</tr>
<tr>
<td>(Alwar Series)</td>
<td>(quartzite)</td>
<td>Gwalior System</td>
</tr>
<tr>
<td>(Raijhol L.St. and)</td>
<td>(Aravalli System)</td>
<td>(position uncertain)</td>
</tr>
<tr>
<td>(quartzite)</td>
<td>Intrusive epidiorites, granite and pegmatite</td>
<td></td>
</tr>
</tbody>
</table>

Heron (1923), Geology of Western Jaipur.
few brown and black limestones. They are usually fine-grained, reddish, yellow or grey in colour and softer than the typical Alwars occurring elsewhere in the region. He also found that the width of the Alwar outcrops abruptly decrease where granites intruded into them.

He also introduced Ajabgarh rocks as white and reddish, thinly bedded and micaceous flagstones with slates dipping regularly to north-west. They are not much metamorphosed and almost free from igneous intrusions. The main ridges located about ten miles from Singhana, have an elevation of over 2,000 above M.S.L. where the ancient forts of Khetri and Bagor were built.

Heron (1923) gave a brief account of the igneous intrusives in the Delhi System and broadly classified them into the following:

1. Epidiorite Sheets and veins
2. Granite bosses
3. Pegmatite veins.

He preferred the term epidiorite for the basic intrusive rock instead of amphibolite which is generally used. He also pointed out the significance of the granites occurring all over the belt and their possible role in the copper mineralisation. He also found an extreme modification of the pegmatites in the form of quartz tourmaline vein rock in which tourmaline crystals are often zonally arranged. His work was largely based on field observations which gave a firm footing to the later workers.

Roy Chowdhury and Das Gupta (1965) divided the main rock types of the area into sedimentary, metamorphic and intrusive rocks of Precambrian
age and followed broadly the classification of the rocks suggested earlier by Heron (1923) and added some new rock types in order to make it comprehensive. The Alwar Series is characterised by arenaceous rocks while the Ajabgrah Series by argillaceous rocks. They found that the contact between the two series was gradational and at places anthophyllite-cummingtonite bearing rocks resulting from metasomatism attendant with mineralization were well-developed. They recognised a distinct group of intrusive rocks consisting of amphibolites (metamorphosed dolerites), granites and the related rocks (mainly synkinematic replacement), in addition to some younger basic dikes (Post-kinematic) which were least disturbed tectonically. They attached some genetic importance to the granites for copper mineralization although the rocks are not prominently exposed in the area.

The regional strike of the metamorphic rocks is roughly NE-SW and dip at angles varying from $30^\circ$ to $70^\circ$, generally towards west. They are folded into anticlines and synclines plunging south-westerly. There is also a series of major doubly plunging anticlinal folds, the cores of which are occupied by the Alwar quartzites.

The authors also found in the area various types of faults such as transverse faults, strike faults, reverse faults and lateral faults and observed that some of them served as conduits for the transportation of mineralizing solutions.

The grade of metamorphism is higher in the northern part of the belt where it is in the proximity with granites and is rather low where
there is no granite. Generally the grade of metamorphism decreases from north to south.

According to them copper is distributed in a variety of rock types such as schists, quartzites, phyllites, etc., instead of remaining confined to a single rock type. Shear zone fractures & fault planes were found to be the favourable loci for mineralization. They also held mineralisation responsible for a large scale iron-magnesia metasomatism producing anthophyllite-cummingtonite, chlorite and biotite schists. Other effects contemporaneous to mineralization were sericitization and silicification.

The primary sulphide minerals in order of abundance and also in paragenetic sequence are pyrite, pyrrhotite and chalcopyrite. Pyrrhotite gradually decreases towards the south and at Dhanaota it is totally absent. They believed in the hydrothermal origin of the copper deposits.

The generalized tentative stratigraphic succession as given by Roy Chowdhury and Das Gupta (1965) is presented in Table 2.

Several other earlier workers have also made some substantial contributions which are briefly outlined here.

Crookshank (1948) and Arogyaswamy (1949) gave a brief account of the geology, structure and economics of the Khetri Copper Belt. Both of them described the occurrences of copper in metamorphic rocks and emphasized the necessity of prospecting the area in detail.
### TABLE - 2  Stratigraphic succession as proposed by Roy Chowdhury and Das Gupta (1965)

<table>
<thead>
<tr>
<th>Intrusives</th>
<th></th>
<th>Delhi System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ankerite-Chert, Quartz veins</td>
<td>(3. Amphibole quartzites, amphibole gneisses, marbles, etc.</td>
</tr>
<tr>
<td></td>
<td>Younger basic dikes</td>
<td>(2. Arkosic quartzites, quartzites with intercalated phyllites and schists.</td>
</tr>
<tr>
<td></td>
<td>Granites, pegmatites, quartz veins, etc.</td>
<td>(1. Phyllites and schists</td>
</tr>
<tr>
<td></td>
<td>Older basic rocks</td>
<td></td>
</tr>
<tr>
<td>Ajabgarh series</td>
<td>(6. Quartzites, phyllites, schists, etc.</td>
<td></td>
</tr>
<tr>
<td>(about 1300m)</td>
<td>(5. Marbles, calc-gneisses, etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4. Various types of schists and phyllites</td>
<td></td>
</tr>
<tr>
<td>Gradational Contact</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delhi System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alwar Series</td>
<td>(about 1300 m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Phyllites and schists</td>
<td></td>
</tr>
</tbody>
</table>

Base not exposed
Based on thin section studies of some metamorphic rocks containing traces of copper minerals, Deb (1948) pointed out that usually the carbonate minerals form superficial encrustation in the secondary enrichment zone of most of the metamorphic rocks. He found sulphide minerals to be in a highly disseminated state and occurring only in the amphibolites and garnetiferous quartzites. The same author also noticed that the degree of metamorphism was less intense in these rocks as compared to the older rocks of the Aravalli System.

Later some of the officers of the Geological Survey of India investigated the area in a greater detail, major part of which is in the form of unpublished reports. Chandra and Aditya (1956) mapped some parts of the area and submitted a report on the future prospects of exploration of copper ore. Roy, B.C. (1958), while working on the economic geology and mineral resources of Rajasthan and Ajmer pointed out that the deposits are worth exploring. Roy Chowdhury, Prasad Rao, Venkatesh, Ramienger and Das Gupta (1962) studied the geologic potential of the belt. They made many useful recommendations on the test drilling and prospecting for copper. Das Gupta (1964) also attempted to demonstrate the close relationship between deformation, grade of metamorphism and mineralization. He indicated that in the northern part of the belt, mineralization took place under mesothermal while in the southern part under epithermal conditions. He believed that the ore forming fluid was initially rich in iron, precipitating magnetite and later in copper and sulphur leading to crystallization of sulphides.
Verma and Patni (1962) also discussed the copper deposits of Khetri and pointed out that the mineralized zone comprised a system of fracture-filled linked ore veins which are flanked by disseminated sulphide in the brecciated wall rocks. They assumed faults to have acted as feeder channels and shear fractures and foliation planes as ore receptacles. The authors described that the deposits represented high temperature hydrothermal replacements and the mineralising solutions were thought to have been derived from the pre-mineral intrusion of Erinpura Granite. Verma and Krishnanauni (1963), while contributing to the origin of copper deposits of Khetri indicated some important factors which control the copper mineralization. They also described the distribution of minor elements in the sulphide minerals and their correlation with the temperature of formation of the ores. They regarded mineralization to be epigenetic and assumed it to have occurred under mesothermal condition. The mineralizing solutions appear to be connected with the late stage of emanations from the granitic magma.

Mukherjee, A.D. (1966), studied some ore minerals from the Kolihan section and reported first the occurrence of valleriite/mackinawite, ilmenite and rutile from the deposits. He also discussed the structural and textural features of the ores and suggested the probable nature of physico-chemical environment during the mineralization. He also outlined a probable paragenetic sequence of the ore minerals.

Rao and Rao (1968) carried out ore microscopic examination of metallic minerals in some detail. They pointed out the structural
variance of ore minerals and observed the occurrence of intergrowths of other sulphide minerals in them. On the basis of textural study they indicated the presence of at least two generations of sulphides, the dominant minerals being pyrrhotite and chalcopyrite in both generations. They also observed that the textural features indicate a high temperature of formation of the deposit.

Muktinath, Natarajan and Mathur (1968) described the occurrence of zinc in shear zones near Saladipura in the southern part of Khetri Copper Belt. They found the shear zones to be rich in pyrite and pyrrhotite with small amounts of sphalerite, chalcopyrite and galena below the gossans. The authors found that sphalerite was chiefly associated with pyrrhotite carrying about 1% of zinc which might be extracted as a by-product.

Recently Das Gupta (1970) reported a massive pyrite-pyrrhotite deposit at Saladipura where a steeply plunging anticline localised the mineralization. The core of the anticline is formed of amphibolite in which the sulphide ores occur. He found the deposits to be composed essentially of pyrrhotite with a subordinate amount of pyrite and a silicate gangue. The author remarked that chlorine metasomatism was responsible for altering plagioclase and part of hornblende into scapolite. He also pointed out that the Fe of the Pyrite and pyrrhotite has been derived from the pre-existing iron rich silicates and oxides.
Stratigraphic Position

The stratigraphic nomenclature of Delhi System was first introduced by Heron (1923). It includes the rocks of the Alwar Series and Ajabgarh Series, a part of which is exposed in the so-called Khetri Copper Belt, Rajasthan.

The stratigraphic position of the Delhi System in Rajasthan was given by Krishnan (1968) as follows:

Vindhyans of W. Rajasthan
Malani suite of igneous rocks
Delhi System
Raialo Series
Aravalli System
Archean (Banded gneissic complex and Bundelkhand gneiss).

The rocks belonging to the Delhi System extend from near Delhi in the north, through Ajmer and Mewar to Idar and Palanpur in the south. They overlie the older gneisses and schists and at places the Raialos with a great unconformity which Heron (1917) named as Eparchean interval. They are overlain by the lower Vindhyans system unconformably. Between the Aravallis and the Delhi or Raialos Heron (1923) described, "a violent and very clearly seen unconformity which has been traced in a general way for over 300 miles" (see Pascoe, 1950).

The Delhi System has been placed in the Purana group of the Indian stratigraphy and includes all the Precambrian rock formations occurring...
between the Eparchean unconformity and the Cambrians. However, this classification has not been much favoured by the Indian Geologists in recent years.

The rocks of the Delhi System differ from the other late Precambrian formations of India in having suffered extensive folding and intrusion of igneous rocks. They also show intense and widespread metamorphism in the central and southern parts of Rajasthan similar to that of the underlying Aravalli System. The resemblance in the rocks of these two systems is so striking at places that their true identity becomes difficult.

The Delhi System has been correlated with the Dharwar System of Mysore, but there is a difference of opinion as regards their lithology, degree of metamorphism and an unconformity which separates the two. At the same time the Alwar quartzites of Rajasthan do not have any equivalent in the Dharwar rocks.

The age of the Delhi System is widely taken to be Algonkian. It has further been confirmed by the radioactive age determinations of some samples of uraninite from Bisundni, Ajmer, Merwara (735 m.y.) and monazite from Soniana, Mewar State (Age ranges from 700 to 865 m.y.) which were found in the pegmatites occurring in the Erinpura granite intrusions (Aswathanarayana, 1964). This may be true only when it is accepted that the Erinpura granite belongs to Delhi age. The pegmatites and Bajalos do not have any radioactive mineral and thus radiometric dating was not possible in these cases as yet.
Recent investigations by Crawford (1969) on the basis of radiometric dating (Rb-Sr method) indicate that the Delhi System is much older than that it was earlier believed. The age of the Berach granite which intrudes the Delhi System has been determined to be 1,650 m.y. He correlated the Delhi System with the Gwalior lavas whose age was found to be 1810 ± 200 m.y.

**Structural Setup**

A brief summary of the geological structure of the area is presented hereunder:

The rocks of the area have undergone intense folding and faulting due to which its structural history became complicated. There are a number of elongated NNE and NE-SW doubly plunging anticlinal folds throughout the area. The regional strike of the formations is NE-SW. Their dips vary from 30° to 70° towards west or east. The cores of the folds are occupied by the rocks of Alwar Series. Micro coaxial folds are also developed on the limbs of the major doubly plunging folds.

The intense folding is accompanied by numerous faults and dislocations. There is a series of transverse, oblique and strike faults. Transverse faults are frequent. These are indicated by the occurrence of fault breccia, slickensides and displacement along the fault planes. This was particularly indicated where felspathic quartzite displaced the overlying magnetite-haematite band as it is in Madhan-Kudhan Section
According to Roy Chowdhury and Das Gupta (1964) strike faults are located either at the contact of the Ajabgarh and Alwar Series or along the contacts between different lithological units.

In the Madhan-Kudhan section the mineralized zone has been displaced by faulting and accordingly, they are some post-mineralization faults. Therefore, they cannot be regarded as channels for hydrothermal solutions. According to Roy Chowdhury (1965) the development of sub-parallel shear zones in association with the major faults is common and is more important than the faults themselves from the point of mineralization.

Although the rocks have been subjected to an intense deformation, some of the primary sedimentary structures are well-preserved in some rocks. The felspathic quartzite of Alwar Series and sericite quartzite of Ajabgarh Series show current bedding and gradded bedding. Bedding strike is from N25° to N70° dipping northwesterly and the dips of the beds vary for obvious reasons as they depend on the position of folds and faulting. Ripple marks are also present in these rocks. Some quartzites (massive and magnetite-haematite quartzite) and brecciated rocks occurring at the contact of granites and conglomerates are however exceptions.

**Metamorphism**

Metamorphism has resulted in much mineralogical and textural rearrangement in rock units. The mineral assemblage of the argillaceous rocks is garnet, chlorite, kyanite, staurolite, andalusite and amphibole. This mineral assemblage reaches to quartz-albite-epidote-almandine
subfacies (B 1-3) of the green-schist facies (Turner and Verhoogen, 1962) and to the high grade amphibolite facies. These minerals indicate progressive regional metamorphism with increasing temperature. The mineral assemblage in the arenaceous rocks is simple. Amphiboles, chlorite and epidote are the common associated minerals suggesting relatively lower grade of metamorphism.

Chloritization of garnets (garnetiferous quartz-chlorite-schist) and sericitization of andalusite (biotite-andalusite schist) indicate retrograde metamorphism.

The grade of metamorphism is higher near the granitic rocks and low away from them. Large scale felspathization of quartzites in the vicinity of granites indicate contact metamorphism. Andalusite bearing rocks occur near amphibolites indicating the possibility of their formation due to the intrusion of basic rock.

According to Roy Chowdhury and Das Gupta (1965) metamorphism is accompanied and followed by metasomatism resulting in the felspathization of schists in Jasrapura, Babai and Kotri, and scapolitization of amphibolites (see Das Gupta, Chakravorty, 1962) in the area.

The predominating iron-magnesia metasomatism of quartzites and schists is represented by anthophyllite-cummingtonite and chlorite in the northern portion of the belt. These processes are connected with the wall rock alteration and superimpose the products of regional and thermal metamorphism.
The host rocks of copper are intermediate metamorphic rocks represented by garnetiferous quartz-chlorite-schist, biotite schist, amphibole-schist, etc. High grade metamorphic rocks (amphibolites) are not good host while low grade metamorphic rocks (quartzites and phyllites) welcomed the ore mineralization very well.

**Ore Deposits**

**Occurrence:** The sulphide ore deposits of Khetri have been reported to occur all along the belt running from Singhana in the north to Baghunathgarh in the south. In most places their presence was indicated at the surface by the occurrence of gossan consisting of oxidized ores of copper and iron having stains of malachite and azurite, boxwork of lenticular limonitic or red ochre bands. Realising the economic importance of the ore deposits, the ancient miners sank innumerable pits which could be seen even today scattered all over Singhana which is also known as the ancient smelting and marketing centre of copper in the area. Most of the present day prospecting is guided by the location of ancient working.

The names of the localities in the northern part of the area where prospecting and some mining for copper is in progress are Peeliwali (28°4'15" : 75°48'45" ), Ghatiwalli, Madhan (28°4'15" : 75°48'30" ), Kudhan (28°4'15" : 75°47'25" ), Masjidwali (28°4' : 75°48' ), Dundumwali (28°4'15" : 75°4'45" ), Kolihan (28°1' : 75°44' ), Khetri (28° : 75°47' ) & Akwali (27°56' : 75°46' ).

The Hindustan Copper Ltd., a Government of India undertaking, holds
mining and prospecting lease in most of the above mentioned localities.

Copper is also being prospected at Satkui (27°49' : 79°35' ), Dhanaota (27°44'45" : 75°30' ) and Charana (27°42' : 75°25' ) in the southern part of the area.

Exploratory work is still in progress at Saladipura (27°38' : 75°31' ) where a promising pyrite deposit has recently been located.

Copper has mineralized both the Ajabgarh and Alwar Series of rocks, but the extent of mineralization is relatively wide in the former series. The mineralization, however, is not confined to any particular rock type of either of the two series. Local as well as regional shift in mineralization is not uncommon in this area.

In the northern part around Madhan-Kudhan section, although the chief host rock is garnetiferous quartz-chlorite-schist, yet others such as garnetiferous amphibole-chlorite-schist, amphibole-quartzite are also mineralized to some extent. The chlorite-schist continues to be the chief host rock in the Kolihan mine though garnetiferous biotite-schist, andalusite-schist, phyllites and amphibolites also have some indications of copper mineralization.

Passing further south, the occurrence of copper has also been reported from the biotite-schist and phyllites occurring around Akwali.

There is a marked change in the nature of host rock at Satkui and Dhanaota in the southern part of the belt. Here the quartzites and phyllites are the chief host rocks. A few schistose rocks (chlorite and
biotite-schists) are locally mineralized around Dhanaota. At Saladipura biotite-quartzite, biotite amphibole-scapolite quartzite, carbonaceous phyllites (Muktinath, 1968) are the host rocks for pyrite-pyrrhotite deposits having insignificant amounts of sphalerite, chalcopyrite and galena.

Mineralogy and Composition: Pyrite, pyrrhotite and chalcopyrite are the primary sulphide ores present in order of abundance. The paragenetic sequence of the ores was first determined by Roy Chowdhury and Das Gupta (1965).

According to the compilation work done by Sikka and Chatterjee (1966) the mineral assemblage and paragenesis of the Khetri Copper deposits are as follows:

**Mineral Assemblage**

<table>
<thead>
<tr>
<th>Copper minerals</th>
<th>Chalcopyrite, cubanite, bornite, valleriite, tetrahedrite, cuprite and tenorite.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paragenesis</td>
<td>Pyrrhotite-pentlandite-pyrite-chalcopyrite</td>
</tr>
<tr>
<td>Other Minerals</td>
<td>Cubanite-wellerite-melnicovite</td>
</tr>
<tr>
<td>Associated gangue minerals</td>
<td>Quartz, chlorite, biotite, calcite, scapolite, muscovite, sericite, zircon, garnet, amphiboles apatite, andalusite, cordierite, sideroplesite.</td>
</tr>
</tbody>
</table>

Form and Shape: Much information was gathered from the old stopes, bore hole data and underground working to evaluate the nature of the ore bodies. Since the ore control criteria are not dependable, the true form and shape
of the ore bodies remain confusing. A general assessment on the basis of the above knowledge reveals that the ore shoots are lens-shaped dipping steeply towards the west. Where such occurrences are frequent they are usually arranged in an en-echelon pattern and occasionally displaced by transverse faults.

The mineralization also occurs in the form of impersistent stringers, disseminations, veins and veinlets, blebs and patches, replacements, etc.

Individual ore shoots vary in length from a few meters to 200-500 meters. Their plunge depends on the nature of the host rock. Usually it varies from $10^\circ$ to $40^\circ$ south-westerly or north-westerly in the northern portion of the belt. Little is known about the form of ore bodies in the southern part of the belt because of the fact that no regular prospecting work has yet been done in this area.

**Control of Ores**

The exact nature of control in the belt is still dubious as it is not possible to say conclusively whether or not the ore-deposits have lithological, stratigraphical or structural controls.

**Lithological** - There is no lithological control in the belt in a true sense. As stated earlier that there is a shift in the mineralization from schistose rocks to quartzites, phyllites and amphibolites. The shift cannot be attributed to the parent composition of the metasediments which are found to have had different chemical compositions. The present author
recorded the original sediments by plotting the determined analytical results of phyllite, quartzites, epidosite and amphibole-schists on ACF diagrams. They are found to be clays and shales and greywackes. It is, therefore, evident that the distribution of sulphide ores has not been controlled by the lithology of the host rocks.

**Stratigraphic** - Since the mineralization is not restricted to any particular horizon there appears to be no stratigraphic control on the ore-deposits. In the northern part of the belt the contact zone between Alwar series and Ajabgarh series is believed to be the probable site of copper mineralization. Towards south around Akwali the mineralization shifts from the contact zone to the overlying phyllites and schists of the Ajabgarh series. At Satkui and Dhanaota the younger Alwar quartzites as well as the phyllites of the lower Ajabgarh series are chiefly mineralized.

According to Hore et al. (1966) the mineralisation at Satkui is localized along a major strike slip fault developed at the contact of massive hard quartzite and soft phyllitic quartzite of Ajabgarh Series.

Roy Chowdhury and Das Gupta (1965) are of the opinion that this progressive shifting of the zones of mineralization higher in the sequence was not possibly due to any broad stratigraphic control but due to inter-communicating structures in different formations.

**Structural** - According to Roy Chowdhury et al. (1965) the chief structural features controlling the ore localization in the area are the normal and the
reverse faults. Fractures and shear zones which were developed as a consequence of major folding and faulting are also the important structural features controlling the mineralization. Fault zone fractures played more important role than the fold zone fractures. Moderately dipping shear zones are richly mineralized while steeply dipping shear zones are barren except those which run parallel to the fold planes. Roy Chowdhury et al. (1965) have made important observations that the fractures and shear zones sub-parallel to the main faults were the favourable sites for deposition of ores whereas the faults themselves were the main conduits of transportation of mineralizing solutions. In support of their observations they agreed that in some cases the ore shoots were located at the point of intersection of shear zones and faults.

But they also stated that there are cases where shear fractures do not show mineralization although they run parallel to the mineralized veins. These were believed to have been developed by late deformation contemporaneous to the period of mineralization. The author observed that at places shearing was of low intensity but the host rocks were richly mineralized (Madhan-Kudhan section) while the poorly mineralized foot wall quartzites were intensely sheared.

The schistose rocks are generally rich in copper. Cleavage planes of the schistose rocks which run parallel to the bedding are highly mineralized. Mineralized quartz veins run parallel to the strike of foliation. Roy Chowdhury et al. (1965) observed that most of the transverse faults are post-mineralization but there are pre-mineralization faults
also which are later than the strike fault. It is interesting to note the pre-mineralization transverse faults which intersect the main shear zones are richly mineralized (Madhan-Kudhan section). But it is also true that all faults are not mineralized across their intersection. At places there are also some transverse faults which have displaced the ore bodies (Madhan-Kudhan section) indicating that they are post-mineralization faults. Such faults have also been located at Dhanaota. These post-mineralization transverse faults are invariably barren. In the Madhan-Kudhan section some of these barren transverse faults were intersected by later quartz-veins and basic dykes.

The folds do not show significant ore control. Smaller folds near the fault zones are mineralized while larger folds are barren. The nose of the folds and the axial zones are poorly mineralized.

The fault breccia in the Kudhan mine section is barren while the brecciated marble near Satkui is mineralized. Joints (Saladipura) and tension fractures have played but minor roles in controlling mineralization. Almost all joints in the fault zones show slickensides with or without mineralization.

An interesting observation was made both in the Madhan-Kudhan and the Kolihan sections where the host rocks were found to be largely mineralized in the hanging wall but beyond it there is a barren massive quartzite probably serving as a barrier to ore-fluids.
Chapter - III

LABORATORY METHODS OF STUDY

Systematic analyses of rock samples for major elements by conventional chemical methods

The analyses was carried out in order to determine fourteen major constituents in igneous and metamorphic rocks. The elements determined and the procedure followed are summarized below:

Total water (H₂O +) was determined with the help of Penfield tube at 800°-900°C. Moisture was determined by taking a known weight of the sample in a platinum crucible and heating it upto 110°C in an oven.

Silica: Each sample was fused with anhydrous sodium carbonate (1:6 ratio by wt.) in a platinum crucible. The fused mass was cooled and dissolved in 1:1 HCl. Double dehydration was done and the solution was prepared in HCl (1:1). Filtered and the residue was ignited in a platinum crucible at 900°C and weighed. Silica was determined by hydro-fluorizing the acid insolubles.

The residue left after hydrofluorization was fused with potassium pyrosulphate, dissolved in HCl (1:1) and the solution was added to the original stock.

R₂O₃ were determined by precipitating the hydroxides with ammonia in the presence of NH₄Cl. The precipitate was filtered and then dissolved
in HCl and reprecipitated by ammonia. Filtered, ignited initially at 900°C and finally heated to red hot on a blast burner (about 1,100°C). Necessary correction for platinum of the crucible (dissolved during pyrosulphate fusion) was made by precipitating it (Pt) with H₂S from acid solution. The precipitate was then filtered, ignited and weighed.

Total iron (FeO + Fe₂O₃) oxides were determined by titrating a known aliquot against K₂Cr₂O₇ (N/20) solution after reducing it by silver reductor.

Ferrous iron was determined by taking fresh sample in a silica conical flask. Silica was hydrofluorized and the solution was prepared in CO₂ atmosphere. Boric acid was added and the solution was immediately titrated against standard K₂Cr₂O₇ (N/20).

Titanium oxide (TiO₂) was determined colorimetrically by developing colour by H₂O₂ in the presence of H₂SO₄ and H₃PO₄. The percentage transmittance was measured spectrophotometrically.

Manganese oxide was also determined colorimetrically by converting it to permanganate and measuring colour intensity spectrophotometrically.

Calcium oxide was determined from the filtrate left after the precipitation of hydroxides in R₂O₃ determination. Precipitation was done in highly ammoniacal solution by oxalic acid solution. The precipitate was dissolved in HCl and reprecipitated. The final precipitate was filtered, redissolved in H₂SO₄ and the warm solution was titrated against standard solution of KMnO₄ (N/10).
Magnesium oxide was determined from the filtrate left after calcium determination. Magnesium was precipitated by dihydrogen ammonium phosphate solution in alkaline medium. Dissolved, reprecipitated, filtered and ignited in a muffle furnace at 900°C.

Alumina (Al₂O₃) was determined by subtracting the weight per cent of the oxides of iron, titanium and manganese from that of R₂O₃

\[ \text{Al}_2\text{O}_3 = R_2\text{O}_3 - (\text{Fe}_2\text{O}_3 + \text{FeO} + \text{TiO}_2 + \text{MnO}) \]

Alkalies (K₂O and Na₂O) were determined by taking fresh sample in a platinum crucible. Silica was removed by hydrofluorization. Hydroxides were precipitated and a pinch of ammonium carbonate plus a little ammonium oxalate were added. The volume was made up and left for 3-4 hours. Filtered and the alkalies were determined with the help of E.E.L. flamephotometer.

Sulphur was determined by carefully fusing the sample with sodium peroxide (1:6 ratio by weight) in a nickel crucible and taking the mass in water. Filtered and precipitated as BaSO₄ by BaCl₂ solution (10% solution) in acidic medium.

Carbon-dioxide was determined by absorption method. A known weight of the sample was decomposed by orthophosphoric acid in a nitrogen atmosphere. The liberated carbon dioxide was absorbed in already weighed ascerite tower and U-tube. Increase in weight in ascerite tower and U-tube determines the quantity of carbon dioxide present.
Separation of minerals from rock samples

Ten different samples of granites and granitic rocks from different outcrops of the belt were selected to separate their ferromagnesian and felsic mineral constituents. The ferromagnesian minerals commonly are biotite, hornblende and chlorite, epidote, etc. The felsic group essentially includes quartz and feldspars.

Six samples were selected from three varieties of rocks (amphibole-quartzite, garnetiferous quartz-chlorite-schist, garnetiferous quartz-biotite-schist) which host the copper ores at the Madhan-Kudhan as well as Kolihan mines. The minerals separated are garnet, biotite, hornblende and chlorite and magnetite. Felsic group comprised of quartz and a little of feldspars.

Six samples of copper-iron sulphide were taken for the separation of pyrite, pyrrhotite and chalcopyrite. Pyrrhotite and chalcopyrite were further separated as pure mineral fractions. Pyrite, on account of its occurrence in small quantity (Kolihan samples), was omitted for final purification.

Initial treatment - Thin sections of the selected rock samples were examined under the microscope to identify their mineral constituents, grain size, the nature of grains, inclusions and their parting distance. The copper ore samples were examined under ore-microscope.

Sample preparation - For the purpose of magnetic separation -80 to -120 and up to +200 mesh grain-size was used. Sometimes still finer powdering was necessary, particularly in case of garnet which on account of its fine
inclusions of quartz needed finer powdering to decrease the number of foreign grains.

The powder was first stirred with distilled water in a beaker to remove adhering dust particles. Washing was repeated till the layer of water above it became clear. Then the sample was dried in an oven at 110°C.

Magnetite was removed with the help of a strong hand magnet by wrapping it in a tracing paper and combing it over the sample powder repeatedly.

**Separation by Frantz Isodynamic Magnetic Separator**

**Principle** - The principle of the isodynamic magnetic separator depends on the relative magnetic susceptibilities of minerals.

The powdered sample was run through the separator repeatedly (3 or 4 times) increasing gradually the amperage after each run until about 95% of a mineral fraction appeared in the magnetic side. This range determined the magnetic susceptibility of the mineral. Remaining impurities were removed by repeatedly passing the last separated fraction at a slow rate. Where necessary (e.g., garnets) the last fractions were further powdered to still smaller grain-size and the operation was repeated.

**Separation of minerals** - A little of powdered granites was taken and magnetite was first separated by hand magnet. Then the magnetite free powder was transferred into the hopper. The forward slope of the magnet was kept at 20° and the side slope at 10-15°. 0.8 ampere current was passed and the vibration was kept at medium range. Biotite, hornblende
and chlorite, and epidote fell on the magnetic side while quartz and feldspars fell on the non-magnetic side. Then the ferromagnesian minerals were taken for separating them from one another. The current was increased gradually from zero ampere. Biotite was separated at 0.5 ampere. Hornblende and chlorite were difficult to separate and therefore separated together at 0.8 ampere on the magnetic side. Epidote was separated at a current value of less than 0.8 ampere. The separated fractions were passed several times to get maximum concentration and purity. Quartz and feldspars were collected together on the non-magnetic side at a current value of 0.8 ampere.

The powdered host rocks were run through the instrument individually and the mineral separation was done effectively in the same manner as above. Garnet was magnetically separated at 0.4 ampere on the magnetic side. The bigger crystals of garnet were handpicked before fine grinding.

Chalcopyrite containing pyrrhotite were treated differently. Pyrrhotite being highly magnetic was first separated by a hand magnet and finally the sample was run in the magnetic separator at a low current. Pyrrhotite adhered to the sides of the chute and was removed by putting off the current. Chalcopyrite was collected on the nonmagnetic side.

Panning of the concentrated fractions - A foolscap size paper of ordinary thickness was stretched and kept sloping at 30°. Then the sample was sprinkled. One end was kept holding and the other left free. The paper was then slowly tapped on the sides. The mineral fractions moved down under the influence of gravity. Lighter ones moved faster than the heavier
ones and thus separated. This was particularly effective in case of micas.

**Separation by heavy liquids** - Bromoform (sp.gr. 2.85 to 2.90 at 20°C) was used for further concentration of heavy minerals. The desired specific gravity was obtained by diluting bromoform with alcohol. Sometimes the finer fractions were subjected to centrifuging.

**Pure separation** - The separated fractions of sufficiently high purity were checked under the binocular microscope or mounted on a glass slide to identify the combined fractions. Final separation was done by hand picking using a forcep and a brush under the binocular microscope. The purity of the sample was estimated by mounting it on a slide and point counting.

**Trace element analyses by Atomic Absorption Spectrophotometer**

The application of Atomic Absorption Spectrophotometer to the analysis for various elements particularly those present in traces has got momentum in recent years. It was first described in 1955 by Walsh, Alkemade and Milatz. Since then it became an important instrumental technique of analyses. It has got less chemical interference and interpretation of results is simple.

**Principles** - Its principle is opposite to emission spectros-copy. When a substance is volatilized in an arc or a flame it gets ionized. Some of the electrons of the atoms of metal get energized and jump to higher levels. When they fall back to lower energy levels, they emit light energy of specific wavelengths which are characteristic of the elements present. Only 1–5% of atoms get excited while the larger percentage remains in
so-called ground state. These atoms in the ground state are capable of absorbing light of the same wave-length as that emitted if they were excited. The absorption is measured electrically which determines the quantity of the element present. The Atomic Absorption Spectrophotometers used for the present investigation are Perkin-Elmer (303-model) and Jarrel-Ash model.

Decomposition of sample and preparation of solution

One gram of the sample was weighed in a platinum basin (100 ml.). A few drops of double distilled water were added followed by the addition of 5 ml. of perchloric acid and 20 ml. hydrofluoric acid. The basin was kept on an electrically operated hot plate at low temperature for slow evaporation for 5-6 hours. When copious fumes of perchloric acid continued and the mass became viscous, the platinum basin was removed from the hot plate and allowed to cool. Again 2 ml. of perchloric acid and 5-8 ml. of hydrofluoric acid were added. The basin was again kept on the hot plate at low temperature. When the mass attained condition as before, the basin was removed from the hot plate and cooled. The sides of the basin were washed with double distilled water. 5 ml. of perchloric acid was added and the basin was heated till perchloric acid fumes started coming. Cooled and diluted to about 20 ml.

Filtered through Whatman (No. 42) filter paper in a 100 ml. volumetric flask. Washing was done with warm distilled water for 5-6 times. Cooled and the volume was made up to 100 ml. The sample solution was ready for feeding to the instrument.
Preparation of Blank - A blank was prepared along with each set of the samples following the same procedure as adopted for sample solution.

Preparation of standards - Stock standard solutions of 1000 ppm. were prepared for each element of interest. Further fractions of 0.1 ppm. to 100 ppm (as desired) were prepared by diluting the stock solutions. The acidity of the solutions was maintained to 5% in all cases using perchloric acid.

Some modifications were made in the case of determination of silver and lithium. For silver, the solution was made up to 100 ml with 7% of ammonium acetate and 0.1 gm of KCN was added to it. For lithium 50 ml of the solution was taken and 10 ml of sodium chloride solution (equal to 500 ppm of Na) was added and the volume was made up to 100 ml.

Soil samples were digested in a mixture of HCl and HNO_3 (2:1) and the solution was prepared for analyses by Atomic Absorption Spectrophotometer.

Advantages

1) There are no spectral interferences as the monochromator allows the line of the wavelength characteristic of the cathode.

2) There are no chemical interferences. The elements sought are simply to be dissociated from its chemical bonds. No excitation is required. A little difference in the temperature of the flame would have
negligible effect on the results.

3) Since the number of atoms involved in absorption are more than 95%, the analytical results are of great precision and accuracy.

4) The instrumentation technique is simple.

5) Most of the elements can be determined from a single solution.

6) Major elements can also be determined with equal accuracy but it needs more care in preparation of sample and dilution.

7) Calculations are easy.
Chapter - IV

**OCCURRENCE, LITHOLOGY, PETROMINERALOGY AND PETROCHEMISTRY OF ROCKS**

The rocks of the area have been divided into the following two major groups.

1. **Intrusives**
   - Granites and granitic rocks
   - Pegmatites and quartz veins
   - Basic dykes

2. **Metamorphics**
   - Quartzites
   - Schists and phyllites
   - Carbonate rocks

**Occurrence and lithology**

**Granites and granitic rocks** - These rocks are further classified into:

   a. Pink granite and granite gneises
   b. Grey granite and granite gneises
   c. Aplite

a) **Pink granite and granite gneisses** - Pink granite is comparatively abundant in the area with colours varying from light to deep pink. It is a coarse-grained rock and shows gneissic banding at some places.

   In some cases augens of potash feldspars are distinctly seen. The rock comprises mainly of potash feldspars, quartz and some ferromagnesian minerals, viz., epidote, hornblende and biotite. In the gneissic variety the ferromagnesian minerals are usually concentrated in the darker bands and schlieren.
b) Grey granite and granite gneisses - The grey granite is a light coloured rock and has only a few occurrence in the area. They are medium to fine-grained rocks composed mainly of plagioclase feldspars and quartz with some biotite as the ferromagnesian mineral. The gneissic variety is of two types -- one with amphibole as the predominant ferromagnesian mineral and the other with biotite. The augen structure is mostly found in the latter variety.

c) Aplite - The aplite is fine-grained and light pink in colour. It comprises mainly of potash feldspars and quartz with a little of amphibole.

For the sake of convenience the description of the granites and granitic rocks has been presented sectorwise as follows:

1. Gotro sector - There is an outcrop of pink granite southward from Gotro village which extends up to 3 km beyond which it is covered under alluvium. Occasional veins of quartz (see Plate I Fig. 2) measuring from a few inches to three feet or more wide and several feet in lateral extent are found cross-cutting the granite. The contact of the granite with the surrounding felspathic quartzite is not sharp. A brecciated rock occurs at the contact of granite with felspathic quartzite (see Plate IV Fig. 1).

   The granite is dotted with a dark green amphibole and epidote which are also concentrated along some of the joint partings and give rise to schlieren structure (see Plate IV Fig. 2).

2. Nizampur road sector - There is an isolated small outcrop of pink granite at Nizampur road. The outcrop is strewn with big and small boulders of granite and is surrounded by quartzites.
It is a medium-grained rock more or less equigranular having biotite as the chief ferromagnesian mineral.

3. Gorwala sector - Between Gorwala-ki-Dhani and Tihara-ki-Dhani, there are several small exposures of pink granite-gneisses which presents a low lying rolling topography. Its contact with quartzites is not clear as a large part of the outcrop is covered under alluvium or residual soil.

Biotite which is present in noticeable amount is arranged in bands to give gneissic appearance.

4. Biharipur sector - There is prominent outcrops of pink granite covering a considerable area south of Biharipur. Small quartz veins often occur in the granites having a cross-cutting relation. Its contact with the quartzites is also not distinct.

Biotite is the main ferromagnesian mineral. Occasionally the rock is foliated.

5. Chappoli sector - There is an extensive occurrence of pink granite gneisses and grey granite and grey granite gneisses near Chappoli. Several prominent outcrops are found in the east of Chappoli near Mandaora and south and southwest of Chappoli.

Near Mandaora the outcrop of granite is bounded within the curvature of an arcuate quartzite ridge due to which its contact with the latter is easily made out. Near the contact zone the granite is altered and brecciated.

The rock is generally coarse-grained but becomes fine-grained near the contact with quartzite. Joint planes in both fine and medium grained granites have some iron oxide coatings due to supergene deposition and action of
surface water.

6. **Udaipur sector** - In the east of Udaipur there is a small outcrop of grey granite gneiss in contact with quartzite. It is intruded by minor veins of pegmatite which are disposed almost parallel to the gneissic bands. (see Plate IV Fig. 3).

The rock is dark coloured medium-grained. The main ferromagnesian mineral is amphibole which is segregated in distinct bands.

7. **Saladipura sector** - South and southwest of Chappoli particularly west of Saladipura, several outcrops of pink and grey granite gneisses generally occur as low lying exposures. They are medium to coarse-grained rocks and have augen structure at places. The size of the augens in pink granite gneisses varies from 0.2 mm to 1 cm. (see Plate V, Fig. 1).

The outcrops cover large areas and are lenticular in shape. They are covered with big boulders. Their contact with quartzites is sharp in the southwest of Chappoli.

The pink gneisses have augens of potash-felspars and a little of biotite. The grey gneisses have amphibole and biotite as the main ferromagnesian mineral.

**Pegmatites** - Pegmatites occur only at/few places in the belt. They vary in their mode of occurrence and also in mineral composition.

Northwest of Madhan-Kudhan mines there are a few small outcrops of pegmatites intruding the quartzites. One pegmatite vein was found to be about 20 feet wide and about 200 feet long. They are mainly composed of quartz, feldspars and tourmaline. Muscovite is present only rarely. In some cases the crystals of tourmaline are very well developed and are usually
of big size. There are instances of tourmaline measuring up to 10 inches also in length and having perfectly developed prismatic faces. Sometimes slender crystals of tourmaline are arranged in a radiating fashion in some outcrops. (see Plate V, Figs. 2 and 3).

A distinctive feature of this pegmatite is that it has been folded which becomes apparent by the arrangement of tourmaline, quartz and feldspar crystals (see Plate VI, Fig. 1). In some specimens tourmaline and quartzofelspathic minerals are segregated along bands. Schorl rock also occurs in the vicinity of the pegmatite veins.

Good exposures of pegmatites are also found near Papurna. They are tourmaline-free, white and pink pegmatites. The pink variety is devoid of muscovite, while in the white variety muscovite is scantily present.

Near Chappoli there is a vein of pegmatite in mica schist. It is rich in mica but poor in tourmaline.

Quartz veins - Almost all the rock types of area have quartz veins of varying dimensions. In the mineralised zone these veins have traces of sulphide ores indicating that they are of post mineralization age. Sometimes the veins are several metres in length and vary from a few centimeters to a metre in width. The larger quartz veins are more frequent in the northern part of the belt and are found associated particularly with the granite of Gotro. (see Plate I, Fig. 2).

Basic dykes - The entire area of the Khetri copper belt shows a number of dolerite dykes. Their occurrence is more prominent near Papurna and Babai where they assume considerable dimensions. Some smaller dykes are seen near
Gotro village, SE of Madhan-Kudhan mines section. Such smaller dykes are usually found all over the belt. They are more common SW of Chappoli and also near Udaipur in the southern part of the belt. The rock is dark coloured and fine-grained. There are certain dolerites having porphyritic structure. (see Plate VI, Fig. 2).

Quartzites - Quartzites are the predominating type of rock of the belt. They show distinct variation in mineral composition. Accordingly, they have been classified as follows:

1. Feldspathic quartzite
2. Amphibole quartzite
3. Magnetite-haematite-quartzite
4. Massive quartzite
5. Sericite quartzite

This classification is to be applied in a broad sense as there is a lateral gradation of one type into another. At a few places some of the primary sedimentary features are still preserved in them.

The felspathic quartzites are widely distributed particularly in the northern part of the belt (see Plate I, Fig. 3). Their colour varies from buff to light pink. Compositionally they range from ortho- to arkosic-quartzites which are usually medium to coarse-grained. Infrequently they have well-preserved ripple marks and current beddings. Occasionally a few quartz veins are also found in quartzites. Starting from its contact with granite near Gotro the felspathic quartzite grades into amphibole quartzite on its western side.

The felspathic quartzite near the Madhan-Kudhan mine is associated with a thin bed of magnetite-quartzite which is faulted repeatedly across its strike (see Plate II, Fig. 1).
The massive quartzite is thin bedded and is one of the widely occurring types of quartzite of the belt. Its largest outcrops are seen around Bahai and Gurha-Ponk.

The rock has colours varying from grey, creamy white to light pink. Fine to medium-grained texture is common.

Sericite quartzite is thin bedded and occurs largely at the top of the quartzite formation in the northern part of the area. It extends to a considerable extent south of Madhan-Kudhan section and further up to Kolihan. Occasionally the ripple marks are preserved in the quartzites.

**Schists and Phyllites**

This group of rocks shows a wide variation in mineral assemblages. The distribution bears relationship with the structural and geological set-up of the area.

**Schists** - The following types of schists commonly occur in the area:

1. Garnetiferous quartz-chlorite schist
2. Garnetiferous quartz-biotite schist
3. Garnetiferous anthophyllite-cummingtonite schist
4. Amphibole-biotite schist and amphibole schist
5. Biotite-muscovite schist

Others of minor occurrence are biotite, muscovite, quartz and chlorite schists.

Garnetiferous quartz-chlorite schist, one of the host rocks of copper ores, forms the foot wall of the mineralized zone. It is the chief rock type of the Madhan-Kudhan mine section, (see Plate II Fig.2 ).
The schists strike N 30°E to N 50°E and dip 40° to 65° due north. A few transverse and strike faults are recorded. They also show folding and jointing on a minor scale. They overlie amphibole quartzite with which they have a gradational contact.

The schist is greenish in colour mainly due to the abundance of chlorite. Garnets are of variable size (0.1 to 1 cm in diameter) and have a tendency to concentrate along the planes of schistosity. In a few cases they form irregular but distinct bands with some parallelism to the schistosity. (see Plate VI & VII, Figs. 3 & 1).

The garnetiferous anthophyllite-cummingtonite schist resembles in lithology with garnetiferous quartz-chlorite schist. Garnets show more or less similar lithological character as in the case of garnetiferous quartz-chlorite schist.

The garnetiferous biotite-schist occurs mainly in the Kolihan mine section. The rock is dark coloured with reddish garnets of variable sizes. Biotite is the predominating flaky mineral and quartz is present in subordinate amount.

Amphibole biotite-schist shows a wide mineralogical variation mostly due to the variation distribution and type of amphibole. Quartz, biotite and feldspars form the chief mineral constituents. Garnet is present but in a few rocks.

The amphibole schist has anthophyllite-cummingtonite as the predominating type of amphibole. The amphibole is light greenish in colour and occurs in the form of fibrous or lamellar crystals. Feldspars occurs in minor amounts. The rock is found in the Madhan-Kudhan section.
Biotite-andalusite schist is a dark brown coloured coarse-grained rock. Flakes of biotite occur in abundance. Some large prismatic crystals of andalusite range in size from 2 to 3 cms in diameter and 8 to 10 cms in length. Most of the crystals have a preferred orientation. Cross section of andalusite crystal shows inclusions of some carbonaceous material in the central part while a vertical section shows a continuous thread of carbon all over the crystal length. (see Plate VII, Fig. 2). The rock has good exposures in the Kolihan section and in the southwest of Khetri. It was found to occur mostly in the vicinity of epidiorite dykes.

Phyllites - Textures of phyllites are present in the northern part of the area, near Madhan-Kudhan and around Kolihan mines. They overlie garnetiferous, quartz-chlorite schists. The rocks are grey to dark grey in colour and frequently puckered (see Plate VII, Fig. 3). Cleavages are parallel to the bedding laminations. Phyllites are highly folded with a general NE-SW trend of their fold axes. The beds dip at 45° to 75° due NW. Occasional bands of quartzite and carbonate rocks also occur as interlayered.

A river valley cuts across a large part of the phyllite formation near Madhan-Kudhan and runs in NE-SW direction parallel to the fold axis. The exposures are highly weathered.

Carbonate rock - (Impure Marble): Carbonate rocks of mainly impure marble type are distributed all over the belt but not in any significant amount. Their outcrops are found in lowlying areas generally interbedded with the schists. Amphibolization is a common feature in impure marble (see Plate II, Fig. 3). Commonly the amphiboles form lath-shaped and bladed crystals of dark green colour. The colour of rock varies from greenish grey to dark grey.
depending on the proportion of amphibole present.

The carbonate rocks occurring in between the Madhan-Kudhan, Kolihan, and Akwali mines are appreciably rich in amphiboles while those belonging to the southern part of the area, viz., south of Chappoli are poor in amphibole.

**PETROMINERALOGY**

**Pink granite and granite gneisses**

The chief mineral constituents in the order of decreasing abundance, are feldspars (potash-felspars predominating), quartz, amphibole, epidote, biotite and opaque minerals while in case of gneisses, biotite predominates.

**Mineralogy**

1. **Quartz** - Colourless, anhedral crystals, weakly birefringent and having wavy extinction. The anhedral crystals of quartz are partially enclosed in feldspars (plagioclases) and generally they have inclusions of fine particles and also of epidote. In some grains sutured contacts are clear.

2. **Feldspars**
   A. **Potash-feldspars** - Microcline and perthite are the chief feldspars.

   Clear microcline anhedral crystals with characteristic cross-hatched twinning (M. type) and extinction angle on (001) is from 15° to 17°. The microcline megacrysts are traversed by fine-grained veins of ground-mass material (see Plate VIII, Fig. D). It encloses quartz and other feldspar grains partially along the borders. In a few cases the phenocrysts are of microperthites. The microcline-microperthite contact is indistinct. Islands of quartz occur in optical continuity with perthites. Veins of epidote are
seen along fracture planes. Micrographic intergrowth commonly present
(see Plate IX, Fig. 1)

B. Plagioclase-feldspars - Plagioclase feldspars are less abundant
as compared to potash-feldspars. The crystals are lath-shaped with extinction
angle on (001) zone from $0^\circ$ to $18^\circ$ indicating albite-oligoclase composition.

The plagioclase crystals show two types of twinning. One on a very
fine scale (lamellar) which is often patchy and a second, somewhat coarser
of albite type (see Plate VII, Fig. 2). The latter type of twinning is
characteristic of bigger plagioclase crystals. Some of the plagioclase
crystals display X-carlsbad twinning. In the case of granite gneisses the
plagioclases display extinction angles of about $12^\circ$ on (010) zone which
indicates that it is albite. The bigger crystals are irregular with inclu-
sions of epidote and quartz concentrated along the border zone. Clouding
of plagioclases is a common feature. Feldspars show fracturing along
cleavages. Bigger crystals sometimes show deformation and dislocation of
twin compositional planes (see Plate VIII, Fig. 3). Where microcline pre-
dominates, plagioclase, if present, is usually oligoclase.

3. Amphibole - Light pale green prismatic, with two sets of perfect
cleavages at $120^\circ$, moderate birefringence and extinction angle ($Z \perp C$) =
$12^\circ$ to $15^\circ$.

It is distinctly pleochroic. The pleochroism scheme is as follows:

- $X = $ Pale green
- $Y = $ Bluish green
- $Z = $ Greenish blue

Absorption scheme: $Z > Y > X$
The amphibole is, therefore, of hornblende type. Hornblende commonly alters into epidote. The alteration is more pronounced along the borders of the crystals.

4. **Biotite** - Tabular crystals, strongly pleochroic from very deep greenish brown to pale brown. Pleochroic haloes are present. Bird’s eye structure is characteristically present. Some of the biotite flakes are seen enclosed by plagioclase.

5. **Sphene** - Rhomb-shaped crystals of light brown colour, weakly pleochroic from colourless to light brown, showing high order white interference colours.

   Interference figure - biaxial positive.

   Frequently it occurs in association with epidotes. In some cases it is partially enclosed in feldspars. In the granitic gneisses it occurs in close association with biotites.

6. **Epidote** - Generally equidimensional and markedly pleochroic from yellowish yellow to yellow/green colours. Their relief is high and high birefringence. Interference figure obtained is biaxial negative. Two varieties of epidotes have been identified.

   a) **Pistacite** - Showing pleochroism and high order interference colours.

   b) **Clinozoisite** - Almost colourless. Interference Figure - Biaxial negative.

Epidote crystals are enclosed in potash-feldspars. It is commonly associated with hornblende. Frequently it surrounds hornblende crystals so completely that islands of unaltered hornblende in epidote may be seen.
The leached borders of hornblende in contact with epidote indicate their alteration into the latter.

7. **Cordierite** - Colourless crystals and are usually big and anhedral. Abundant inclusions of flaky minerals (see Plate IX, Fig. 2). Simple twinning and zoning are distinct in some cases. Optic figure - biaxial negative.

**Minor accessories**

1. **Garnet** - Garnet occurs as almost colourless and roughly rounded grains. It is isotropic and is generally surrounded by biotite flakes.

2. **Zircon** - Crystals are colourless, prismatic with high relief and interference colours. The crystals are length slow. They are commonly present and generally occur as inclusions in biotite.

3. **Tourmaline** - Tourmaline crystals are prismatic and light grey in colour. They are markedly pleochroic from colourless to light pink. Extinction is parallel and the interference figure is uniaxial negative. The variety is schorlitech.

4. **Fluorite** - Fluorite crystals are almost colourless and euhedral. It has distinct cubic cleavages and is optically isotropic.

5. **Calcite** - It occurs as colourless, spherulitic grains showing double refraction.

6. **Opaque minerals** - They are commonly iron ores which occur in relatively greater quantity in granites.
Grey granite and granite gneisses

They are light to dark grey in colour, medium to fine-grained. The chief mineral constituents are feldspars and a subordinate quantity of quartz. Lineation and schlieren were observed frequently. Hornblende and biotite are the main ferromagnesian minerals. Iron ore grains are present in small amounts.

Quartz - Anhedral crystals with minor cracks are present. It is present in varying amounts and size. Most of the grains show wavy extinction and other evidences of crushing and deformation. Dusty inclusions are also present. They are largely surrounded by feldspars. Contacts are sutured.

Potash-feldspars - Microcline and perthite are the main feldspars. Crystals are anhedral. Extinction angle on (001) varies from 16 to 18°.

The augen gneisses have feldspars as the predominant mineral. Perthite is the chief feldspar of augens. Some rounded quartz inclusions are present in optical continuity. Microcline at places surrounds perthite grains and shows patchy and M-twinning (see Plate VIII, Fig. 1). The contact between microcline and micro-perthite is not sharp. Clouding in feldspars is not common.

Plagioclase-feldspars - Albite-oligoclase are in smaller quantity than the potash feldspars. The crystals are subhedral, lath-shaped with equal extinction angle on (010) zone varying from 3° to 18°.

The crystals show lamellar as well as X-Carlsbad twinning. Some of the plagioclase crystals have fractures along the cleavages. Clouding of plagioclases is seen. Inclusions of quartz and ferromagnesian are present.
Amphibole - The chief amphibole present is hornblende.

The pleochroism scheme of amphibole was determined in a number of thin sections. It is as follows:

\[ X = \text{light brown} \]
\[ Y = \text{Brownish green} \]
\[ Z = \text{Deep brown}. \]

The angle \( Z \wedge C \) varies from \( 17^\circ \) to \( 21^\circ \) showing it to be a hornblende variety. The crystals in most of the cases are arranged parallel to the foliation planes (see Plate LX, Fig.3).

Biotite - Flaky crystals of biotite are generally arranged parallel to the foliation planes. The crystals show distinct pleochroism from pale yellow to deep brown. Pleochroic haloes around zircon are present in a few cases. Bird's eye structure is characteristically present.

Accessories - Minor accessories are opaque minerals (ores), sphene, zircon and apatite.

Basic dykes

The basic dykes are metamorphosed dolerites and the chief mineral constituents are amphibole, epidote, plagioclase, feldspar and minor quartz, sphene and opaque ores. The term epidiorite has been used for them (see Heron, 1923). The relict of porphyritic and ophitic textures present in them (see Plate X, Fig.2) indicating that they were doleritic before metamorphism.

Amphibole - The amphibole found is an almost colourless variety of hornblende-uralite. It is weakly pleochroic and contains needles of green amphibole. Some of the crystals are strongly pleochroic (\( X = \text{Pale}, \ Y = \text{green}, \ Z = \text{blue} \))
colourless crystals of epidote of clinozoisite variety are frequently seen.

They are formed from the alteration of feldspars. Some intensely altered feldspars are still visible. Comparatively fresh plagioclases form phenocrysts and show zoning (see Plate X, Fig.2). Symmetrical extinction angle of 30° indicating labradorite composition. Acid andesine shows extinction angle of 22° and forms the ground mass. Quartz is mostly interstitial and present in low amounts. Sphene forms the common accessory mineral but in some cases its proportion is higher but never exceeds the accessory limit. Opaque ores are seen distributed in all the sections in varying proportions.

**Pegmatite** - Thin section study of the pegmatites of the belt shows variation in mineral composition. The pegmatites from the northern part of the belt show feldspars, tourmaline, quartz and flaky minerals as their main constituents. But those from the southern part of the belt are more or less devoid of tourmaline and the flaky minerals are also less at most of the places. The mineral constituents of the pegmatites in general are plagioclase-feldspar, potash-feldspar, quartz, tourmaline, mica and opaque ores.

**Feldspars** - Plagioclase feldspars are more abundant than the potash feldspars. The plagioclases are usually lath-shaped crystals with extinction on (010) zone from 0° to 16° indicating albite-oligoclase composition. They show lamellar and X-Carlsbad twinning. Some of the plagioclase crystals show clouding.

The potash-feldspars are less common. The microcline shows distinct cross-hatched twinning. Extinction angle varies from 16° to 18°. Inclusions of quartz are present.
Quartz - Quartz is present in subordinate quantity and is usually surrounded by the feldspars.

Tourmaline (schorlite) - Tourmaline is present in varying sizes. The crystals are prismatic and usually grey in colour. Strongly pleochroic from light yellow to deep blue. Some of the tourmaline crystals show distinct zoning (see Plate X, Fig. 1).

Muscovite - Muscovite occurs as colourless flaky mineral. Where present it is usually arranged in a regular pattern.

Opaque ores are present in smaller amounts.

Quartzites - The petromineralogy of all the types of quartzites has been presented collectively.

The chief mineral constituents are quartz, feldspars, amphibole, sericite and opaque minerals.

The optical characters of individual minerals are mentioned below:

Quartz - The size of the quartz grains varies in different varieties. Some of the grains show distinct wavy extinction. The bigger grains are often rounded to subrounded and enclosed in a sericite matrix. They also show a little deformation and some recrystallization. Minute inclusions of apatite are frequently present.

In magnetite-haematite quartzite, quartz has innumerable inclusions of opaque minerals. Some grains are fractured and show strain shadow effect. Quartz in this rock is medium to fine-grained and generally shows mosaic texture. Some clear vein-quartz of microscopic size, completely free from magnetite or any other inclusions, were noted in quartzites. The vein-walls are lined by continuous layers of iron oxide.
In some cases there are angular to sub-angular fragments of quartz. Quartz porphyroblasts are rare (see Plate X, Fig. 3).

**Feldspars** - Feldspars are next to quartz in order of abundance. In some cases feldspars are in minor amounts while they are in appreciable amount in feldspathic quartzite. Both soda-lime feldspars and potash-feldspars are present.

Plagioclases are usually small and occur as tabular crystals. They show characteristic twinning. Most of the plagioclase crystals give extinction angles on (010) zone varying from $3^\circ$ to $16^\circ$ which indicates that they are albite to oligoclase. Where there is a predominance of oligoclase albite becomes less. They are cloudy due to partial kaolinization.

Among potash-feldspars, perthite is common. It occurs as anhedral crystals. Microcline is present in smaller amounts.

**Amphiboles** - The amphiboles are hornblende and actinolite types, of which the former is more abundant.

**Hornblende** - Pleochroism scheme

- $X =$ light greenish
- $Y =$ Brownish green
- $Z =$ Deep greenish brown

$Z \wedge C$ varies from $17^\circ$ to $21^\circ$.

The former is generally prismatic. The crystals are somewhat oriented. Some inclusions of quartz are present.

**Actinolite** - In a few thin sections amphibole of actinolite variety was identified. It generally occurs as radiating needles and is enclosed within the quartz crystals.
Sericite - Sericite is the common constituent of sericite-quartzite which is one of the predominating rock types of this group. It is scaly and light pink to greyish white in colour.

Minor accessories - Among the other accessories the following minerals were identified. Biotite, tourmaline, opaque minerals, chlorite, epidote, muscovite, sphene, zircon, etc. Their relative abundance varies according to the composition of the rock.

Schists and phyllites

The petromineralogical characters of the schists have been described.

The rocks, in general, have well developed foliation. Flaky minerals, like chlorite and biotite are oriented parallel to sub-parallel to schistosity. Garnets, wherever present, are arranged along the planes of schistosity. The schists have lepidoblastic or nemaoblastic texture according to the shape and orientation of the minerals.

Mineralogy - The grain-size of quartz varies from medium to coarse-grained. Most of the quartz grains in the schists were deformed as indicated by their wavy extinction. Quartz is also present as inclusions in some ferromagnesian minerals.

Garnet: Garnet shows marked variation in shape and size. It occurs as xenoblasts as well as idioblasts. It varies in size from 0.1 cm to 1 cm in diameter. The mineral is pinkish in colour and, probably, of almandine variety. Inclusions of quartz, etc., are present. Three types of garnet have been recognised: They are as follows:

Garnet I (see Plate XI, Fig.1) - Xenoblastic, with 'S' arrangement of
inclusions. It was formed during earlier metamorphism.

**Garnet II** - Highly sheared and fractured garnet with parallel crack, filled with chlorite. It shows alteration to chlorite (penninite variety).

**Garnet III** (see Plate XI, Fig.2) - Idioblastic in shape with rounded and oriented quartz inclusions. Formed, probably, from the recrystallization of garnet I and II (see Das, 1966).

The garnet porphyroblasts in a few cases show many helicitic inclusions mainly of quartz, arranged in layers (oriented) and in continuity, with the planes of schistosity of the rock. Such type of crystals may or may not have undergone rotation. The shape of some of the garnet meta-crysts is like 'S' which distinctly shows that they are rotated crystals. The quartz inclusions are also arranged in a similar pattern ('S') which is very apparent under the crossed nicols.

Due to rotation of garnet crystals some of the fragments are separated. The spaces in between the fragments is occupied by chlorite of secondary origin. It is also filled up by a deep brown, somewhat anisotropic, oxide of iron. Some micaceous minerals are also arranged around the garnet crystals. This in addition to the pattern of inclusions, indicates rotation of garnet during its growth due to shearing movements.

In some other cases euhedral garnet porphyroblasts present no evidence of rotation. The inclusions of quartz in them, also, do not have any definite orientation. They have been altered into chlorite, biotite and some epidote retrogressively without showing any evidence of rotation.

**Chlorite** - Chlorite is light yellowish green in colour with inclusions
of quartz. Typical "Berlin blue" interference colours characterise them. Some finer lamellae impart orange-red interference colours. They are flexured and crenulated.

Chlorite is mostly concentrated along certain planes and around the garnet porphyroblasts. The bands are highly folded. These bands indicate planes of differential movements in the rock and it is along such planes that garnets have undergone rotation.

Chlorite is studded with brownish patches of iron oxide and black opaque minerals which are widely dispersed. It swings around the lenticles of quartz wherever present.

Amphiboles - The amphiboles present are anthophyllite-cummingtonite and hornblende.

i) Anthophyllite cummingtonite: They are almost colourless, needle-like and weakly pleochroic (see Plate XI, Fig. 3). Twinning is poly-synthetic. They have positive optic sign. Extinction is inclined.

ii) Hornblende: The pleochroism schemes of the amphiboles determined in various thin sections are as follows:

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>X = Pale to light brown</td>
<td>X = Yellowish</td>
</tr>
<tr>
<td>Y = Brownish green</td>
<td>Y = Green</td>
</tr>
<tr>
<td>Z = Deep greenish brown</td>
<td>Z = Greenish blue</td>
</tr>
</tbody>
</table>

The angle \( Z \wedge C \) varies from 18° to 22°. 

The optical characters suggest that the amphibole is a normal hornblende type. The crystal aggregates are also acicular and oriented parallel to the foliation plane. They are also enclosed within biotites and sometimes
grade into them. Bigger crystals show strain effects.

**Biotite** - Biotite crystals are flaky in habit and show a preferred orientation. Pleochroism is from pale to very deep brown. Pleochroic haloes and zircons are present. Occasionally inclusions of sphene are present. In some cases biotite (of amphibole-biotite schist) appears to have formed subsequent to hornblende and opaque ores as the biotite encloses these minerals.

In biotite-muscovite schist, biotite occurs in abundance and shows some dusty inclusions particularly in the central part of the crystals.

**Feldspars** - Plagioclase feldspars are present in biotite schist and amphibole schist. They are twinned on albite law and distinctly zoned. The shape of the optic figure suggests a large value of 2 V. The extinction angle on (010) zone varies from \(10^\circ\) to \(15^\circ\) giving albiclasite composition. A number of untwinned feldspars (plagioclases) are also present with clear zoning. In zoned crystals the inner zone is generally of oligoclase composition and the outer one of albite. They have some inclusions of quartz and amphiboles.

**Andalusite (Chianstolite)** - Andalusite of schists, are porphyroblastic with moderate relief and two sets of prismatic cleavages. Their birefringence is low and extinction is parallel. The crystals are length fast and their cross-section shows carbonaceous inclusions regularly arranged in the form of crosses, which are characteristic of the chianstolite variety. Inclusions of flaky minerals, like muscovite, sericite, etc., are distributed throughout the crystals. They alter into chlorite.
Muscovite - It occurs as a few flaky crystals, arranged in foliation planes. They are generally colourless and of small size.

Opaque minerals are disseminated throughout the rock. In some cases they are euhedral in shape and are present as clots.

Other mineral accessories are zircon, sphene and tourmaline.

Phyllites - A brief description of the mineral constituents of the phyllites is given as follows:

Quartz - Quartz is common and generally fine-grained (0.05 mm to 0.5 mm). The grains are somewhat elongated the longer direction being parallel to the foliation. They usually show wavy extinction as a result of strain. There are occasional inclusions of sericite and muscovite (see Plate XTV, Fig. 1).

Feldspars - Feldspars are next to quartz in abundance. Plagioclase feldspars being more common, occur as tabular and lathshaped crystals and show characteristic albite twinning. The extinction angle according to M-Lavy's method varies from 12° to 15°. Some of them are strained.

Among flaky minerals, biotite, sericite and chlorite, show a linear arrangement. Contortion of bedding planes in the rock is apparent by the arrangement of these minerals.

There are a few grains of prismatic crystals of tourmaline, with dusty inclusions arranged in the core. Its pleochroism scheme is: O = brown, e = light reddish to colourless.

Absorption $\omega > \varepsilon$. It was thus identified as schorlite.

Opaque minerals occur in appreciable quantity in the form of fine bands on the microscopic scale.
Carbonate rocks

The chief minerals in order of abundance are calcite, dolomite, amphibole and opaque minerals.

Carbonate minerals

Calcite and dolomite show characteristic twinkling and glide twinning in a few cases. The texture (composite) is crystalloblastic with fine-to medium-grained size.

Amphibole - The amphibole present is tremolite. It has bladed crystals which are of variable sizes. The basal section shows two sets of prismatic cleavages. Pleochroism is feeble from colourless to light greenish. In a few crystals green colour is more pronounced but the greenish tint is non-uniform. The $CZ$ angle varies from $15^\circ$ to $17^\circ$. Inclusions of opaque minerals are present. The mineral is sometimes replaced by carbonate minerals along the fracture planes.

The opaque minerals are present in negligible quantity. Chlorite, mica, etc., form the minor accessories.
PETROCHEMISTRY

Granites and granitic rocks

The petrochemistry of granites and granitic rocks has been studied and the nature of these rock types has been indicated, (see text Fig. 1).

Samples are selected from different rock outcrops occurring in the area. They include granite, microgranite resembling alaskite, diorite and pink granite gneiss. These were analysed for all the fourteen major constituents. The analytical data were recalculated as percentage values for plotting on Al SF diagram as proposed by Osann (see Johannsen, 1962), where

\[
S = \text{SiO}_2 + \text{TiO}_2
\]

\[
\text{Al} = \text{Al}_2\text{O}_3
\]

\[
\text{F} = \text{CaO} + \text{FeO} + \text{MgO} - \text{C}
\]

\[
\text{C} = (\text{Al}_2\text{O}_3 - \text{A})
\]

The total of \( S + \text{Al} + \text{F} = 100 \)

The diagram shows that the points for granite (pink), microgranite and diorite of the northern part of the belt fall in the igneous field while the point for granite gneiss (pink) of the southern part of the belt falls outside the igneous field. This indicates that granite of the northern part near Gotro village is an intrusive igneous rock. The granite gneiss of the southern part appears to be of non-magmatic origin.
TEXT FIG. NO. 2 VARIATION DIAGRAM
Metamorphic rocks and dolerite

An attempt has also been made to study the petrochemistry of metamorphic rocks and one dolerite sample of the area. Firstly, the variation pattern of different oxides with respect to SiO₂ has been considered and secondly, the weight percentages of different oxides are plotted on A.C.F. diagram for determining the original nature of the rocks.

Five rock samples were selected and analysed like granites and granitic rocks. The samples include quartzites, schist, epidosite and dolerite. The determined analytical results were taken up for the two-fold study.

Variation pattern of oxides in metasedimentary and igneous rocks when plotted against silica (SiO₂), see Text Fig. 2.

The variation pattern of different oxides was studied in order to determine the chemical behaviour of major elements in various rock types. The oxide percentages were plotted against SiO₂ percentages graphically and the observations made thereby are summarised below.

The SiO₂ percentage varies from 39.71% (epidosite rock) to 83.62% (quartzite). It was observed that generally where silica (SiO₂) was low (39.71%), the percentage of CaO (22.05%), Al₂O₃ (20.97%) and Fe₂O₃ (10.70%) were high while the contents of the other oxides were invariably low. Where silica was high (81.83%), alumina (Al₂O₃) continued to be relatively higher (8.31%) while the other oxides were generally having low values. In the case of garnetiferous quartz-chlorite schist, Al₂O₃ and Fe₂O₃ were appreciably higher as compared to the other oxides. The dolerite sample was found to have relatively higher content of Al₂O₃, CaO and MgO.
TEXT FIG. NO. 3  A C F DIAGRAM
It was observed that the variation pattern was not simple and the oxides did not form smooth curves when plotted against silica percentages. Thus, they do not appear to have been derived from the common parent material. It indicates the possibility of more than one suite of original material which recrystallised and gave rise to the present rock types.

Analytical results plotted on A.C.F. diagram to indicate parent material (see Fig. 3)

The petrochemistry of these rocks was further studied on A.C.F. diagram with a view to trace out the original nature of the existing rocks. The A.C.F. diagram was developed by Eskola (see Winkler, 1965), which allows the representation of many rocks of not too unusual composition and having an excess of silica. The diagram is divided into different areas, each of which represents the area of a particular set of original material from which the corresponding rocks have been derived. The specifications of each area are as follows:

- **IA** - Al-rich clays and shales
- **IB** - Clays and shales either free of carbonate or containing upto 35% carbonate. Between arrows: marls containing 35-65% carbonate.
- **II** - Greywackes
  1. Ultrabasic rocks.
  2. Basaltic and andesitic rocks.

The analytical results were plotted on A.C.F. diagram after recalculating the percentage values of oxides where:

- \( A = (\text{Al}_2\text{O}_3) + \text{Fe}_2\text{O}_3 - (\text{Na}_2\text{O}) + (\text{K}_2\text{O}) \)
- \( C = (\text{CaO}) - 3.3 (\text{P}_2\text{O}_5) \)
- \( F = (\text{MgO}) + (\text{MnO}) + (\text{FeO}) \)
The total of \( A + C + F = 100\% \), as they are expressed in terms of molecular percentages.

The points fell on different areas in the diagram and the parent material recorded with its help is shown below:

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Sample No.</th>
<th>Existing metasedimentary/igneous rock</th>
<th>Parent material recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HR\textsubscript{3}M</td>
<td>Amphibole quartzite</td>
<td>Greywackes.</td>
</tr>
<tr>
<td>2</td>
<td>FR\textsubscript{4}T</td>
<td>Garnetiferous quartz-chlorite schist</td>
<td>Clay and shales free from carbonate.</td>
</tr>
<tr>
<td>3</td>
<td>LR\textsubscript{1}E</td>
<td>Epidosite</td>
<td>Clay and shales containing upto 35% of carbonate.</td>
</tr>
<tr>
<td>4</td>
<td>MR\textsubscript{1}W</td>
<td>Felspathic quartzite</td>
<td>Clay and shales free from carbonate.</td>
</tr>
<tr>
<td>5</td>
<td>NR\textsubscript{3}E</td>
<td>Dolerite</td>
<td>Basaltic or andesitic rocks</td>
</tr>
</tbody>
</table>

The above observations are in conformity with the previous results available from the oxide variation diagram which indicates that the original materials of these rocks were of more than one kind.
Chapter - V

GEOCHEMISTRY AND DISTRIBUTION OF TRACE ELEMENTS IN ROCKS, MINERALS AND SOILS

General statement

The general recognition of the trace elements is not of recent origin. Earlier workers particularly, in the beginning of the 20th century, have emphasized the significance and the distribution of trace elements in geological materials. Washington (1913) while discussing the distribution of the elements in the earth's crust, described that the minor elements were not only related to the rock types but also to the major elements constituting the rock. Vogt (1918) and Buddington (1933) pointed out certain complications in the distribution of the trace elements.

In recent years, vast knowledge has accumulated regarding the geochemistry of the trace elements. Colossal work is being done on the distribution of trace elements in igneous rocks and their geochemical behaviour during the fractional crystallization of magma. Goldschmidt (1937), one of the pioneer workers in the field of geochemistry, has made certain useful observations regarding element distribution in rocks and minerals and proposed a geochemical classification of the elements based on their chemical affinity. He observed that the elements indicated preference to enter into an iron phase, sulphide phase and a silicate phase, and classified them as siderophile, chalcophile and lithophile elements respectively. Shand (1947) proposed the term thiophile.
substituting the term chalcophile. Goldschmidt (1937) found that the distribution of the chemical elements in these phases depended on the electronic configuration of their atoms. Further, he assumed that mutual replacement (diadochy) of ions in magmatic minerals was purely ionic. He explained certain interesting interionic relationships on the basis of ionic radii and charge. In fact, the concept of ionic radius was first given by Bragg (1937), who found that when two ions come closer to each other, a repulsive force is generated and which prevents them to come closer than a certain limiting value of interatomic distance. He defined this effective distance as a characteristic radius of each ion.

A comprehensive study led Goldschmidt to propose three basic rules governing the distribution of elements in rocks and minerals. The first rule is based on his own observation while the rest two were derived from inverse square law of electrostatic attraction applied to ionic lattices.

Recent advances in geochemistry revealed that the Goldschmidt's rules needed modification. Greater emphasis has now been given on the significance and the nature of chemical bonding. According to Fyfe (1951), partial covalent bond in zinc compounds brings certain departures from the laws governing isomorphism. Ramberg (1925), Shaw (1953) and Ahrens (1953) were of the opinion that chemical bonding could explain for most of the geochemical relationship of elements during crystallization.

Ringwood (1955a) used electronegativity as "an indicator of bond type in minerals and rocks". The concept of electronegativity was originally given by Pauling (1955), who defined it as "The power of an atom
in a molecule to attract an electron unto itself". Pauling (1940) stated that when two atoms of similar electronegativity are joined by a bond, it would be a covalent bond. But when there is a difference in electronegativity in the two atoms, the shared electron will be pulled closer by the atom having a higher electronegativity. This results in creating an ionic component into the bond. When the difference in electronegativity is greater, the bond will be more ionic.

Ringwood (1955a), following Fyfe (1951), applied electronegativity to the distribution of trace elements and proposed the following rule:

"Whenever diadochy in a crystal is possible between two elements possessing appreciably different electronegativity, the element with the lower electronegativity will be preferentially incorporated because it forms a stronger and more ionic bond than the other".

The rule satisfactorily applies to such cases in which the difference in the electronegativity is more than 0.1.

Ringwood (1955a) also favoured the use of ionization potential, suggested earlier by Ahrens (1953) and Goldschmidt (1954), as a possible replacement of electronegativity criteria.

Ringwood's (1955a) modifications to Goldschmidt's rules was criticised by Curtis (1963) and others because they found it difficult to explain the behaviour of elements when ionic radius and/or charge and electronegativity act in opposition. Nockolds (1966) also felt this difficulty and pointed out that "bond length to oxygen may play an equally important part and need consideration also".
Further, the distribution of elements in a crystal structure during the fractional crystallization is also governed by the geometric arrangement of atoms (see Krauskopf, 1967).

The geochemistry and distribution of individual elements has been discussed in the foregoing description in the light of the above cited work.

**Copper in rocks and minerals**

Copper is a strongly chalcophile element. It occurs chiefly as sulphides. Small amounts of copper have also been reported from the silicate phase. Buddington (1927) reported that traces of Cu were commonly associated with diorites. Sandell and Goldich (1943) observed that Cu has a greater tendency to be enriched in the basic igneous rocks. According to them acid igneous rocks have about 1/10 of Cu content as compared to the basic igneous rocks. Rankama; and Sahama (1950) stated that Cu largely occurred as sulphide in most igneous rocks. Wager and Mitchell (1951) have experimentally shown that during the earlier stages of crystallization of a basic magma, copper being free, would be incorporated in the silicate minerals. Wager et al. (1957) found chalcopyrite in the lower layered rocks at Skaergaard.

The granites and granitic rocks of the Khetri Copper Belt have Cu content varying from 10 to 48 ppm (20 ppm, Vinogradov, 1962). The higher concentration is generally in the gneissic variety. The quartzites, schists and phyllites in general show anomalous values particularly those near the mineralized zone. The dolerites also have indications of copper mineralization
and show values varying from 10 to 445 ppm (87 ppm, Turekian and Wedepohl, 1961). The separated ferromagnesian minerals show preferable concentration of Cu as compared to felsic minerals.

Copper is the chief element of ore complexes. The chemistry of its being accommodated in the silicate phase, and later concentrating in the residual magma is discussed below.

It is well known that copper has a strong tendency to concentrate in residual magmas and precipitate as chalcopyrite. The reason being that during the crystallization of a magma Na\(^+\) (0.96\(\text{Å}\)) in the plagioclases camouflages Cu\(^+\) (0.96\(\text{Å}\)). Similarly in the ferromagnesian minerals, Fe\(^{++}\) (0.74\(\text{Å}\)) camouflages Cu\(^{++}\) (0.72\(\text{Å}\)) although both the univalent and divalent copper have ionic radii less than the respective elements, Na\(^+\) and Fe\(^{++}\). Goldschmidt's rules fail to explain such a behaviour.

Ringwood (1955a) explained this anomaly on the basis of electronegativity. He compared the electronegativity of Cu\(^+\) (1.8) and Na\(^+\) (0.9) and pointed out that Cu\(^+\)-O bond would be weaker as compared to the Na\(^+\)-O bond. Similarly in the case of Cu\(^{++}\) (2.00) and Fe\(^{++}\) (1.65), the Cu-O bond would be weaker as compared to the Fe\(^{++}\)-O bond. Therefore, as a rule the elements forming stronger bonds with oxygen will be preferably incorporated.

**Copper in residual soils**

The geochemical behaviour of copper during the formation of residual soils is not well worked out. Generally the copper contents in the residual soils are less than the parent rock.
It is also known that among the ferromagnesian minerals which are the chief host for Cu, biotite is usually more resistant to chemical weathering than hornblende (see Goldschmidt, 1954). It also indicates that the ferromagnesian minerals formed at a higher temperature are more susceptible to chemical weathering than those formed at a lower temperature (see Krauskopf, 1967).

Residual soil samples of Khetri in case of granites and granitic rocks and schists and phyllites generally show higher content of metal than the parent rock while in case of quartzites the case is reverse. This anomaly has been discussed in the foregoing pages where a comparative study of the primary and secondary dispersion patterns has been made.

**Lead in rocks and minerals**

Lead was found to concentrate mostly in the acid igneous rocks. Sandell and Goldich (1943) found that the acid rocks have twice as much lead as the basic rocks. Hevesy (1931) reported that the lead content in normal granitic rocks is six times greater than that of gabbros and similar rocks. Goldschmidt found 5-50 ppm of Pb concentrating in normal granites. According to Wedepohl (1956) and other workers, among feldspars, microcline in pegmatites often shows maximum lead concentration. The enrichment of lead in the late syenite differentiates has also been reported by some workers. Apatite is a good host and generally has upto 50 ppm of Pb. The radiogenic Pb usually remains associated with its parent elements.

Lead has a controlled dispersion in all the samples of the belt and
the values range from 10-126 ppm. Among igneous rocks in general, pink granites and pink granite gneisses gave values upto 85 ppm (20 ppm, Vinogradov, 1962) while dolerites record upto 69 ppm of Pb (8 ppm, Vinogradov, 1962). Quartzites, schists and phyllites both from and away the mineralisation zone show a limited range of dispersion of Pb. Even the sulphide ores do not record abnormal values. Ferromagnesian minerals show enrichment in Pb. The felsic group (quartz + feldspars) also gave higher values.

Pb is a chalcophile element and an element of ore complexes. The factors governing its capability to crystallize as sulphide or enter into the silicate phase are discussed below.

Generally it is the belief that Pb\(^{++}\) preferably occurs in the potash feldspars (5-50 ppm) of silicate rocks. Goldschmidt (1937) was of the opinion that lead could possibly replace K\(^+\), Sr\(^{++}\), Ba\(^{++}\) and to some extent Ca\(^{++}\) also. Since the ionic radius of Pb (1.20\(\text{Å}\)) is smaller and the charge is higher than K (1.33\(\text{Å}\)), obviously Pb can replace K\(^+\) from early formed potash-minerals (see Goldschmidt, 1954). But other workers, viz., Bankham and Sahama, 1949; Nockolds and Mitchell, 1948 suggested that Pb could not enter potash lattice as efficiently as K\(^+\) but could concentrate in the residual magma.

Ringwood (1955a) qualified these observations by explaining them on the basis of their electronegativity as follows:

The electronegativity of Pb is 1.8 while that of K\(^+\) is 0.8. The Pb-O bond is therefore, more covalent and thus weak as compared to K-O bond.
in potash-minerals. Therefore $K^+$ enters with relatively greater ease into potash-minerals while $Pb$ concentrates in the residual magma.

It is therefore evident that primary lead exists mostly in the sulphide state on account of its great affinity towards sulphur. Either it may occur as a primary sulphide mineral, viz., galena or formed by the interaction between the $Pb$ present in the silicate lattice of feldspars and the available sulphur compounds.

**Lead in the residual soils** - Not much is known about the geochemical behaviour of lead during the process of weathering of silicate rocks. Whatever information is available about the behaviour of the metal, it is largely from its association with the sulphide ores. It is, however, known that lead sulphide in the zone of oxidation changes to $PbSO_4$. Frequently $PbCO_3$ is also formed by its reaction with available $CO_2$.

The soil samples of the area under study, in general, show low values of dispersion of $Pb$ than the rock samples. Its geochemical behaviour during chemical weathering has been discussed in the foregoing chapter of dispersion patterns.

**Zinc in rocks and minerals**

The occurrences of zinc in rocks and minerals in the form of sulphide and silicate have been reported by several earlier workers. Clarke and Washington (1924) reported a value of 40 ppm of $Zn$ in the upper lithosphere. Newhouse (1936) did not find any sphalerite in the igneous rocks. Sandell and Goldich (1943) found that the concentration of zinc in a basic rock was twice as much as in an acid rock. Lundegaordh's (1948)
investigations show that zinc concentrates in granodiorites in preference to gabbros and granites. He also found out that zinc was closely associated with the amount of biotite in granitic rocks.

Zinc in the granites and granitic rocks of this area has dispersion values upto 82 ppm (60 ppm, Vinogradov, 1967) except in a few cases. Quartzites have less Zn content than the schists and phyllites. The various rock samples from the Khetri copper mines show normal values for Zn while the sulphide ores have higher content. Dolerites in general record values upto 340 ppm (130 ppm, Vinogradov, 1962). Among mineral fractions, ferromagnesians are found to be the chief hosts of Zn.

Zinc is a chalcophile element and an element of ore complexes. It forms sulphides and also shows a tendency to enter into the silicate lattice. Its geochemical behaviour in both the cases is discussed as follows:

The ionic radius of zinc (0.74Å) is very much similar to those of the elements in the iron-magnesian group. It is, therefore, expected that zinc should be able to replace Mg\(^{++}\) (0.66Å) and Fe\(^{++}\) (0.74Å) contents of all such mafic minerals. Investigations have shown that olivine and pyroxene have distinct traces of zinc, while higher concentrations were recorded in amphiboles (200 to 2,000 ppm) and biotites.

It is now known that high co-ordination exists when zinc is bonded to fluorine (see Ahrens, 1964). Further it was observed that amphiboles and biotites have some water and fluorine. Ahrens (1964) pointed out that it might be due to the presence of fluorine in these minerals that zinc co-ordination tended to be octahedral and it replaced Mg\(^{++}\) and Fe\(^{++}\) easily,
resulting thereby concentration of zinc.

The concentration of zinc in the residual magma was explained by Ringwood (1955a) on the basis of electronegativity. The electronegativity of Zn is 1.7 while of Fe$^{2+}$ is 1.65. Obviously more of zinc than Fe$^{2+}$ will be concentrated in the residual magma. Zinc sulphide has also a marked capacity of capturing traces of other metals.

**Zinc in the residual soils** - Little is known about the geochemistry of zinc in the process of chemical weathering. The present knowledge is, however, largely based on the weathering of primary rocks in the oxidation zones of zinc ore deposits. The products formed are usually sulphates and to a certain extent, carbonate of zinc.

The geochemical behaviour of zinc in the residual soils of the area, under study, shows that during chemical weathering it is generally more affected than Cu. Its details have been discussed in the foregoing chapter of dispersion patterns.

**Nickel and cobalt in rocks and minerals**

The distribution of nickel in rocks and minerals was first studied by Vogt (1923). According to Clarke and Washington (1924) the igneous rocks were found to have 0.001 per cent of Co and 0.02 per cent of Ni. Newhouse (1936) found that femic rocks have more sulphide minerals than salic rocks. Later Sandell and Goldich (1943) determined Co:Ni ratio as 3:10 for upper lithosphere, while Goldschmidt (1958) gave a ratio of 4:10. Wager and Mitchell (1951) investigated ferromagnesian minerals of early crystallisation to be enriched in Ni. Nockolds and Mitchell (1948) while working on some
Caledonian plutonic rocks, confirmed the observation of Vogt (1943) that Ni has a tendency to concentrate in the early magmatic differentiates. Turekian and Carr (1960) found that Cr and Ni were generally higher in early-formed pyroxene crystals than in the later ones in a particular extrusive or intrusive cycle.

Cobalt was reported to be usually concentrating in the ultrabasic rocks. Sandell and Goldich (1943) generally found the granites to have less than 1 ppm cobalt. Their observations were largely based on the granites from Minnesota. Nockolds and Mitchell (1948) found the value of Co to be below 15 ppm in granites and granodiorites. Lundegaordh (1945) and Du Rietz (1955) found the values of Co to be varying from 50 to 200 ppm in some ultrabasic rocks of Sweden. Turekian and Carr (1960) on the basis of their investigations on Stillwater complex, found Co to be following very closely only Mg in granitic rocks.

The sulphide minerals generally accommodate an appreciable amount of Co and it enters with greater ease in pyrite and pyrrhotite than chalcopyrite (see Gavelin and Gabrielson, 1947). An interesting observation was made by Hegemann (1943) who observed that the amount of Co in the sulphides was directly proportional to the degree of metamorphism of the sulphide deposits.

The granites and granitic rocks of the area show a maximum dispersion of 60 ppm of Ni (8 ppm, Vinogradov, 1962) and 8 ppm of Co (5 ppm, Vinogradov, 1962). The granite gneisses in general give higher values for
both the elements. Dolerites have values ranging from 18 to 140 ppm (130 ppm, Turekian and Wedepohl, 1961).

In the separated mineral fractions of granites and granitic rocks and host rocks of copper ores, both Ni and Co show concentration in the ferromagnesian phase. The separated sulphide ores have anomalously higher values for the Ni and Co contents. Ni was found to be essentially concentrated (upto 621 ppm) in the pyrrhotite. The Ni/Co ratio in the separated chalcopyrite and pyrrhotite fractions is 1.23 to 1.49 and 1.5 to 1.70 respectively.

Both the elements show a consistency in their dispersion and are generally associated with the copper ores. Thus they may be used as indicator elements of the regional geochemical background in the area under study.

In igneous rocks, the Co and Ni are usually present in the silicate structure. In the absence of any sulphide mineral, the silicates usually host all the Co and Ni contents of a rock and Co content in the granitic rocks increases at the expense of Ni (see Goldschmidt, 1958).

Generally, it is believed that the ionic radii of Ni$^{2+}$ (0.69Å) and Co$^{2+}$ (0.72Å) being very near to those of Mg$^{2+}$ (0.66Å) and Fe$^{3+}$ (0.74Å), either Ni or Co or both should be able to replace one or both of the latter metals. Goldschmidt (1944) suggested that Ni is likely to be enriched in the Mg-bearing minerals because Ni-O bond is stronger than Mg-O bond on account of its more covalent nature. But the idea did not sustain the criticism of Ringwood (1955a) who stated "that the effect of increased
covalent bonding is to weaken the bond". He (1955a) pointed out that since the radius of Ni$^{2+}$ is smaller than Fe$^{2+}$, the former could substitute the latter and further Fe-O bonding is weaker than Ni-O bonding and Fe$^{2+}$ is more mobile than Ni. This may render Fe$^{2+}$ to be easily substituted by Ni$^{2+}$.

Earlier Ahrens (1953) attempted to explain it on the basis of his field function concept. He suggested that "when competing for a site in a growing crystal Ni$^{2+}$ is likely to arrive and perhaps enter before Fe$^{2+}$ and Mg$^{2+}$ because the positive field about Ni$^{2+}$ is greater than that associated with the other two ions".

Co has generally been found to be concentrated in the mafic minerals. The ionic radii of Co$^{2+}$ (0.72Å) and Fe$^{2+}$ (0.74Å) have such a small difference that a close relationship between these two elements should exist. But there is a little variation in Co/Mg ratio as compared to Co/Fe ratio as one passes from basic to acid rocks (see Carr et al., 1961). Thus a linear relationship between Co and Mg was envisaged. The same authors also reported that the Co content in high-calcium granites was generally high (6.6 ppm) and low in low-calcium granites (0.88 ppm).

Chromium in rocks and minerals

Usually the ultrabasic rocks have a high concentration of chromium. Wager and Mitchell (1945) found 1,000 gms/ton Cr in olivine from a gabbro-picrite. Lundegaardh's (1946) investigations show that Cr has a tendency to be enriched in forsterite-rich olivine. The fayalite-rich olivines were found to be deficient in Cr. Nockolds and Mitchell (1948) while working on some Caledonian plutonic rocks, found Cr to be concentrated in the early
differentiates of the magma. Carr and Turekian (1961) found that the biotites in granitic rocks were good hosts for Cr (190 ppm). They also found that the magnetites separated from high-grade metamorphic rocks from the Adirondacks as well as phyllites have less than 3 ppm Cr.

Chromium generally has a low dispersion in the granites and granitic rocks of the belt except in a few cases where the value is as high as 90 ppm (22 ppm, Carr, et al., 1961). Dolerites give anomalous values up to 580 ppm (170 ppm, Turekian and Wedepohl, 1961). Quartzites record lower values as compared to the schists and phyllites (upto 245 ppm). The rock and ore samples from mines and the separated mineral fractions do not have unusual dispersion. Ferromagnesians show relatively higher concentrations.

Chromium has been taken as an element of the regional geochemical background because of its chalcophile character and regularity of dispersion in the area. The chemistry of its ionic replacement is discussed below.

It has been generally observed that Cr is preferably incorporated in the silicate phase. Its chalcophile character comes into play only when oxygen is either low or absent (see Goldschmidt, 1958). It occurs as an oxide as well as silicate in igneous rocks.

According to Goldschmidt (1958), \( \text{Cr}^{3+} \) may replace \( \text{Fe}^{3+} \) and \( \text{Al}^{3+} \) diadochally. Wager and Mitchell (1951) found that \( \text{Cr}^{3+} (0.63\text{Å}) \) was camouflaged by \( \text{Fe}^{3+} (1.80) \) during fractionation of magma. Therefore, high concentration of Cr in the ferromagnesian minerals cannot be explained on the basis of simple ionic radius. Ringwood (1955a) observed that the smaller electronegativity of \( \text{Cr}^{3+}(1.6) \) than that of \( \text{Fe}^{3+}(1.8) \) might be responsible
for such a behaviour. Carr and Turekian (1962) observed a good correlation between Cr and Mg contents in a granitic rock. Further, they found that Cr contents in high-calcium granitic rocks were 12 to 22 ppm, while in low-calcium granitic rocks were 3 to 4 ppm.

**Cadmium, lithium and silver in rocks and minerals**

These elements do not show any significant dispersion quantitatively in the samples of the Khetri copper belt. Their geochemical behaviour has been briefly described here.

**Cadmium** - The geochemistry of cadmium is not studied much by the research workers. It has a strong chemical affinity for sulphur. Sandell and Goldich (1943) found that absolute amount of Cd is higher in gabbroid rocks than in granites. Cadmium is usually present in sphalerite crystals. It has been investigated that in the early magmatic sulphides the amount of Zn and Cd are low. These two elements go to the late differentiates and form substantial constituents of late crystallizing ore fluids which intrude the neighbouring rocks in the form of apophyses. Cadmium could not be estimated in the rocks of the Khetri copper belt because of its low traces.

**Lithium** - Lithium is an alkali metal but in many respects it follows Mg. The Li:Mg ratio shows a steady increase in the late crystallizing rocks and minerals. Strock (1936) who made a careful study of this ratio for various igneous rocks suggested that this element could be used as an index to the stage of differentiation reached by a rock. During fractional crystallization the concentration of Li ions increases in the liquid phase while that of Mg ions decreases and thus favourable conditions for
Li to enter into early crystallizing ferromagnesian minerals. The element is more enriched in the granitic rocks than syenites and nepheline syenites. Generally the granite gneisses of the Khetri copper belt show little content of Li. Schists and phyllites also have limited dispersion while in quartzites it is not detectable. Dolerites and the mine samples also have insignificant traces of Li.

Silver - The geochemistry of silver is known considerably. It is found to be more connected with the gabbroid magmas than with granites and highly siliceous rocks. In the case of hydrothermal sulphide deposits Ag, preferably concentrates in chalcopyrite than pyrrhotite. Its presence and qualitative assessment indicates the chemical history of the deposit particularly as regards the temperature of crystallization. It is therefore used in the present study as an element indicating stage of mineralization.

All the samples of the Khetri copper belt have low traces of silver which could not be estimated by the Atomic Absorption Spectrophotometer.
Interpretation of Analytical Data

Rocks and ores

The work is based on the analyses of granites and granitic rocks (25 samples), quartzites (31 samples), schists and phyllites (27 samples), rocks and ore samples from the Madhan-Kudhan and Kolihan mines (23 samples), dolerites (8 samples), amphibolites (4 samples), pegmatites (3 samples) carbonate rocks (3 samples), etc. for trace elements viz., Cu, Pb, Zn, Ni, Cd, Cr, Li and Ag by Atomic Absorption Spectrophotometer (Perkin-Elmer, Model 303). Additional determination for Co was done from the samples of granites and granitic rocks and also those from the Madhan-Kudhan and Kolihan mines.

Residual soil samples

Eighty-two residual soil samples of various groups of rocks, viz., granites and granitic rocks (21 samples), quartzites (20 samples), schists and phyllites (25 samples) and a miscellaneous group (16 samples) consisting of dolerites, pegmatites, amphibolites, carbonate rocks, were analysed for determining the traces of Cu, Pb and Zn, by Atomic Absorption Spectrophotometer (Jarrell and Ash).

The analytical results are plotted on histograms on ppm ranges for rock as well as residual soil samples. The pattern of arrangement of the samples in the figures, the epithets used and the points observed to arrive at certain generalizations are the same in both the cases.

The background values for granites and granitic rocks have been taken from other workers. For metamorphic rocks and the copper mine samples
the values have been calculated from the determined analytical data as has been discussed in Chapter VI.

The sample numbers in the figure are arranged according to their location in the Khetri copper belt. The first sample was taken from the extreme north while the last sample from the extreme south of the belt.

The epithets used in the interpretation are listed below. They connote the following order of relative abundance of elements. The same terminology has been used in Chapter VI:

1. "Insignificant" Below the limit of sensitivity of the instrument.
2. "Poor /Low/Depleted" Much lower than the background value
3. "Marginal" Within a close range of background value.
4. "High/abundant/enriched" Much above the background value.
5. "Anomalous" Distinctly above the threshold value.
6. "Highly anomalous" Many times higher than the background value.

Rocks and ores (see Text Figs. 4 & 5).

Granites and granitic rocks:

1. There is a general depletion in the Cu, Cr, and Li content and enrichment in Pb, Zn, Ni, while Co, Cd and Ag have insignificant values.

2. Cu is rarely high (38 ppm). Dispersion of Cu in the granite gneisses of the southern part of the belt is relatively higher than in the granites of the northern part of the same belt.

3. Ni, Zn and Pb show abundance as compared to their respective background values. Their concentrations are relatively high in the granite gneisses of the southern part of the area.
4. The values for Co in granites vary from 3 ppm to 8 ppm which are quite significant as very little of Co content was reported from the granites of other places.

5. The samples having high Cu content have ordinarily higher values for the other trace elements as well.

6. Pb and Zn show antipathic relationship with each other. Frequently, where Pb records a high value (70 ppm), the value of Zn becomes correspondingly low (26 ppm), and where the value of Pb is comparatively low (15 to 25 ppm) the value of Zn is usually high (95 to 200 ppm).

7. Ni and Co also have antipathic relationship. Where the values of Ni are 10 ppm, the values for Co are as high as 8 ppm. Similarly where the value of Ni is high (42 ppm) the value of Co goes down (3 ppm).

8. Cr gives anomalous values in the case of two samples of the northern part of the belt. Samples having higher Cr contents show enrichment in Zn and Ni but rarely in Cu.

9. Li is confined to a few samples of the granite gneisses only.

There was no distinct inter-relationship among these trace-elements. Generally Ni and Co show antipathic relationship, Cu to some extent has sympathetic relationship with Zn. Pb and Zn also show antipathy in some cases.

Quartzites

1. There is a general enrichment in Cu, Pb, Ni and Cr, and depletion in Zn, while Cd, Li and Ag have insignificant values. All the above trace elements show scattered dispersion all over the belt.
2. Cu gives very high values (770 to 1160 ppm) but only in a few exceptional cases. Where Cu shows anomalous values, Pb is also high (36 to 44 ppm) while Zn remains low (20 to 21 ppm). Ni and Cr are either low (except in one case) or absent.

Where Cu is low or insignificant, Pb and Zn are usually low while Ni and Cr show appreciable enrichment.

3. The samples of the northern part of the belt, particularly the amphibole quartzites, show enrichment in Cu and Pb contents and depletion in Zn, Ni and Cr. On the other hand the samples of the southern part of the belt (mostly felspathic and massive quartzites) show comparatively low dispersion of Cu and Pb and enrichment in Cr, Zn and Ni (in order of increasing abundance). There are, of course, a few exceptions to this generalisation.

4. Commonly Pb and Zn have antipathic relationship, and the value of Pb concentration is anomalous (74 ppm), Zn is either low (20 ppm) or insignificant (< 5 ppm) and where Zn content is high (89 ppm) the value for Pb becomes low (12 ppm).

5. A sample of amphibole quartzite collected from the quartzite ridge of Singhana recorded anomalous values for Cu, Pb, Zn, Ni and Cr. It, however, appears to be an exception.

6. Ni and Cr showed sympathetic relationship in a number of cases.

7. Li in general is insignificant. Only two samples recorded a value of 12 ppm.

8. Sericite quartzite (peak quartzite) was found to be barren of any mineralization.
It is evident from the above observations that the trace elements concerned hardly have any inter-relationship among each other. In some cases in which Pb and Zn have antipathy Ni and Cr have sympathetic relationship.

**Schists and phyllites**

1. Generally, Cu, Cr, Pb, Ni, Zn and Li show a general enrichment (in order of decreasing abundances), Cd and Ag occur in insignificant amounts.

2. There is a greater abundance of Cu in the schistose rocks than in the phyllitic rocks. In both cases where Cu is high (125 to 750 ppm) the value for Zn is low (30 to 57 ppm), Pb is appreciably constant (30 to 46 ppm) because the fluctuation in values is little. In some cases where Cu is low (15 ppm) Cr is exceptionally high (245 ppm) and so is the case with Ni (90 ppm).

3. Generally Cu occurs in greater abundance in the rocks of the northern part of the belt than those occurring in the southern part barring only one sample in which Cu is high (750 ppm).

4. Chlorite-schists and mica-schists show exceptionally high concentrations. Andalusite-schist also records higher values of Cu (55 ppm), Pb, Ni and Cr.

5. To some extent Zn and Ni and distinctly Ni and Cr show sympathetic relationship.

6. Except Cu (to some extent Zn also) none of the trace elements show selective enrichment in a particular part of the belt. Zn has appreciable enrichment in the samples NW of Saladipura (90 to 160 ppm).
TEXT FIG. NO. 5
7. Ni and Cr are more concentrated in the schists and phyllites than in the quartzites and granites or granitic rocks.


Zn gives higher values NW of Saladipura. Cr show enrichment in the northern portion of the belt. Ni and Pb have a distinct dispersion all over the belt.

**Khetri copper mines samples**

The samples include several types of schists and quartzites (host rocks), amphibolites, dolerites, etc. Some of the ore samples and separated chalcopyrite and pyrrhotite samples have also been analysed for elements other than Cu. Copper being exceptionally high in certain cases has been shown along the full length of the histograms.

1. There is a general enrichment in Cu, Co, Ni, Pb and Cr in the decreasing order of abundance. Zn occurs in appreciable amounts while Cd and Ag have insignificant values.

2. Schists have significantly abundant of Cu content (3^0 ppm). Co, Ni and Cr are also present in abundance in these rocks.

3. The quartzites have poor concentrations of Cu as compared to schists. Quartzites have high Co content particularly, the amphibole-quartzite (Co, 216 ppm).

4. Phyllites are generally low in Cu (75 ppm) but relatively enriched in Pb, Ni, Cr and Co. Zn is appreciably low (25 ppm).
5. The amphibolites have very low dispersion of Cu (20 ppm) but indicate higher concentration of Ni (55 ppm) and Pb (45 ppm).

6. Dolerites are relatively high in Cu (45 ppm) and so is the case with other trace elements as well.

7. The copper ore samples generally have higher concentration of Zn (250 ppm), Ni (235 ppm) and Co (360 ppm). Cr and Li give poor dispersion values (15 ppm and < 10 ppm, respectively).

8. Commonly, the samples of host rocks with Cu are having higher contents of Cu give higher values for Ni and Co and low for Zn.

No assessment could be made of the inter-relationship of elements because of a wide variety of rock types obtained in this section.

**Dolerite**

1. The samples show general enrichment in Cu, Zn, Ni and Cr content while Pb and Li are marginally higher.

2. The values for Cu vary from 10 to 445 ppm showing its higher dispersion in the northern part of the belt.

3. Zn does not show any sector of preferential concentration and the values range from 48 to 340 ppm.

4. Ni contents do not show wide variation (18 to 140 ppm) while Cr contents have values varying from 10-580 ppm.

5. Both Cd and Ag lie below the sensitivity limit of the instrument except in one sample.
**Pegmatites**

1. Pegmatites do not show any abnormal concentration of Cu. The lowest value obtained is 10 ppm from pegmatites near Papurna and the highest value is recorded from the pegmatites SW of Chappoli (90 ppm). A sample from pegmatite vein NW of Madhan-Kudhan mines gave a value of 29 ppm.

2. Lead content appear to show direct relationship with copper because the samples having high copper values also show higher dispersion of lead.

3. Zn, Ni and Cr appear to be inversely proportional to Cu and Pb content.

4. Cd, Li and Ag show values < 5 ppm.

**Amphibolites**

1. Amphibolites show low dispersion of Cu except in one case in which the value is 45 ppm.

2. Pb has a consistent dispersion in almost all the samples.

3. Zn values range from 40 to 175 ppm showing a general enrichment.

4. Ni has values almost directly proportional to zinc. The values range from 30 to 130 ppm.

5. Cr shows poor dispersion except in one case (190 ppm). The values range from 10 ppm to 190 ppm.

6. Cd, Li and Ag have values < 5 ppm.

**Carbonate rocks**

1. The values for Cu vary from 10 to 65 ppm. There is no significant concentration.
2. Pb and Zn values appear to be dependent on each other and show general enrichment.

3. Ni shows variation from 32 to 66 ppm.

4. Cr has dispersion values ranging from 70 to 100 ppm.

**Residual Soils** (See Text Fig. 6)

**Granites and granitic rocks** - In general, Cu, Pb and Zn show a low dispersion. Rarely, the Cu content is high and touches a maximum value of 168 ppm. Samples having higher Cu content usually show depletion in the content of Pb and Zn. Similarly where Cu gives low values (16 ppm), Zn is usually high (45 to 77 ppm) and Pb is usually low (6 to 13 ppm).

Frequently Pb is more affected by the change in the Cu content and has a closer antipathic relationship with Cu than with Zn. The relationship is between Pb and Zn/rather uncertain and, therefore, it does not lead to any firm generalization.

Sometimes where Pb is high (38 ppm), Zn also records high value (63 ppm) and on the other hand, where Pb is low (9 ppm), Zn gives high values (76 ppm). Similarly, where Zn falls to a low value (21 ppm), Pb is either absent or records a low value (9 ppm). Such departures from any definite pattern lead to generalise that Pb and Zn relationship is antipathic in some cases and sympathetic in others.

The figure clearly shows that the samples on the left hand side (i.e., northern part of the belt) give relatively higher values for Cu than the samples on the right hand side (i.e., southern part of the belt). Further it was observed that the samples collected from the western margin of an outcrop had relatively higher values.
Quartzites - The samples show marked enrichment particularly in the Cu content.

There is a general enrichment of Zn while Pb has a low dispersion except in one sample of the southern part of the belt (44 ppm).

There is a wide variation in Cu-content. The values ranged from 12 to 610 ppm. Commonly the samples having higher Cu-content (377 to 610 ppm) give relatively low values for Pb (9 to 20 ppm) and Zn (50 to 53 ppm). Where the value for Cu is low (16 ppm) the value for Zn is usually high (82 ppm).

Pb and Zn do not show a clear relationship. The values of Pb came down to as low as 5 ppm while Zn shows appreciable and almost uniform dispersion all over the belt. Cu show antipathic relationship with Zn.

It was found that Cu is anomalously high in the samples of the northern part of the belt.

Schists and phyllites - Schists have higher dispersion in the northern part of the belt. Phyllites also show appreciable concentration of Cu.

There is a general improvement in the concentration of all the three elements. Cu shows anomalously high values to a maximum of 1436 ppm where the values for Cu are higher (364 to 1436 ppm), Pb and Zn have relatively low values. But such a relationship was not frequent. It was also true that some samples having a fairly high Cu content (106 ppm) give high value for Pb (53 ppm) and moderately high value for Zn (45 ppm). Further the samples having a low Cu content (18 ppm) have higher values for Zn and Pb (59 and 77 ppm respectively).
An antipathic relation exists between Pb and Zn in the samples recording low Pb content. But in some other cases where the value for Pb is high (46 ppm) Zn is generally high (71 ppm).

The samples distinctly show a higher concentration of Cu in the northern part but it gradually decreases in the schists and phyllites of the southern part of the belt. The values of Pb are comparatively high but it has not concentrated in any particular part of the belt.

Residual soils of other rock types

The residual soil samples of other rock types include soils of dolerites, pegmatites, amphibolite and carbonate rocks. A general quantitative assessment is made in the following way.

There is an appreciable concentration of all the three elements in the samples. Cu gives appreciably high values sometimes as high as 702 ppm. Where Cu gives high value (702 ppm) usually the value of Pb is low (9 ppm), where Cu is low (13 ppm), both Pb and Zn have higher values (63 and 65 ppm, respectively).

The dolerites have exceptionally high Cu value (702 ppm). Pegmatites do not show any enrichment. The amphibolites have comparable Cu content (30 ppm) though rarely the values of Zn are high (73 ppm). Carbonate rocks clearly show enrichment in the Zn content (106 to 142 ppm).

Based on a comparative study of the residual soil samples of granites and granitic rocks, quartzites, schists and phyllites and the other rock types, an overall picture of the trace element distribution is presented as follows:
1. There is a gradual increase in the Cu traces from granites to quartzites and from quartzites to schists and phyllites.

2. The variation is distinct in the samples of the northern part of the belt. The granites have low dispersion of copper. Felspathic quartzites occurring in contact with granites are also poor in Cu, while amphibole quartzites and phyllites occurring in contact of the schists show appreciable increase of Cu-traces. Schists in turn give highly anomalous values, for Cu. Other rock types in exceptional cases have high content of Cu.

3. Pb has a low dispersion in granites and granitic rocks and poor in quartzites. Schistose rocks and phyllites indicate appreciable abundance of lead. The other rock types also show some enrichment in Pb contents. There is no such area in the belt which can be said to have any sort of preferential concentration of Pb.

4. Zn records a marginal fluctuation (as compared to the background value) in all the samples. In most cases it shows an antipathic relationship with Cu. In general Zn shows a controlled dispersion.
DISTRIBUTION OF SOME TRACE ELEMENTS IN THE SEPARATED MINERAL FRACTIONS OF GRANITES AND GRANITIC ROCKS AND HOST ROCKS OF COPPER ORES

Granites and granitic rocks (see Text Fig. 7)

Ten samples were selected from the different outcrops of granites and granitic rocks of the area. Their ferromagnesian and felsic mineral fractions were separated and analysed for traces of Cu, Pb, Zn, Ni, Co and Cr and the results were plotted in histograms.

The ferromagnesian minerals viz., epidote, hornblende and biotite were separated as more or less pure monomineralic fractions (about 95 per cent pure). Only in two samples (No. 1 and 2) in which hornblende and epidote coexist, they had to be separated from one another. The results of analyses are plotted separately. Quartz and feldspars have been collected together as a felsic group for analyses.

All plotting has been done on ppm values. The serial number of the samples in the figure is with reference to their location in the belt. For example Sample No. 1 belongs to the extreme northern part while Sample No. 10 to the extreme southern part of the belt where such rocks are exposed.

A quantitative assessment is made in two ways. Firstly, a general trend of elements in the ferromagnesian and felsic group is considered and their order and preference of concentration are discussed. Secondly, the behaviour of these trace elements in each rock sample and their variation in the belt is considered.
General assessment

Cu, Pb, Zn, Ni, Co and Cr are preferably concentrated in the ferromagnesian phase.

Cu entered both hornblende (58 ppm) and biotite (62 ppm) with almost equal ease. This was particularly observed in the samples of hornblende-granite gneiss and biotite-granite gneiss from the southern part of the belt. In general Cu has a greater concentration in hornblende than biotite and relatively more in biotite than epidote (38 ppm).

Cu in all the samples of the felsic group reads insignificant values.

Pb, Zn, Ni and Cr are concentrated in hornblende, biotite and epidote in order of decreasing abundance.

Zn is exceptionally high in hornblende (415 ppm) and biotite (295 ppm) in the southern part of the belt.

Pb (10 to 29 ppm) and Zn (3 to 47 ppm) value are quite low in all samples of the felsic group.

Ni and Cr to some extent show a consistency in being accumulated in the ferromagnesian fractions. They preferably concentrate more in hornblende than in biotite and least in epidote.

Co behaves differently. It has slightly greater concentration in biotite (69 ppm) than hornblende (60 ppm) and least concentration in epidote (29 ppm).

Ni has a very low accumulation (6 to 13 ppm) in the felsic group.

Co and Cr are characteristically absent in all samples of felsic group.

Northern part

1. Hornblende - Where Cu is high, the values of Pb, Zn and Ni are low and where Cu is low, the values of Pb, Zn and Ni are high. Co and Cr remain low in both the cases.

2. Epidote - Where Cu is high, the values of Pb, Zn and Cr are high, while Ni and Co are low. Where Cu is low, the values of Pb and Cr are low while
SEPARATED MINERAL FRACTIONS OF HOST ROCKS OF COPPER ORES

TEXT FIG. NO. 8
Zn, Ni and Co are high.

3. **Biotite** - Where Cu is high, the values of Pb, Zn, and Co are low, while those of Ni and Cr are moderate. Where Cu is low the value of Pb, Zn and Co are high while Ni and Cr continue to record intermediate values.

**Southern part**

1. **Hornblende** - Where Cu is high, the value of Pb is low. Zn shows an exceptionally high value while Cr, Ni and Co are appreciably high.

2. **Biotite** - Where Cu is high, the value of Zn is intermediate. Pb and Cr give low values while Ni and Co are relatively low. Where Cu is low, the values of Pb, Ni and Co and Cr are high, while Zn continues to read intermediate values.

**Felsic group**

The felsic group does not show any specific pattern. The values of Cu, Pb, Zn and Ni are almost insignificant and do not indicate any relationship with one another.

**Host Rocks** (see Text Fig. 8)

Six samples were selected from the host rocks of copper ores. Three samples were collected from Madhan-Kudhan copper mines and three samples from Kolihan copper mine. The separated mineral fractions (95 per cent purity) include garnet, amphibole, biotite and quartz plus feldspars (felsic group). They were analysed for traces of Cu, Pb, Zn, Ni, Co and Cr. The analytical results were plotted in histogram.
General Assessment. - The following assessment has been made considering the points as stated in the case of granites and granitic rocks.

Cu, Pb, Zn and Co show preferable enrichment in amphibole. Ni and Cr are relatively higher in biotite. Garnet have comparable concentration of all the above trace elements. Felsic group has the least metallic content.

Copper is predominently concentrated in amphibole (363 ppm) than garnet (330 ppm) and biotite (313 ppm). The garnets of garnetiferous biotite-schist (Kolihan copper mine) have low Cu content (85 ppm) while garnets of the garnetiferous quartz-chlorite schist of Madhan-Kudhan mine give higher content of Cu (330 ppm). The amphibole from amphibole quartzite of the Kolihan mine contain 295 ppm of Cu while that of Madhan-Kudhan mine records 363 ppm of Cu.

The felsic group does not have any Cu content in all the samples.

Lead and zinc are generally concentrated more in amphibole than biotite and least in garnet.

Nickel is high in biotite (60 to 80 ppm) than in amphibole (58 ppm, amphibole and chlorite) and marginally low in garnet (48 to 55 ppm). Amphibole from amphibole quartzite show values varying from 28 to 36 ppm of Ni.

Cobalt has a higher concentration in amphibole (115 ppm, amphibole + chlorite from garnetiferous quartz chlorite schist) than in garnet (72 to 94 ppm) and biotite (59 to 78 ppm). The garnet from garnetiferous quartz-chlorite-schist have relatively more Co content (94 ppm) than in garnet from the garnetiferous biotite-schist (45 ppm).
Chromium is markedly higher in biotite (165 to 250 ppm) than in rest of the separated mineral fractions. Amphibole (amphibole + chlorite) are more enriched in Cr content (132 ppm) than in garnet (68 to 121 ppm). The garnet from garnetiferous biotite-schist gives higher values (121 ppm) of Cr than the garnet of garnetiferous quartz-chlorite-schist (96 ppm).

Generally Pb, Zn, Cr, Co and Ni are present in low concentrations in the felsic group and they occur in decreasing order of abundance.

**Relationship of other trace elements with copper in individual minerals**

1. **Amphibole** - (sometimes with chlorite). Where Cu is high Pb, Ni, Co and Cr are low, while Zn is high. Where Cu is low Pb, Ni, Co and Cr are generally high, while Zn is low.

2. **Garnet** -
   a) **Garnet from garnetiferous quartz-chlorite schist** - Where Cu is high Pb and Zn are low, while the values of Ni, Co and Cr are high. Where Cu is low, the values of Pb and Zn are high, while Ni, Co and Cr generally show low concentrations.
   b) **Garnet from garnetiferous biotite-schist** - Where Cu is high generally all the other trace elements are high and vice versa.

3. **Biotite** - Where Cu is high, generally all the other trace elements are high. Where Cu is low the other elements have marginally lower values.
VARIATION DIAGRAM SHOWING RELATIONSHIP BETWEEN Cu, Pb, Zn, Ni, Co & Cr CONTENT OF THE BULK ROCK & THEIR SEPARATED MINERAL FRACTIONS IN GRANITE & GRANITIC ROCKS

TEXT FIG.NO. 9
RELATIONSHIP BETWEEN Cu, Pb, Zn, Ni, Co, AND Cr CONTENTS OF THE BULK ROCKS AND THEIR SEPARATED MINERAL FRACTIONS IN GRANITES AND GRANITIC ROCKS

A comparative study of the distribution and relationship of some trace elements in granites and granitic rocks and its ferromagnesian fractions is done and the observations made are summarized below (see Text Fig. 9).

The concentration of Cu, Pb, Zn, Ni, Co and Cr are low in the bulk rocks while the ferromagnesians in them show enrichment of these elements.

Investigations carried out by Putnam and Burnham (1963) show that the Cu content of many bulk rock samples of granites are somewhat higher than the amount contributed by the ferromagnesian phase. They attributed this observation to the presence of small amounts of chalcopyrite in granites. The same authors also pointed out the possibility of the presence of small amounts of Cu in feldspars. Earlier Newhouse (1936) and Ramdohr (1940) also reported the presence of small amounts of chalcopyrite in granites.

In the present case the ferromagnesian minerals always give higher values for Cu as compared to the bulk rock. This indicates that no copper ore is associated with these granites and granitic rocks. Further the Cu in these rocks appears to have preferably concentrated in the mafic minerals.

Putnam and Burnham (1963) also found that the Cu contents of biotite coexisting with chalcopyrite in the granites are higher as compared to the coexisting hornblende. Shrivastava and Proctor (1962) found more Cu in the augite-hornblende-chlorite group than in the biotites in quartz-monzonite
which was supposed to be source rock of copper ores. They also reported small amounts of Cu in the feldspars.

In the rocks under study perhaps Cu entered into biotite and hornblende with almost equal ease. Biotites show a marginal edge over hornblende. This indicates that the ferromagnesian minerals of the granites may have some primary copper in them and that they have not been affected by later percolations or permeations. Further, Cu may have entered some of the ferromagnesian minerals by replacing Fe. Little occurrence of Cu in the felsic group may be attributed to the feldspars rather than quartz.

Similar to copper, Pb also shows enrichment in the ferromagnesian minerals. It was also found in appreciable amounts in the felsic group.

It is generally believed that Pb enters into granites diadochally with K⁺ and thereby potash-felspars may contain appreciable amounts of Pb (Goldschmidt, 1958; Wedepohl, 1956). Shrivastava and Proctor (1962) found that although Pb was preferably concentrated in the mafic minerals yet they (mafic minerals) constituted a small fraction of the bulk rock. They further considered feldspars as good hosts for Pb.

Lead in the present case reads higher values in the mafic minerals than the bulk rock. Further, the felsic group, which forms the major part of the bulk rock, has also appreciable amounts of Pb. Obviously Pb has also a significant concentration in the felspars of the felsic group. It was also observed that the pink granite-gneisses rich in potash-felspars have higher concentration of Pb than other rock samples.
Concentrations of zinc have been reported in basic igneous rocks (Sandell and Goldish, 1943) as well as biotites (Lundegaardh, see Wilson 1953). Wedepohl (see Putnam and Burnham, 1963) found occasional presence of Zn in feldspars.

The present analytical data show that the ferromagnesians are enriched in Zn as compared to the bulk rock. Further the felsic group also shows significant amounts of Zn. This indicates that Zn is possibly present in the silicate phase of the mafic minerals and feldspars of the felsic group and not as a sulphide. It might have been accommodated by replacing $Fe^{2+}$ and $Mg^{2+}$ of the mafic minerals (see Ahren, 1964).

Ni and Co are fellow travellers. Both these elements are found preferably concentrated in the ferromagnesians as compared to the bulk rock. The concentration of Ni is more than Co in general. The observations made are as follows:

i) Co and Ni are solely present in the silicate structure (Goldschmidt, 1958).

ii) Co and Ni have antipathic relationship.

iii) Co and Ni may/enriched in mafic minerals possibly substituting $Fe^{2+}$ (see Ringwood, 1955a) and $Mg^{2+}$ (see Carr and Turekian, 1961) respectfully.

Cr is reported to be preferably incorporated in the silicate structure and biotites are considered to be good hosts for Cr (see Carr and Turekian, 1961).

The ferromagnesian are significantly enriched in Cr contents as
compared to the bulk rock. The higher concentration of the metal in hornblende and biotite suggests that Cr is present in the silicate structure. It might have entered the lattice possibly substituting Fe$^{3+}$ (see Ringwood, 1955a).
Chapter VI

GEOCHEMICAL DISPERSION OF TRACE ELEMENTS

Geochemical variation diagrams for Primary and Secondary dispersion aureoles

Variation diagrams were used to represent graphically the geochemical dispersion of Cu, Pb, Zn, Ni, Co, Cd, Cr, Li and Ag, in the various important rock types of the Khetri Copper Belt. They precisely illustrate the dispersion aureoles of these trace elements and their relative abundance in a particular set of rock. An attempt has been made to use them to present the analytical data of geochemical dispersion both for primary and secondary dispersion aureoles.

Primary dispersion aureoles

All the rock types of the area were first classified into 3 major groups based on their lithological and petrological characters. The primary dispersion aureoles of the following major rock groups were prepared separately.

1. Granites and granitic rocks
2. Metamorphic rocks
   (a) quartzites
   (b) Schists and phyllites
3. Khetri copper mine samples (including some ores).

For the quantitative determination of the above mentioned nine trace elements, a total of 130 samples of rocks and ores were analysed by Atomic Absorption Spectrophotometer. Variation diagram was prepared separately for each group of rocks. The details of the points of interest of the diagram are as follows:
Indicator elements - Elements having different geochemical behaviour have been used as indicator elements for different purposes, the reasons for such use have been summarized in the previous chapter.

Li and Ag have been placed as the indicator elements for the stage of mineralization. Cu, Pb and Zn have been used as indicator elements of ore complexes. Co, Cd, Ni and Cr represent elements of the regional geochemical background. Plotting was done on ppm range for all elements. The range variation is 5 ppm and 10 ppm as the lower limits and 1,000 ppm as the upper limit for all elements.

Each diagram has been divided into nine equal quadrants in the cases of granites and granitic rocks and the samples from Madhan-Kudhan and Kolihan mines, and into eight equal quadrants in the cases of quartzites, schists and phyllites.

Concentration circles in ppm range on logarithmic scale were drawn for values of 1,000 ppm, 500 ppm, 100 ppm, 50 ppm, 10 ppm and 5 ppm. Each quadrant was further divided into per cent frequency having sectors of 25 per cent, 50 per cent, 75 per cent and 100 per cent.

Analytical data have been grouped into ranges with an interval of 10 ppm for values up to 100 ppm. Higher values have been plotted separately. Values of < 5 ppm and < 10 ppm have been plotted by drawing thin lines tapering at the centre of the diagram. They indicate values above zero but less than 5 ppm (Cd) and less than 10 ppm (Ag).

Background values are taken from the values given by Carr and Turekian (1961), Taylor, S.R. (1964) and Vinogradov (1962) for granites
and granitic rocks. For metamorphic rocks the average values of the analysed samples of a particular rock group of the two parts of the belt were calculated separately. Finally the average of the two values was calculated and taken as the regional background values of the area. Values for the samples from Madhan-Kudhan and Kolihan copper mines have been calculated as average values from the obtained analytical data.

The residual soil samples of granites and granitic rocks, quartzites and schists and phyllites have also been analysed by Atomic Absorption Spectrophotometer for traces of Cu, Pb and Zn. The analytical data were presented with the help of single geochemical variation diagram. The diagram is divided into three equal quadrants, each of which represents the soil samples of a particular rock group. Each quadrant is again subdivided into three equal divisions for Cu, Pb and Zn. The plotting of analytical results was done similar to that of rock samples. The calculated background values as well as the average values given by Hawkes (1962) have been recorded and discussed.

The diagrams represent all the parameters clearly, with the scope to accommodate any other relevant record. The dispersion patterns were later discussed with a view to study the geochemical behaviour of trace elements in a particular set of rocks or their residual soil samples and the variation trend of these trace elements in that set.

The net of the diagram for the graphical representation of Geochemical data has been used as proposed by Baimalibelli (1964).
GRAPHICAL REPRESENTATION OF GEOCHEMICAL DATA

GEOCHEMICAL VARIATION DIAGRAM FOR PRIMARY DISPERSION AUREOLES OF VARIOUS TRACE ELEMENTS IN GRANITE AND GRANITIC ROCKS

TEXT FIG. NO. 10
**Explanation of geochemical variation diagram for granites and granitic rocks**

*(See Text Fig. 10)*

<table>
<thead>
<tr>
<th>Name of the element</th>
<th>Role of the element</th>
<th>Background value &amp; its reference</th>
<th>Range of Values</th>
<th>Max. frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment &amp; Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator element of ore complexes</td>
<td>20 ppm to 10 ppm; 48 ppm &lt; 10 ppm to 10-20 ppm; 40% = 10-20 ppm</td>
<td>Widening in the middle narrowing at either ends.</td>
<td>1) Granites of the northern part of the belt show depletion in copper content excepting in a few cases where values are marginally higher.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Pb                  | Indicator element of (S.R. Taylor, 1964) ore complexes | 20 ppm to 10 ppm; 126 ppm < 10 ppm to 30-40 ppm; 28% = 30-40 ppm | Fan shaped with the broader end based on group of 30-40 ppm. | 1) Dispersion does not follow the copper trend.  
2) A linear relationship between K-felspars and lead content appears to be present.  
3) Aplites record lowest dispersion values (10 ppm) while in some granites they jump to 85-126 ppm, indicating the relative abundance obviously with the increase in the ferromagnesian minerals.  
4) The dispersion is somewhat controlled and records a general enrichment. |
| Zn                  | Indicator element of (Vinogradov, 1962) ore complexes | 60 ppm to 300 ppm < 5 ppm to 20-30 ppm; 16% = 20-30 ppm; 16% = 40-50 ppm; 40% = 40-50 ppm | Seriated | 1) There is a general depletion like in the case of copper.  
2) The granites and granite gneisses having greater proportions of ferromagnesian content (amphiboles, epidote biotite) show higher values. |
<table>
<thead>
<tr>
<th></th>
<th>Element of</th>
<th>5 ppm</th>
<th>3 ppm</th>
<th>≤ 5 ppm</th>
<th>Coneshaped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>the regional (Vinogradov, geochemical background 1962)</td>
<td>8 ppm</td>
<td>&lt; 10 ppm</td>
<td>= 56%</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>the regional (S.R. Taylor, geochemical background 1964)</td>
<td>0.2 ppm</td>
<td>≤ 5 ppm</td>
<td>≤ 5 ppm</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>the regional (Carr and Turekian, background 1961)</td>
<td>22 ppm</td>
<td>10 ppm to &lt; 10 ppm</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>the regional (Vinogradov, geochemical background 1962)</td>
<td>8 ppm</td>
<td>11 ppm</td>
<td>≤ 10 ppm</td>
<td></td>
</tr>
</tbody>
</table>

3) There is a relative increase in the Zn. Content of the rocks occurring in the southern part of the belt.

4) Aplites show very low values (< 5 ppm)

1) Almost all the samples show enrichment.

2) Granite gneisses show values ranging up to 8 ppm whereas granites show relatively low values (3 ppm) all over the belt.

Quantitative determination could not be made in this case. However, it is evident that the dispersion values are insignificant.

Granites in general show depletion in Cr content barring a few granite gneisses in which the values range up to 90 ppm.

1) Granites and aplites have concentration pattern having three such points lower than the background value with the exception of some of these granites in which concentration goes up to 32-42 ppm, obviously on account of higher proportion of amphibole and epidote.

2) The variation is more pronounced in granite gneisses than in granites.

3) Amphibole gneiss has a value of 43 ppm.
<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Li</strong></td>
<td><strong>Element</strong></td>
<td>30 ppm</td>
<td>10 ppm to &lt; 10 ppm</td>
<td>Shows a triangular dispersion pattern.</td>
<td>1) All granites and granitic rocks show depletion in Li contents.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>indicating (S.R. Taylor, 1964)</td>
<td>18 ppm</td>
<td>10-20 ppm</td>
<td>= 74%</td>
<td>2) Granite gneisses show values of dispersion which lie well below the background value.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>stage of mineralization.</td>
<td></td>
<td></td>
<td></td>
<td>3) Probably the mafic minerals are the chief hosts of Li.</td>
<td></td>
</tr>
<tr>
<td><strong>Ag</strong></td>
<td><strong>Element</strong></td>
<td>0.04</td>
<td>&lt; 10 ppm</td>
<td>&lt; 10 ppm</td>
<td>A thin line from 10 ppm circle is drawn converging towards the centre of the diagram.</td>
<td>Quantitative determination could not be made. Its dispersion is not, however, unusual.</td>
</tr>
<tr>
<td></td>
<td>indicating (S.R. Taylor, 1964)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GRAPHICAL REPRESENTATION OF GEOCHEMICAL DATA

GEOCHEMICAL VARIATION DIAGRAM FOR PRIMARY DISPERSION AUREOLES OF VARIOUS TRACE ELEMENTS IN QUARTZITES

TEXT.FIG.NO. 11
### Explanation of geochemical variation diagram for quartzites (see Text Fig. 11)

<table>
<thead>
<tr>
<th>Name of the element</th>
<th>Role of the element of ore complexes</th>
<th>Background values</th>
<th>Range of values</th>
<th>Max. frequency group/groups &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator element of ore complexes</td>
<td>Northern part: 36 ppm</td>
<td>&lt;10 ppm to 1160 ppm</td>
<td>Dispersion pattern shows a gradual increase in the values and having little projection all through.</td>
<td>1) Significant dispersion having wide fluctuations. Some anomalous values (upto 40 times of the background value) were recorded. 2) Magnetite-quartzite is almost devoid of any copper while the amphibole-quartzite and felspathic quartzites nearer to the mineralized zone in the northern half of the belt give anomalous results. 3) The quartzites in the southern part are relatively poor in copper (upto 35 ppm)</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>Indicator element of ore complexes</td>
<td>Southern part: 21 ppm</td>
<td>&lt;10 ppm to 74 ppm</td>
<td>Shows a broadening in the middle portion and narrowing pattern at either ends.</td>
<td>1) Shows a controlled dispersion all over the belt. 2) The northern part has higher dispersion values than the southern part. 3) The quartzites occurring closer to the mineralized zone recorded higher values (74 ppm).</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>Indicator element of ore complexes</td>
<td>Northern part: 31 ppm</td>
<td>&lt;5 ppm to 150 ppm</td>
<td>Shows two projections, one at a point grouping 10-20 ppm and the other, at a point grouping 80-90 ppm</td>
<td>1) Appreciable variation in dispersion. 2) Higher values were recorded (upto 150 ppm) from the southern part of the belt. 3) Magnetite-quartzite in the northern part does not show any trace of zinc, while the amphibole quartzites recorded zinc content as high as 80 ppm.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Cd</td>
<td>Element of the regional geochemical background</td>
<td>-</td>
<td>-</td>
<td>&lt; 5 ppm</td>
<td>&lt; 5 ppm</td>
<td>= 100%</td>
</tr>
<tr>
<td>Cr</td>
<td>Element of the regional geochemical background</td>
<td>28 ppm</td>
<td>47 ppm</td>
<td>&lt; 10 ppm to 10 ppm</td>
<td>164 ppm</td>
<td>= 64%</td>
</tr>
<tr>
<td>Li</td>
<td>Element indicating stage of mineralization</td>
<td>&lt; 10 ppm</td>
<td>&lt; 10 ppm to 12 ppm</td>
<td>&lt;10 ppm = 96%</td>
<td>Shows a tapering from 12 ppm value towards the centre of the diagram. 1) Poor dispersion all over the belt. 2) Highest value obtained is 12 ppm</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>Element indicating stage of mineralization</td>
<td>-</td>
<td>-</td>
<td>&lt;10 ppm = 100%</td>
<td>Shows a tapering type dispersion pattern from 10 ppm down to the centre of the diagram.</td>
<td></td>
</tr>
</tbody>
</table>

-
GRAPHICAL REPRESENTATION OF GEOCHEMICAL DATA

GEOCHEMICAL VARIATION DIAGRAM FOR PRIMARY DISPERSION AUREOLES OF VARIOUS TRACE ELEMENTS IN SCHISTS AND PHYLLITES

TEXT FIG. NO. 12
Explanation of geochemical variation diagram for schists & phyllites (see Text Fig. 12)

<table>
<thead>
<tr>
<th>Name of the element</th>
<th>Role of the element</th>
<th>Background values</th>
<th>Range of values</th>
<th>Max. frequency group/groups &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator element of ore complexes</td>
<td>Regional background value (average of the two values)</td>
<td>32 ppm</td>
<td>33 ppm 32 ppm &lt;10 ppm to 750 ppm</td>
<td>10-20 ppm = 32%</td>
<td>At the lower end the pattern projects but thereafter it gradually increases &amp; shows a regularity in dispersion.</td>
</tr>
<tr>
<td>Pb</td>
<td>Indicator element of ore complexes</td>
<td>Regional background value (average of the two values)</td>
<td>32 ppm</td>
<td>28 ppm 35 ppm &lt;10 ppm to 61 ppm</td>
<td>20-30 ppm = 28%</td>
<td>Shows a simple dispersion pattern with pinching ends and widened middle portion.</td>
</tr>
</tbody>
</table>

1) Significant variation in dispersion.
2) Schists of the northern part show anomalous values as high as 20 times more than the background value.
3) Phyllites nearer the schistose rocks show value upto 71 ppm.
4) The rocks of the southern part of the belt indicate a relatively low dispersion except in the case of mica-schist, which shows a higher value of 750 ppm.

1) Most of the values are higher than the background value.
2) Phyllites show values upto 36 ppm.
3) In general there is no single sector in the belt which could be distinguished on the basis of preferential concentration for Pb.
<table>
<thead>
<tr>
<th></th>
<th>Indicator element of ore complexes</th>
<th>Zn</th>
<th>54 ppm</th>
<th>66 ppm</th>
<th>&lt; 5 ppm to 160 ppm</th>
<th>20 ppm to 30 ppm = 15%</th>
<th>30 ppm to 40 ppm = 15%</th>
<th>40 ppm to 50 ppm = 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regional background value (average of the two values)</td>
<td>60 ppm</td>
<td>Show three projections in the diagram.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Shows controlled dispersion.  
2) There is no anomalously high value.  
3) Phyllites show poor dispersion.  
4) There is no specific sector or rock type having preferential concentration as it is in the case of lead.  
5) In general the values are lower than the background value.

|   | Element of the regional geochemical background | Cd   | -      | -      | < 5 ppm = 100%    | A thin line converging from the < 5 ppm circle towards the centre of the diagram. |

No unusual dispersion of Cd was observed.

<table>
<thead>
<tr>
<th></th>
<th>Element of the regional geochemical background</th>
<th>Cr</th>
<th>92 ppm</th>
<th>80 ppm</th>
<th>&lt; 10 ppm to 245 ppm</th>
<th>100-150 ppm = 20%</th>
<th>Shows narrow lower end and widening in the upper segment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regional background value (average of the two values)</td>
<td>86 ppm</td>
<td>Show scattered dispersion showing general enrichment.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>Rocks in the northern part have relatively higher dispersion values than the southern part.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Phyllites show values up to 100 ppm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td><strong>Ni</strong> Element of the regional geochemical background</td>
<td>52 ppm 54 ppm</td>
<td>&lt; 10 ppm 10-40 ppm</td>
<td>Dispersion pattern shows broadening at the base with a gradual narrowing at the upper end.</td>
<td>1) Most of the values recorded are above the background values.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional background value (average of the two values) 53 ppm</td>
<td>to 100 ppm = 20%</td>
<td></td>
<td>2) The rocks of the northern part have greater concentration than those of the southern part.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Li</strong> Element indicating stage of mineralization</td>
<td>16 ppm 19 ppm</td>
<td>&lt;10 ppm 10-20 ppm</td>
<td>Simple dispersion pattern with a wide lower end.</td>
<td>3) Phyllites show values higher than the background value.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional background value (average of the two values) 17 ppm</td>
<td>to 45 ppm = 45%</td>
<td></td>
<td>4) General rise in value and restricted dispersion.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ag</strong> Element indicating stage of mineralization</td>
<td>- -</td>
<td>&lt; 10 ppm &lt; 10 ppm = 100%</td>
<td>A thin line from &lt; 10 ppm circle converging towards the centre of the diagram.</td>
<td>Similar to igneous rocks and quartzites, no unusual dispersion.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
GRAPHICAL REPRESENTATION
OF GEOCHEMICAL DATA

GEOCHEMICAL VARIATION DIAGRAM FOR PRIMARY DISPERSION AUREOLES OF
VARIOUS TRACE ELEMENTS IN KHETRI COPPER MINES SAMPLES

TEXT FIG. NO.13
**Explanation of geochemical variation diagram for Khetri copper mines samples** (see Text Fig. 13)

<table>
<thead>
<tr>
<th>Name of the element</th>
<th>Role of the element</th>
<th>Background value</th>
<th>Range of values</th>
<th>Max. frequency group/groups &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cu</strong></td>
<td>Indicator element of ore complexes</td>
<td>100 ppm</td>
<td>10 ppm to 460 ppm and very high values</td>
<td>above 500 ppm = 30%</td>
<td>Shows one projection above 100 ppm and maximum widening at the upper end at 500 ppm and above.</td>
<td>1) Garnetiferous, quartz-chlorite schist, garnetiferous, biotite-schist &amp; amphibole-quartzite show higher values than amphibolite and phyllitic rocks. 2) The values are very high in the samples having pyrite, chalcopyrite and pyrrhotite. 3) Dolerite (45 ppm) and mica-schist (55 ppm) show low values.</td>
</tr>
<tr>
<td><strong>Pb</strong></td>
<td>Indicator element of ore complexes</td>
<td>30 ppm</td>
<td>16 ppm to 55 ppm</td>
<td>30-40 ppm = 35%</td>
<td>Shows a triangular dispersion pattern.</td>
<td>Highly consistent dispersion without much variations in its distribution in all the rock types.</td>
</tr>
<tr>
<td><strong>Zn</strong></td>
<td>Indicator element of ore complexes</td>
<td>60 ppm</td>
<td>11 ppm to 591 ppm</td>
<td>300-500 ppm = 20%</td>
<td>Dispersion pattern showing three projection with widening at the upper end</td>
<td>1) Values appreciably variant. 2) The dispersion appears to have a direct relationship with copper. 3) Shows preferential concentration with the sulphide phase.</td>
</tr>
<tr>
<td><strong>Co</strong></td>
<td>Element of the regional geochemical background</td>
<td>50 ppm</td>
<td>17 ppm to 398 ppm</td>
<td>80-90 ppm = 15% to 300-500 ppm = 15%</td>
<td>Linear dispersion pattern with a wavy appearance from below to the upper segment.</td>
<td>1) Wide variation in dispersion values. 2) Similar to zinc, direct relationship with copper was indicated. 3) Sulphide ore samples are invariably rich in cobalt.</td>
</tr>
<tr>
<td></td>
<td>1</td>
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<td>--------------------------------------------</td>
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<td>--------------------------------------------</td>
</tr>
<tr>
<td>Cd</td>
<td>Element of the regional geochemical background</td>
<td>-</td>
<td>&lt; 5 ppm (sensitivity limit of the instrument)</td>
<td>&lt; 5 ppm</td>
<td>100%</td>
<td>A thin line from 5 ppm circle towards the centre of diagram</td>
</tr>
<tr>
<td>Cr</td>
<td>Element of the regional geochemical background</td>
<td>50 ppm</td>
<td>10 ppm to 142 ppm</td>
<td>10-20 ppm</td>
<td>50-60 ppm</td>
<td>Pointed dispersion pattern</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60-70 ppm</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80-90 ppm</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>Element of the regional geochemical background</td>
<td>55 ppm</td>
<td>25 ppm to 621 ppm</td>
<td>50-60 ppm</td>
<td>20%</td>
<td>Shows two projections, one in the middle and the other at the upper end.</td>
</tr>
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<td></td>
</tr>
<tr>
<td>Li</td>
<td>Element indicating stage of mineralization.</td>
<td>30 ppm</td>
<td>10 ppm to 36 ppm</td>
<td>&lt; 10 ppm</td>
<td>60%</td>
<td>Projection at the lower end and narrowing at the upper end</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10-20 ppm</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td>Element indicating stage of mineralization.</td>
<td>-</td>
<td>&lt; 10 ppm</td>
<td>&lt; 10 ppm</td>
<td>100%</td>
<td>A thin line drawn from 10 ppm circle to the centre of the diagram.</td>
</tr>
</tbody>
</table>
TEXT FIG. NO. 14

GRAPHICAL REPRESENTATION OF GEOCHEMICAL DATA

GRAPHICAL REPRESENTATION OF GEOCHEMICAL DATA OF GRANITIC ROCKS, QUARTZITES AND SCHISTS AND PHYLITIC SCHISTS AND PHYLITIC SCHISTS AND PHYLITIC SCHISTS AND PHYLITIC SCHISTS OF Cu, Pb AND Zn IN THE RESIDUAL SOILS OF GRANITIC AND GRANITIC ROCKS.

ON 31
SSINRAHD ONV SISIHOS QNV S3JI/JDVNO 'SHOOD OMNVHO QNS SSl'NVDIO JO SVOS IVnatSBH 3H1 N!
**Explanation of geochemical variation diagram for residual soils of granites and granitic rocks**

(See Text Fig. 14)

<table>
<thead>
<tr>
<th>Name of element</th>
<th>Role of element &amp; its reference</th>
<th>Background value of the analysed</th>
<th>Range of values &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator of the ore complexes</td>
<td>32 ppm (average of the analysed</td>
<td>10-20 ppm = 48%</td>
<td>Two projections, one at the lower end and the other a little above and narrowing at the upper end.</td>
<td>1) Limited dispersion save in exceptional cases in which dispersion values are high (upto 168 ppm). 2) Soil samples collected from the top of the outcrop have values lower (27 ppm) than those obtained from the base. Further the soils from the base of the granites in contact with the quartzites show higher values (104 ppm) while from the base on the other side of the outcrop show lower values. 3) The northern portion of granite soils particularly around Gotro have higher values. 4) Soils over the low-lying granite gneisses of the southern part of the belt show poor dispersion. 5) There is a general depletion in the copper content.</td>
</tr>
<tr>
<td>Pb</td>
<td>Indicator of the ore complexes</td>
<td>16 ppm (average value of the analysed samples of the area) 10 ppm, Average value, given by Hawkes (1962)</td>
<td>6 ppm to 38 ppm = 75%</td>
<td>A wider base with a quick narrowing at the upper end.</td>
<td>1) Characteristic controlled dispersion throughout the area. 2) No sector of unusual or preferential concentration could be distinguished. 3) There is a general enrichment of the metal.</td>
</tr>
<tr>
<td>Zn</td>
<td>Indicator of the ore complexes</td>
<td>60 ppm (average value of the analysed samples of the area) 36 ppm = 20%</td>
<td>50-60 ppm = 20%</td>
<td>Simple dispersion pattern.</td>
<td>1) Limited dispersion showing no unusual enrichment or depletion as compared to the background value. 2) There is no portion of selective accumulation all over the belt.</td>
</tr>
</tbody>
</table>
**Explanation of geochemical variation diagram for residual soil of quartzites (see Text Fig. 14)**

<table>
<thead>
<tr>
<th>Name of the element</th>
<th>Role of the element</th>
<th>Background value of its reference</th>
<th>Range of values</th>
<th>Max. frequency of group/groups &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator element of ore complexes</td>
<td>35 ppm (average value of the analysed samples of the area)20 ppm, Average value given by Hawkes (1962)</td>
<td>12 ppm to 610 ppm</td>
<td>10-20 ppm to 20-30 ppm = 25% to 70%</td>
<td>Shows broadening at the base and gradual tapering at the upper end.</td>
<td>1) Considerable variation in dispersion. 2) Some anomalous values as high as 20 times of the background value. 3) Soils over the quartzites of the northern portion of the belt nearer the mineralized zone have higher values. Even the soils over magnetite quartzite give a value of 43 ppm. 4) The southern part of the belt shows relatively low dispersion values. 5) General enrichment all over the belt.</td>
</tr>
<tr>
<td>Pb</td>
<td>Indicator element of ore complexes</td>
<td>12 ppm (average value of the analysed samples of the area)10 ppm, Average value given by Hawkes (1962)</td>
<td>5 ppm to 44 ppm</td>
<td>10-20 ppm to 44 ppm = 80%</td>
<td>Shows a widening in the middle and narrowing at both ends.</td>
<td>1) Restricted dispersion all over the belt. 2) No value is anomalous. 3) Marginal general enrichment all over the belt.</td>
</tr>
<tr>
<td>Zn</td>
<td>Indicator element of ore complexes</td>
<td>65 ppm (average value of the analysed samples of the area)50 ppm, Average value given by Hawkes (1962)</td>
<td>32 ppm to 98 ppm</td>
<td>60-70 ppm to 80 ppm = 25% to 70%</td>
<td>Prominent projection at or near the upper margin. Tapering lower end.</td>
<td>1) No abnormal variation in dispersion value. 2) Equally uniform variation in values in both the parts of the belt. 3) General enrichment.</td>
</tr>
</tbody>
</table>
### Explanation of geochemical variation diagram for residual soils of schists and phyllites

(See Text Fig. 14)

<table>
<thead>
<tr>
<th>Name of element</th>
<th>Role of the element</th>
<th>Background value of its reference</th>
<th>Range of values</th>
<th>Max. frequency group/groups &amp; % frequency</th>
<th>Kind of dispersion pattern</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Indicator element of the ore complexes</td>
<td>55 ppm (Average of the analysed samples of the area), 20 ppm, average value given by Hawkes (1962)</td>
<td>20 ppm to 1436 ppm</td>
<td>20-30 ppm to 40-50 ppm = 24%</td>
<td>Shows two projection at the lower end and distinct width at the upper end.</td>
<td>1) Abnormal dispersion with a wide variation in values. 2) The soils over the schists in northern part of the belt near the mineralized zone have anomalous values as high as 70 times of the background value. Soil samples from the phyllites in this part recorded values 20 times higher than the background value. 3) The soils of the southern part do not show any abnormal dispersion. 4) All the values are above the background value.</td>
</tr>
<tr>
<td>Pb</td>
<td>Indicator element of the ore complexes</td>
<td>30 ppm (Average value of the analysed samples of the area), 10 ppm, average value given by Hawkes (1962).</td>
<td>5 ppm to 77 ppm</td>
<td>10-20 ppm = 52%</td>
<td>A projection at the lower end of wide base and a gradual narrowing at the upper end.</td>
<td>1) Unusual variation in the dispersion values, although no anomalous values were obtained. 2) General enrichment.</td>
</tr>
<tr>
<td>Zn</td>
<td>Indicator element of the ore complexes</td>
<td>75 ppm (Average values of the analysed samples of the area), 50 ppm, 123 ppm</td>
<td>35 ppm to 40-50 ppm</td>
<td>40-50 ppm = 28%</td>
<td>Projection at three points. Wider at the lower end and narrower at the upper end.</td>
<td>1) Fluctuates within a narrow limit. 2) General enrichment. 3) No unusual accumulation in any particular area.</td>
</tr>
</tbody>
</table>
VARIATION DIAGRAM FOR PRIMARY AND SECONDARY DISPERSION PATTERN OF Cu, Pb & Zn.

TEXT FIG. NO. 15
Comparative study of primary and secondary dispersion patterns of Cu, Pb and Zn

Sixty-six rock samples of granites and granitic rocks, quartzites, schists and phyllites and an equal number of their corresponding residual soils were taken for a comparative study of the primary and secondary dispersion patterns of Cu, Pb and Zn.

The analytical results were plotted on three diagrams. Each diagram represents a particular group of rock types and their residual soil, in which the variation of Cu, Pb and Zn were shown individually.

Samples of a particular rock group and corresponding residual soil were plotted separately for their contents of Cu, Pb and Zn. Concentration curves are prepared by joining the respective points for rock samples and residual soil samples separately.

Dotted lines represent the variation trend of a metal in the rock and the bold lines represent the variation trend of the same metal in the residual soil. The values are plotted on ppm range and may be read with the help of the graduations shown on the side of the diagrams.

Granites and granitic rocks (see Text Fig. 15)

Copper - The rock samples clearly show low dispersion of Cu while the corresponding residual soil samples show enrichment in the Cu contents. It appears that during chemical weathering of the rock and sorting out of various elements, Cu resisted considerably and as a result of which there is a concentration of Cu in the residual soil. However, it is interesting to note that the general pattern of dispersion of Cu both in the rocks and
QUARTZITIC ROCKS & THEIR RESIDUAL SOILS

VARIATION DIAGRAM FOR PRIMARY AND SECONDARY DISPERSION PATTERN OF Cu, Pb & Zn.
soils is more or less is matching.

**Lead** - The rock samples distinctly show higher dispersion of Pb as compared to the residual soil samples. The effects of chemical weathering on Pb appear to be unlike that of Cu. It indicates that in general Pb was leached out considerably during the chemical weathering leaving the residual soil depleted in its Pb contents.

**Zinc** - The rock samples in the northern part of the area which mostly include granites show low values of dispersion of Zn as compared to the samples of the residual soils. However, the case is somewhat different with the granite gneisses of the southern part of the area where Zn is generally higher in the rock samples. Therefore, it is evident that Zn in granites behaved differently from that in granite gneisses during their chemical weathering.

Zn in the granites appears to be less mobile during chemical weathering and thus the residual soils are enriched in Zn contents. In the case of low lying granite gneisses, Zn was comparatively mobile and thus there is a depletion in Zn contents in the soil samples.

In general, Pb was found to have a greater mobility than Zn, which in turn, was more mobile than Cu.

**Quartzites** (see Text Fig.16)

**Copper** - In general, Cu has a slightly higher dispersion in the rock samples as compared to the samples of the corresponding residual soils. Some of the soil samples of the southern part of the belt show enrichment
VARIATION DIAGRAM FOR PRIMARY AND SECONDARY DISPERSION PATTERN OF Cu, Pb & Zn.

TEXT FIG. NO. 17
in the Cu-contents. It appears that during chemical weathering Cu was slightly leached out from the soil samples which resulted in lowering the Cu-contents marginally in the samples of the northern part.

It was observed that the dispersion patterns of Cu in the rocks and soils have striking resemblances.

*Lead* - There is an overall depletion in the Pb-contents of the residual soil samples. The decrease is more pronounced in the samples of the northern part. This indicates that removal of Pb was fairly affective during chemical weathering.

*Zinc* - Zn shows higher values in the residual soil samples as compared to the rock samples. This enrichment of Zn is more pronounced in the soil samples of the northern part of the belt. It clearly indicates that Zn was not affected much during the chemical weathering.

Finally it was observed that Pb was more mobile than Cu, which in turn has a greater mobility than Zn in the quartzites.

*Schists and phyllites* (see Text Fig. 17)

*Copper* - In general the samples show a slightly higher concentration of Cu in the residual soil samples than in the rock samples. It is more distinct in the samples of the southern part of the belt where the overall dispersion of Cu is comparatively low.

It is, therefore, inferred that the Cu was appreciably resistant to chemical weathering and was not removed in appreciable quantity.
Generally Cu in the rocks as well as in soil samples indicate more or less similar dispersion patterns.

Lead - Pb shows comparable dispersion in the rocks as well as in the residual soil samples except in a few cases of soil samples in which Pb shows marginal enrichment. It is, therefore, obvious that there was a little effect on the dispersion of Pb during the conversion of the rocks into residual soils due to weathering.

Zinc - Zn shows a general enrichment in the residual soil samples as compared to the rock samples. The enrichment is quite distinct in the samples of the northern part of the area. However, some of the residual soil samples from the southern part of the area show depletion in Zn contents. It appears that Zn did not suffer much leaching during chemical weathering and a greater part of it remained with the residual soil.

In this case the mobility of Pb was greater than Zn which in turn was mobile than Cu.

General remarks

All the three figures, therefore, clearly show that the dispersion patterns of Cu in the rocks as well as residual soil samples of granites and granitic rocks, quartzites, schists and phyllites have striking resemblances.

The observations and the general quantitative assessment made in the previous description led the author to suggest the following schemes of relative mobilities of Cu, Pb and Zn during the process of
chemical weathering.

<table>
<thead>
<tr>
<th>Rock groups and its residual soil samples</th>
<th>Scheme of relative mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granites and granitic rocks = Pb &gt; Zn &gt; Cu</td>
<td></td>
</tr>
<tr>
<td>Quartzites = Pb &gt; Cu &gt; Zn</td>
<td></td>
</tr>
<tr>
<td>Schists and phyllites = Pb &gt; Zn &gt; Cu</td>
<td></td>
</tr>
</tbody>
</table>
TRACE ELEMENT ISOCONCENTRATION MAPS

The spatial abundance and distribution of traces of Cu, Pb, Zn, Ni and Cr in the igneous and metamorphic rocks have been shown individually on base geological map of the Khetri Copper Belt. The quantitative analytical data of these trace metals from the various rock types of the belt have been plotted at the intersection points of the grids which correspond to the location of the samples collected. Then the isoconcentration contours are interpolated at known intervals on ppm range.

The isoconcentration pattern of Cu shows that its concentration in the rocks of the northern part of the belt is usually higher than in those of the southern part. Zinc shows sufficient enrichment in the rocks southwest of Saladipura. Further details regarding these two and other elements have been given in the accompanying tables. The maps also show that in certain cases concentration of an element in a particular rock type has been preferential.
### Spatial Dispersion of Trace Elements as Shown by Isoconcentration Maps

<table>
<thead>
<tr>
<th>Parts of the belt</th>
<th>Values of contours</th>
<th>Anomalous values</th>
<th>Areas of low concentration</th>
<th>Areas of relatively high concentration</th>
<th>General assessment and remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern part of</td>
<td>Contours are drawn</td>
<td>448 ppm</td>
<td>1. Singhana</td>
<td>1. Around Madhan-Kudhan mines and south</td>
<td>The areas of anomalous</td>
</tr>
<tr>
<td>the belt from</td>
<td>by joining isocon-</td>
<td>to</td>
<td>of them, continued up to</td>
<td>of them, continued up to Kolihan mine.</td>
<td>values are all under</td>
</tr>
<tr>
<td>Singhana in the</td>
<td>centration points</td>
<td>1160 ppm</td>
<td>Kolihan mine. Maximum</td>
<td>Maximum anomalies obtained both in</td>
<td>detailed prospecting</td>
</tr>
<tr>
<td>north to SW of</td>
<td>of known interval.</td>
<td></td>
<td>anomalies obtained both in</td>
<td>quartzites and schistose rocks.</td>
<td>for copper mineralization,</td>
</tr>
<tr>
<td>Babai in the south.</td>
<td></td>
<td></td>
<td>quartzites and schistose</td>
<td></td>
<td>except the area</td>
</tr>
<tr>
<td>(The same specific-</td>
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<td></td>
<td>rocks.</td>
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<td>lying between the</td>
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<td>ications will</td>
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<td></td>
<td>Nizampur road cross and</td>
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<td>continue for</td>
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<td></td>
<td></td>
<td>the Gorwala-ki-Dhani.</td>
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<tr>
<td>the rest of the</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>description)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern part of</td>
<td>Contours are drawn</td>
<td>152 ppm</td>
<td>1. Around Chappoli</td>
<td>1. Near Saladipura and NW of it.</td>
<td></td>
</tr>
<tr>
<td>the belt near</td>
<td>by joining isocon-</td>
<td>to</td>
<td>and Mandaora.</td>
<td></td>
<td>1. Detailed prospecting for</td>
</tr>
<tr>
<td>Chappoli Mandaora,</td>
<td>centration points</td>
<td>750 ppm</td>
<td>2. Around Satkui</td>
<td></td>
<td>pyrite deposits at</td>
</tr>
<tr>
<td>Satkui, Udaipur</td>
<td>of known interval.</td>
<td></td>
<td>3. East of Udaipur</td>
<td></td>
<td>Saladipura is under</td>
</tr>
<tr>
<td>and Saladipura</td>
<td></td>
<td></td>
<td>4. SW of Saladipura</td>
<td></td>
<td>progress.</td>
</tr>
<tr>
<td>(The same specific-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Satkui is also under</td>
</tr>
<tr>
<td>ications will</td>
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<td></td>
<td></td>
<td>detailed prospecting for</td>
</tr>
<tr>
<td>continue for the</td>
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<td></td>
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<td>copper. But the author did</td>
</tr>
<tr>
<td>rest of the</td>
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<td></td>
<td></td>
<td>not get encouraging</td>
</tr>
<tr>
<td>description)</td>
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<td></td>
<td></td>
<td></td>
<td>dispersion of copper.</td>
</tr>
</tbody>
</table>
### Northern Part

<table>
<thead>
<tr>
<th>L</th>
<th>E</th>
<th>A</th>
<th>D (Map 2b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

- Contours are drawn by joining isoconcentration points.
- Known intervals: 74 ppm to 85 ppm.
- Concentration was recorded from the areas now under detailed prospecting for copper. Higher copper content was noted in some areas.
- Known points include: 1. Around Mahan-Kudhan, 2. Between Ghatro & Khatri town, and 3. Around Gorwar-Pani, West of Papurna, Dhani and Thara around Akwali mine, NE of Babai.
- Contours are drawn by joining isoconcentration points.

### Southern Part

- Contours are drawn by joining isoconcentration points.
- Known intervals: 45 ppm to 51 ppm.
- Concentration was noted in the area under detailed prospecting for pyrite deposits. Anomalies in the area are not active.
- Known points include: 1. East of Chappoli, 2. Near Mandora, 3. Around Satkari, and 4. SW of Chappoli and east of Udaipur.
<table>
<thead>
<tr>
<th>Northern Part</th>
<th>Contours are drawn by joining isoconcentration points of known intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>160 ppm to 340 ppm</td>
</tr>
<tr>
<td>1. Singhana.</td>
<td>1. SW of Khetri town</td>
</tr>
<tr>
<td>2. From Madhan-Kudhan mines to Kolihan mines in the south</td>
<td>2. North of Tihara-ki-Dhani</td>
</tr>
<tr>
<td>5. NW of Babai</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Southern Part</th>
<th>Contours are drawn by joining isoconcentration points of known intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>180 ppm to 380 ppm</td>
</tr>
<tr>
<td>1. Around Chappoli and Mandaora</td>
<td>1. East of Chappoli near Mandaora</td>
</tr>
<tr>
<td>2. Around Udaipur</td>
<td>2. NW of Saladipura</td>
</tr>
<tr>
<td>3. Southwest of Chappoli</td>
<td></td>
</tr>
<tr>
<td>4. Around Satkui</td>
<td></td>
</tr>
<tr>
<td>5. SW of Saladipura</td>
<td></td>
</tr>
</tbody>
</table>

Excepting Akwali NW of Papurna, none of the areas is under detailed exploration for Cu.

Significant anomalies for zinc are obtained from near Saladipura especially the NW sector.

This area appears to be of some interest for zinc content. The area NW of Chappoli does have anomalies but comparatively low.
### Nickel (Map 2d)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Northern part</strong></td>
<td>Contours are drawn by joining isoconcentration points of known intervals 100 ppm to 140 ppm</td>
<td>1. Around Madhan-Kudhan mines. 2. Around Gotro, Garvalaki-Dhani, Tihara-ki-Dhani. 3. Between Khetri town and Akwali mine</td>
<td>1. Between Madhan-Kudhan and Kolihan mine (some parts) 2. Around Akwali mine and NE of Papurna</td>
<td>3. NW of Babai</td>
<td>In general nickel concentration has no relation with the copper (except Akwali area) or lead. Concentrations. It appears more close to Zn in its overall dispersion.</td>
</tr>
<tr>
<td><strong>Southern part</strong></td>
<td>Contours are drawn by joining isoconcentration points of known intervals 60 ppm to 100 ppm</td>
<td>1. NE of Chappoli, around Mandaora. 2. SW of Udaipur 3. Around Satkui</td>
<td>1. NW of Saladipura (about 3km) 2. About 3 km SW of Chappoli.</td>
<td></td>
<td>Since the dispersion is very low in this area, no generalization can be made. In Saladipura area it shows some similarity with copper in its dispersion.</td>
</tr>
<tr>
<td>Northern part</td>
<td>Contours are drawn by joining isoconcentration points of known intervals</td>
<td>100 ppm to 500 ppm</td>
<td>1. Between Gotro and Singhana (leaving some parts around Madhan-Kudhan mines).</td>
<td>1. Between Madhan-Kudhan and Kolihan mine.</td>
<td>2. 2 km NE of Khetri town</td>
</tr>
<tr>
<td>Southern part</td>
<td>Contours are drawn by joining isocentr- nation points of known intervals</td>
<td>105 ppm to 425 ppm</td>
<td>1. Around Satkui near Chappoli</td>
<td>NW of Saladipura south of Chappoli</td>
<td>Saladipura area is the section of proved pyrite deposits.</td>
</tr>
</tbody>
</table>
### Lithium

| Northern part | Contours are drawn by joining isoconcentration points of known intervals | The whole of the northern part of the belt shows low dispersion with a few places where relatively higher values are recorded. | 1. 2 km NE of Khetri. | 2. 1 km NW of Khetri | 3. 2 km West of papurna near Akwali mine | No part of the area has interesting dispersion values. |
| Southern part | Contours are drawn by joining isoconcentration points of known intervals | Almost all the part shows insignificant values. | 1. 4 km NW of Saladipura. | 2. 3 km SW of Chappali | Lithium does not show any significant dispersion values. However, some values are higher than the values of the northern portion but in general the dispersion is poor. |

Map is not enclosed as the dispersion of Li is not significant.
TEXT FIG. 18

VARIATION DIAGRAMS

GRANITE AND GRANITIC ROCKS

HOST ROCKS WITH SULPHIDE ORES
Chapter - VII

SIGNIFICANCE OF TRACE ELEMENTS

Concentration trend of some trace elements

The concentration trend and geochemical behaviour of some trace elements in granites and host rocks with copper ores is studied.

The presentation is made on the lines proposed by Lionel C. Kilburn (1960). Elements have been grouped for representation on triangular and rectangular diagrams. The trace element data obtained for granites and granitic rocks and host rocks with sulphide ores are plotted to study their relative abundance and their significance with respect to copper mineralization.

1. Relationships among copper, nickel, zinc and lead

All the four elements are chalcophile in nature. Their traces have manifold significance. Their geochemical behaviour in the granites and host rock with sulphide ores has been used to understand whether there is any genetic relation between the two.

a) Copper-zinc-lead (see Text Fig. 18)

The data were recalculated to hundred on weight percentage basis and plotted on the coordinates of a triangular diagram both for granites and host rocks with sulphide ores.

Granites and granitic rocks - The diagram shows that granites form a continuous series from Cu-Zn, through Zn-rich to Zn-Pb type. The end segments of
copper and lead concentration are almost blank both for Cu-Zn and Zn-Pb series. The points are concentrated on the boundaries of Zn-Pb series and fairly more towards the zinc end. In the Cu-Zn series concentration of points is more towards zinc end.

**Host rocks with sulphide ores** - The diagram shows that there is a continuous series from the Cu-Zn to the Zn-Pb series in the ores although the concentration on Pb side is not distinct. Lead values are relatively low. The points are concentrated nearer the boundary of Cu-Zn series and distinctly towards the copper end. The consistency in low values for Pb indicate that lead ores are not associated with the copper ores of the area.

The concentration trend of the points in case of granites and granitic rocks and host rocks with sulphide ores is not distinctly similar. Pb shows some regularity in its distribution in both the cases.

b) **Nickel-copper-zinc** (see Text Fig. 19)

When plotted on a triangular diagram the grouping is as follows:

**Granites and granitic rocks** - The presence of Ni is of some interest in spite of its low concentration. The points are grouped on the boundary lines of Cu-Zn and Ni-Zn series. The concentration is more towards Ni-Zn series and particularly towards the Zn end. The Cu-Ni series does not show any grouping of points. The copper rich end has a few concentration. Ni-rich end does not show any concentration.

**Host rocks with sulphide ores** - They show prominent grouping of points near the Cu-rich end. The boundaries of Cu-Zn series also show grouping. Ni contents are not high. The Cu-Ni series does not show any concentration on its boundary. The concentration of points is relatively nearer to Zn than Ni.
Ni/Cu + Zn + Pb

HOST ROCKS WITH SULPHIDE ORES

GRANITE AND GRANITIC ROCKS

VARIATION DIAGRAMS
The Zn-rich end and Ni-rich ends are equally blank.

**General assessment** - There is a similarity in the zinc and nickel behaviour in granites and host rocks with copper ores.

Similar to the Cu-Pb-Zn series, the copper-rich end shows concentration of points in the sulphide ores, while in the granites the frequency of concentration of points is nearer to the zinc end. The Cu-Zn series in granites as well as in host rocks with sulphide ores show almost a similar trend. The Cu-Ni series particularly towards the Ni-rich end are equally blank in both the cases. The overall behaviour of Ni-Cu-Zn in the granites is in some respects similar to those in the host rocks with sulphide ores.

Nickel in Ni-Cu series behaves like lead in Cu-Pb series in granites as well as in the sulphide ores.

c) **Nickel-copper-zinc-lead** (see Text Fig. 20).

The values of the elements are recalculated to one hundred per cent and plotted on a tetrahedral coordinate system.

**Granites and granitic rocks**. - The tetrahedral representation clearly shows the behaviour of Ni/Cu+Zn+Pb against Cu-Zn and Zn-Pb series. It forms a continuous series from Cu-Zn rich through Zn-rich to Zn-Pb series.

In the Cu-Zn series the points are concentrated towards Zn-rich end rather than the Cu-rich end. The pattern shows a gradual increase in the Ni/Cu+Zn+Pb ratio from copper rich end towards the Zn-rich end forming a smooth curve. There is a prominent grouping of points on the boundary of zinc-rich end.

In the Zn-Pb series, like the Cu-Zn series, the concentration of
points is towards the Zn-rich end rather than the Pb-rich end. The points show a pattern having a regular increase in the Ni/Cu + Zn + Pb ratio from Zn-rich end towards Pb-rich end. It is represented by a straight line.

Host rocks with sulphide ores - When the sulphide ores are plotted on a tetrahedral coordinate system like granites and granitic rocks, they show striking resemblance with the latter in many respects. They also form a continuous series from Cu-Zn series through Zn-rich to Zn-Pb series.

In the Cu-Zn series they show a gradual increase in the Ni/Cu + Zn+Pb ratio from Cu-rich end towards Zn-rich end. The pattern is represented by a curve which shows a significant similarity with that of granites and granitic rocks.

The concentration of points is towards the Cu-rich end and not the Zn-rich end but there is no grouping on the boundary of zinc as it is in granites.

In the Zn-Pb series the similarity in the distribution of points of Ni/Cu+Zn+Pb is more pronounced. There is also a regularity in increase in Ni/Cu + Zn + Pb ratio from Zn-rich end to Pb-rich end. The pattern is represented by a straight line which is very similar to that of granites and granitic rocks. The overall point distribution is almost the same in both the cases.

It has been observed that the concentration trend of points in the triangular diagram for Cu-Zn-Pb in case of granites and granitic rocks and host rocks with sulphide ores does not show much similarity. But when plotted for Ni-Cu-Zn on a triangular diagram and for Ni-Cu-Zn-Pb on rectangular diagram, the general trend of the distribution of points shows
distinct similarity. As pointed out by Kilburn (1960) such a criterion may be used to establish a genetic relationship between the intrusive and the adjacent ore deposit. It is, therefore, possible that, in the area under study, the granitic rocks have a genetic relationship with the copper deposits.

**Geochemistry as applied to the Khotri copper ores**

The application of geochemistry to the genesis of ore deposits in the last two decades has opened new horizons and rethinking of the whole issue. It has now been fairly established that the studies of trace elements have an important bearing on the genesis of certain ores. The criterion of isotopic composition of elements is a further step advanced in this field. Much evidence has been collected either to discard or accept the idea of genetic connection between granites and the ores.

Even after a colossal work has been done on the genesis of ores in different countries of the world, it is not certain whether the related intrusives should show depletion or enrichment in their metallic contents. It is generally believed that "either enrichment or depletion of an intrusive in ore metal could be taken as evidence for considering the intrusive as the source of the ore" (see Krauskopf, 1967).

The present investigation shows that the granites and granitic rocks of the area are generally depleted in the copper content although in certain exceptional cases Cu as high as 38 ppm was recorded.

Investigations by Shrivastava and Proctor (1962) on the quartz-monzonite intrusive, Searchlight, Nevada, have indicated that the depletion
in the copper content in the quartz monzonite may account for its genetic connection with the associated copper deposit. Belt (1960), on the basis of his work on Cu and Zn deposits of New Mexico, pointed out that the enrichment of a metal in an intrusive particularly, in an altered one, may mean that ore-bearing solutions from elsewhere concentrated as deposits and permeated the adjacent intrusive rocks. Stringham (1958) pointed out the preferential association of copper with the quartz monzonite rock. Warren and Devault (1950) extracted copper with aqua regia and found that Cu content in the intrusives associated with the ore deposits are several times higher than in the barren intrusives. He attributed this enrichment to later permeations by ore forming fluids rather than to consanguinity. Such an attempt was not considered necessary in the present investigation because the granites of the area are not enriched but depleted in copper. Recently, however, Kilburn (1960), Putnam and Burnham (1963) reported enrichment of copper in some acid igneous rocks associated with the copper deposits.

The granitic rocks of the area under study, show a general depletion in Cu content. In the light of the investigations carried out by earlier workers elsewhere as referred to above, this general depletion may be attributed to a possible genetic connection between the Cu-ore and the granites.

Another interesting feature observed in the area was that the granite gneisses of the southern part of the belt gave relatively higher values of copper (no enrichment in general) than the granites of the northern part. This difference in the copper content may be attributed to the difference in the proportion of mafic and felsic contents of the rocks of
the two parts.

Mafic minerals, being relatively better hosts, may accommodate more copper. It may, therefore, be reasonably assumed that the granites of the northern part of the belt being poor in the ferromagnesian content could retain very little copper with them. This resulted in depletion of copper in the granites. It is, therefore, more likely that the bulk of copper moved away from the granites and concentrated in the adjacent rocks.

On the other hand, the granite gneisses of the southern part of the belt, being rich in the ferromagnesian content, could retain relatively more copper with them. This resulted in relatively enriching the granite gneisses with copper ores. The above observations made in the two parts of the area suggest to predict a larger copper deposit in the northern part of the area as compared to the southern part provided that the genetic relation between the intrusive and the ore is established. Such an assumption may not at first appear sound. But it has been estimated that a depletion of about 3 ppm of the metal in 100 km$^3$ granite is sufficient to concentrate a million ton of Cu, Pb, or Zn ore (see Krauskopf, 1967). Thus, a slight depletion or enrichment in the copper content in granites and granite gneisses of the area may account for the magnitude of the copper ore deposit.

It is true that the granites of the northern part of the belt particularly, those near Gotro village do not occur over a large area and the further no granite has so far been encountered in/underground sections of the Madhan-Kudhan and Kolihan mine sections. Therefore, an attempt to associate such a small exposure of granite as the possible source of a large
copper deposit in the adjoining area will be doubted. But it has been
universally accepted that granite batholiths are huge masses and their
major portion usually lie concealed at deeper levels. Possibly, the outcrop
of granite near Gotro village comprises an insignificant part of a deeply
buried batholith. Its extent at still deeper mine levels cannot be entirely
ruled out at present.

Further attempts to tackle the problem of ore genesis on the basis
of geochemical studies have been made by studying the behaviour of trace
elements in the separated mineral fractions. Several workers have carried
out investigations on these lines and the results obtained are worth
exploring.

Recently Putnam and Burnham (1963) investigated that the mafic
minerals in certain intrusive rocks of Arizona have a higher content of
copper in the areas of copper mineralization. Parry and Nackowski (1963)
recorded that the Basin and Range quartz-monzonites have biotites with
higher content of copper near the copper deposits while zinc shows depletion
and Pb gives normal values.

In the case under study, the separated ferromagnesian mineral
fractions of the granites and granitic rocks which include hornblende,
epidote and biotite, show a general enrichment in copper. Both hornblende
and biotite are good hosts for copper. The values for zinc are fluctuating
while that of lead are almost consistent in all cases. Such an observation
as made by Parry, and Nackowski (1963) may be tried here to correlate the
intrusive rocks and the ore.
The views as stated above were further strengthened when the weight percentages of certain trace elements were plotted on triangular and rectangular diagrams in the course of discussing the subject. The chemical trend of these trace elements in granites and granitic rocks and the host rocks with copper ores were found to have distinct similarities in cases of (a) Cu-Zn-Pb, (b) Ni-Cu-Zn, (c) Ni-Cu-Zn-Pb as it has been discussed earlier in this chapter.

Kilburn (1960) is of the opinion that the similarities in the trends and the general geochemical relationship of trace elements in rock and ore may be considered as a possible means to establish a genetic connection in between the two.

As has been discussed earlier, these elements have distinct similarities in their distribution trends and there is a close interrelationship of elements in the rocks as well as copper ores. It is, therefore, reasonable to believe that the granites were the source rocks of the ore fluids.
Chapter - VIII

SUMMARY AND CONCLUSIONS

In the present investigation, which the author started in November 1968, an attempt has been made to emphasize the importance and precise use of geochemical data in the distribution of certain metals and their probable relation to the productive copper deposits in the Khetri Copper Belt, Rajasthan. The study revealed certain interesting geochemical behaviour of the major and some trace elements in different rock groups, residual soil samples and separated mineral fractions of granites and granitic rocks, the sulphide ores and their host rocks in this area. Rock and soil samples were collected largely from the surface, divided into grids and picking up the samples at an interval of one km on a 4" to a mile map. Some samples from the underground copper workings were also collected. Additionally, a considerable attention was given to study in sufficient detail the lithology and petro-mineralogy of various types of rocks encountered. A brief summary of the investigation and the conclusions arrived at are recorded as follows:-

1. The Khetri copper ore deposits are mainly confined to the argillaceous group of metasediments belonging to Ajabgarh series, which is a part of the Delhi System of Precambrian age. Copper mineralization has taken place largely along a major strike fault at the contact of Ajabgarh and Alwar series. A large part of the area has been intruded by a number of
igneous intrusives. There is a series of faults of several types and
the rocks have a number of doubly plunging folds. The general trend of
strike of the rocks series is NE-SW and dip varies from 30° to 70° towards
west and north-west.

The major host rock of copper is the garnetiferous quartz-chlorite
schist. Pyrite, pyrrhotite and chalcopyrite are the dominant sulphide
minerals, whose paragenetic sequence has the same order of arrangement
as recorded above. The degree of metamorphism of the rocks is generally
higher in the north and gradually becomes low towards south.

The copper ores do not show any significant evidence of strati-
graphic or lithological control. Structural features appear to have some
control on the localization of ores. The shape of the ore bodies are
generally lensoid.

2. Pink and grey granites, granite gneisses and aplites of varying
mineralogical compositions occur in the area. Their lithological and
structural characters are also variable. Dolerite dykes occur frequently.

Among the metamorphic rocks, various types of schists, quartzites and
phyllites are common. The carbonate rocks have limited occurrence and
amphibole is commonly associated with them.

The petromineralogical and petrochemical studies also indicate
that the granites in the vicinity of Gotro village are intrusive. Some
of the metamorphic rocks are comparable to the amphibolite facies of
Eskola in their grade of metamorphism. Three kinds of garnets have been
identified in the garnetiferous quartz-chlorite schist. Some of these
garnets show evidence of rotation. Anthophyllite/cummingtonite usually
occur as coexisting amphiboles.

Petrochemical evidence from the ACF diagram points out that the parent material of the metamorphic rocks were grey-wackes, clay and shales and that of basic intrusive were andesitic and basaltic rocks.

3. The complete analyses of four granites and granite rocks, four metamorphic rocks and one metadolerite were done in order to determine all the fourteen major constituents of those rocks. Further, the mineral fractions of ten granites and granitic rocks and six host rocks of copper ores are separated by Frantz Isodynamic Magnetic Separator. About 250 samples, including almost all the rock types of the area, separated mineral fraction of some rocks and ores, and residual soil samples were analysed for determining quantitatively some of the important trace metals by Atomic Absorption Spectrophotometer.

The significance and distribution of these trace elements in the parent rock/mineral was studied with a view to probe their inter-relationship. The granite gneisses of the southern part of the belt show a higher concentration of Cu, Zn and Ni as compared to the granites of the northern part. The granite gneisses have abundant ferromagnesians as compared to the granites. This indicates that Cu, Zn and Ni are usually concentrated in the ferromagnesian phase and their abundance is controlled by the ratio of mafic and felsic minerals in case of such rocks.

Copper is concentrated both in the quartzites and schists but it has a higher concentration in schists than in quartzites. The samples of Khetri copper ores as well as their host rocks show distinctly higher values
for Cu, Zn, Ni and Co. Nickel was found to be concentrating more in pyrohotite than in the coexisting chalcopyrite. Dolerites also give good indications of the presence of Cu, Zn, Ni and Cr. Generally Pb has a limited dispersion in all the rock types of the area.

The concentration trend of Cu, Pb and Zn in the residual soil samples of almost all the rock types of the area was studied. The trend is somewhat similar to that of the respective parent rocks.

The studies of trace elements in the separated mineral fractions in granites and granite rocks show that they are preferably concentrated in the ferromagnesian phase. Cu, Pb, Zn, Ni and Cr show distinctly higher concentration in hornblende than in biotite and least in epidote. The felsic group (quartz-feldspar) does not show any significant trace of these elements except Pb. Similarly, the separated mineral fractions of host rocks show that Cu is more concentrated in amphiboles than in garnet or in biotite. The felsic group, in this case, shows traces of Pb, Zn and Cr.

Further, the relationship between some trace elements in granites and granitic rocks and their separated mineral fractions is studied and the nature of the occurrence in silicate and sulphide phase is indicated.

4. The geochemical dispersion of certain trace elements has been studied with the help of geochemical variation diagram. The pattern of dispersion aureoles (primary and secondary) of each trace element in a particular rock group and corresponding residual soil has been studied and the observations have been recorded in a tabular form.
Cu, Pb and Zn have been taken as indicator elements of ore complexes on the basis of their geochemical behaviour during the fractional crystallization of magma as has been worked out by many previous workers. Ni, Cd and Cr have been grouped as indicator elements of the regional geochemical background on account of their controlled dispersion and close association with the sulphide ores in the area. In accordance with the views expressed by some earlier workers, Li and Ag have been taken as the elements indicating the stage of mineralization.

5. A comparative study of the primary and secondary dispersion patterns for Cu, Pb and Zn in various rock groups and their residual soil samples has been made. It led the author to work out a scheme of relative mobilities of these trace elements during the chemical weathering of rocks and their conversion into soils which is presented below.

<table>
<thead>
<tr>
<th>Rock Group</th>
<th>Relative mobilities of elements</th>
</tr>
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<tbody>
<tr>
<td>Granites and Granitic rocks</td>
<td>Pb &lt; Zn &lt; Cu</td>
</tr>
<tr>
<td>Quartzites</td>
<td>Pb &lt; Cu &lt; Zn</td>
</tr>
<tr>
<td>Schists and Phyllites</td>
<td>Pb &lt; Zn &lt; Cu</td>
</tr>
</tbody>
</table>

6. The isoconcentration maps have been prepared in order to show clearly the distribution of Cu, Pb, Zn, Ni and Cr in all the rock groups of the area. Copper shows anomalously high values in the northern part of the belt around the Madhan-Kudhan, Kolihan and Akwali mine sections which are now being developed for the exploitation of copper. Satkui also shows indications of copper mineralization. There is an unusual dispersion of zinc in some of the rock samples north-west of Saladipura. The dispersion of other trace elements, however, is as usual.
7. An attempt has also been made to investigate a probable connection between the intrusive granites and the copper ores of Khetri. Following Kilburn (1960) the weight percentages of Cu, Zn, Pb and Ni have been plotted on triangular and rectangular diagrams in which the trends of concentration of these elements are very significant. The concentration trend and geochemical behaviour of Cu-Zn-Pb and Ni-Cu-Zn in the triangular diagrams and Cu-Zn-Pb plotted against Ni/Cu+Zn+Pb in the rectangular diagrams show distinct similarities in cases of granites and granitic rocks as well as host rocks of copper ores. This similarity has been used as a criterion to establish a possible genetic relationship of granites with the copper ores.

Again, according to similar investigations made elsewhere by some previous workers, which are now widely accepted, the general depletion of copper content in the granites and granitic rocks of the belt provides some useful evidence to establish a genetic connection between the copper ore and the intrusive. This view is further supported by the observation that copper shows higher concentration in hornblende and biotite separated from the samples of the intrusive granite.

The above observations led the author to believe that the copper ores of Khetri are of epigenetic origin and the adjacent granite of Gotro is the probable source rock for the ore fluids.

---- 1964 The significance of the chemical bond for controlling the chemical distribution of the elements. Physics & Chemistry of the earth, Vol. 5, pp.3-54.


Belt, C.B. 1960 Intrusion and ore deposition in New Mexico. Econ. Geol., Vol. 55, pp. 1244-1271.


- 152 -
<table>
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<th>Year(s)</th>
<th>Title</th>
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<td>Clarke &amp; Washington</td>
<td>1924</td>
<td>See Goldschmidt, 1958</td>
</tr>
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<td>Das Gupta, S.P.</td>
<td>1961</td>
<td>Petrological studies in the Khetri copper belt, Rajasthan, Ind. Min., Vol. 15, No. 4, p. 46.</td>
</tr>
<tr>
<td></td>
<td>1962(a)</td>
<td>Petrological studies in the Khetri copper belt, Rajasthan, Ind. Min., Vol. 16, No. 1, p. 67.</td>
</tr>
<tr>
<td></td>
<td>1962</td>
<td>Paragenesis of scapolite bearing amphibolites, Khetri copper belt, Rajasthan, Ind. Min. No. 4, p. 413.</td>
</tr>
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<td></td>
<td>1944</td>
<td>Crystal chemistry and geochemistry, Chemical Products 7 (5/6), pp. 29-34.</td>
</tr>
<tr>
<td>Heron, A.M.</td>
<td>1923</td>
<td>Geology of Western Jaipur./Geol. Surv. Ind., Vol.LIV, pp. 345-397.</td>
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<tr>
<td>Hobbie and Arthur Holmes</td>
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<td>Parry, W.T. &amp; M.P. Nackowski</td>
<td>1963</td>
<td>Copper, lead and zinc in biotites from Basin and Range quartz monzonites</td>
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<tr>
<td>Shaw, D.M.</td>
<td>1953</td>
<td>The camouflage principle and trace element distribution in magmatic minerals</td>
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Vinogradov, A.P. 1962 See Barnes, H.L., 1967
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<th>Year</th>
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EXPLANATION OF PLATES

Field Photographs

PLATE I

Fig. 1 Bird's eye view of Khetrinagar and Gotro village showing low lying outcrops of pink granite.

Fig. 2 A view of quartz/cutting across the outcrop of pink granite. Locality Gotro village.

Fig. 3 Prominent shear jointings in felspathic quartzite, northwest of Madhan-Kudhan mine section.

PLATE II

Fig. 1 An outcrop of magnetite-quartzite near Madhan-Kudhan mine.

Fig. 2 An outcrop of garnetiferous quartz-chlorite schist in the vicinity of Madhan-Kudhan mine.

Fig. 3 An outcrop of amphibole marble showing bands of dark coloured amphiboles. Locality near Kolihan mine.

PLATE III

Fig. 1 A contact between faulted magnetite-quartzite and quartz vein.

Fig. 2 A panoramic view of the northern part of the Khetri copper belt.

Fig. 3 An old surface working in the vicinity of Madhan-Kudhan mine.

Photographs of hand specimens

PLATE IV

Fig. 1 A contact breccia collected from the contact of granite and felspathic quartzite.

Fig. 2 A pink granite showing bands of amphibole (dark) along joint planes.
Fig. 3  A grey granite gneiss with a thick lighter band of felspathic material.

PLATE V

Fig. 1  A pink granite gneiss with augens of potash feldspars.
Fig. 2  A pegmatite specimen showing radially arranged crystals of tourmaline.
Fig. 3  Pegmatite showing three big crystals of tourmaline (black) arranged in a somewhat radiating fashion.

PLATE VI

Fig. 1  Folded pegmatite showing occurrence of tourmaline and felspathic material in alternate bands.
Fig. 2  Meta-dolerite showing big porphyries of plagioclase feldspars.
Fig. 3  Garnetiferous quartz-chlorite schist showing garnets arranged along the planes of schistosity.

PLATE VII

Fig. 1  Garnetiferous quartz-chlorite schist showing irregular bands of garnets (dark grey).
Fig. 2  Biotite-andalusite schist showing a crystal of andalusite (greyish-white) with a carbonaceous streak in the centre.
Fig. 3  A hand specimen of puckered phyllite.

Photo micrographs

All magnifications 35 X.

PLATE VIII

Fig. 1  Microcline megacrysts in pink granite showing veins of ground mass material.
Fig. 2  A big crystal of twinned plagioclase in pink granite.
Fig. 3  Deformation and dislocation of the twin compositional planes of a crystal of plagioclase in pink granite.
PLATE IX

Fig. 1  Micrographic intergrowth texture in pink granite.

Fig. 2  Cordierite crystals with abundant inclusions of flaky minerals in a pink granite gneiss.

Fig. 3  Hornblende crystals arranged parallel to the foliation planes of grey granite gneiss.

PLATE X

Fig. 1  Tourmaline crystals in pegmatite showing zoning.

Fig. 2  Relict of porphyritic and ophitic texture in epidiorite, and zoning in plagioclase crystals.

Fig. 3  Mosaic texture in the massive quartzite.

PLATE XI

Fig. 1  A xenoblast of rotated garnet with "S"-shaped arrangement of inclusions in the garnetiferous quartz-chlorite schist.

Fig. 2  An idioblastic garnet crystal with rounded and oriented quartz inclusions.

Fig. 3  Prismatic crystals of anthophyllite/cummingtonite in garnetiferous quartz-chlorite schist.

PLATE XII

Fig.  A section of phyllite showing the early stage of development of schistosity.
PERSONAL VITAE

I was born in a Sunni Muslim family in Bhopal, Madhya Pradesh, India, where we are settled for over a hundred years. My father and grandfather were in the service of the Nawab of Bhopal. My father expired in 1947 and my mother remained solely responsible for my upbringing and education.

I had all my education in Bhopal. I obtained Master's degree in Chemistry in 1960 from Vikram University (Ujjain) and started my career as a Lecturer in Chemistry in Saifia Degree College, Bhopal. While on job I did M.Sc. in Geology in 1962 from Vikram University. My desire to engage myself in laboratory work prompted me to seek appointment in a non-gazetted capacity in the Chemical Laboratory, Geological Survey of India, Hyderabad, in December, 1962. I was promoted to Assistant Chemist (Gazetted II) in the G.S.I. in January, 1964.

During my stay at Hyderabad with my maternal uncle, Mr. Syed Sajid Ali, B.A., B.T. (Alig.), retired Deputy Director of Public Instructions, Hyderabad, I received immense encouragement from him in pursuing my professional as well as educational ambitions.

I was inspired to take up research in 1964, after attending the International Geological Congress held in New Delhi, along with my friends Mr. Noman Ghani, Lecturer in Geology, Aligarh Muslim University, Aligarh, and Mr. H.H. Khan, Assistant Geologist, Geological Survey of India, Bhopal. Since I had the background of Chemistry as well as of Geology, I was keen to work on some problem in Geochemistry closely connected with my laboratory assignments.

After my marriage (February, 1965), I was transferred (1966) from Hyderabad to Bhopal, my home town. I visited Aligarh in July 1968 where
Professor F. Ahmad, Head, Department of Geology, Aligarh Muslim University, Aligarh, was kind enough to allow me to join research leading to the degree of Ph.D. and Dr. S.H. Rasul kindly consented to supervise my work. After three years of research work I have been able to complete my thesis in the present form.

During the course of this study Mr. Noman Ghani extended invaluable help to me by way of giving fresh ideas and inspiration.

On this occasion I wish to dedicate this thesis to my revered mother but for whom my long patient work would not have been possible. I owe my gratitude to my wife and love to my two little daughters, Faiza and Farah, who played a vital role in the completion of this work.