Petrography of the Crystalline Rocks and paragenetic studies of the sulphide ore deposits around Askote, Pithoragarh district, Kumaon Himalaya

THESIS SUBMITTED TO THE ALIGARH MUSLIM UNIVERSITY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF PHILOSOPHY IN GEOLOGY

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This is to certify that Mr. Shahid Parooq has carried out the present investigation for the award of the degree of Master of Philosophy in Geology of the Aligarh Muslim University, Aligarh. The investigations, carried out under my supervision, are original contributions to the knowledge of the hitherto unexamined base metals of Askote area, Pithoragarh district, Kumaon Himalaya, and definitely contribute new information which has not been published anywhere.

He is allowed to submit the thesis for the award of M.Phil degree of this University.

ALIGARH

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## CONTENTS

<table>
<thead>
<tr>
<th>Chapter I</th>
<th>INTRODUCTION</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter II</th>
<th>GEOLOGY AND STRUCTURE OF THE KUMAON HIMALAYA</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tectonic evolution</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Geophysical investigations</td>
<td>14</td>
</tr>
<tr>
<td>THE LESSER HIMALAYA OF KUMAON</td>
<td>Page No.</td>
<td></td>
</tr>
<tr>
<td>Inner Sedimentary Belt</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Outer Sedimentary Belt</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>The Crystalline Units</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter III</th>
<th>TECTONICS AND STRUCTURAL EVOLUTION OF THE ASKOTE CRYS'TALLINES</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Structural set up</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Lithostratigraphy</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Mesoscopic Structures</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Tectonic history</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Metamorphism in relation to structure</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter IV</th>
<th>PETROGRAPHY OF THE MINERALISED ZONE AND WALL ROCK ALTERATION</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Petrography</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Alteration</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Alteration-mineralisation Zoning</td>
<td>45</td>
</tr>
<tr>
<td>Chapter V</td>
<td>Sulphide Mineralisation and Paragenesis</td>
<td>Page No.</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>Mineralisation</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Criteria for determining paragenesis</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Paragenesis</td>
<td>52</td>
</tr>
<tr>
<td>Chapter VI</td>
<td>Discussions</td>
<td>57</td>
</tr>
<tr>
<td>Chapter VII</td>
<td>Summary and Conclusions</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Explanation of Plates</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Appendix</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>77</td>
</tr>
</tbody>
</table>
Location map of Asxote
Chapter -I

INTRODUCTION

Base metals play a vital role both in war and peace and are particularly necessary for the industrialisation of a country. Copper, lead, and zinc rank next to iron and aluminium as metals essential to modern civilisation. Unfortunately India, at present, is in short supply in regard to most of these metals, and valuable foreign exchange is spent every year in importing these. In the face of growing world scarcity of these metals and quick industrial growth, it would become very difficult to buy them from outside, and we must, therefore, depend on our own resources.

Very little investigations have been carried out in areas in which workable deposits are not known. Our proved resources are limited and inadequate and new resources are costly to find, and when found, usually turn out to be of lower grade.

Copper (including its alloys — brass, bronze and scrap) import during 1975 and 1976 was 22,655 and 40,813 tonnes respectively. Against this the production of copper metal during 1976 was only 17,012 tonnes. During the same year the production of lead and zinc concentrates in the country was of the order of
15,858 and 45,025 tonnes respectively.

The debates and doubts being on a grand scale, the guidance for mineral exploration in the Himalaya from stratigraphic, geochronologic and tectonic considerations remains minimal. Mineral exploration in the Himalaya had a late start and there are possibilities of interesting new discoveries of many commodities in the Lesser and Higher Himalaya. During the British rule in India a considerable part of the Himalayan territory was made up of a number of princely states where the urge for mineral exploration and development was marginal.

Mineral exploration in the Himalaya gained some momentum in the late fifties, initially for cement grade limestone, magnesite, and base metal deposits and then for phosphorite, potash, and other minerals. Two decades of prospecting in a mountainous terrain like the Himalaya can hardly be expected to yield exhaustive information on the total mineral reserves. Hence the Himalaya, by and large, are still unexplored.

There are many occurrences of base metals in the Lesser Himalaya, extending from east to west. There are several old workings of copper in the Lesser Kumaon Himalaya notably at Rain-Agar, Patti, Dewal-Thal, Askote, and Kanalichhina in Pithoragarh district; Dhauladari and Bageshwar in Almora district. The mineralisation is confined to the crystalline dolomites and talc-schists of the Garhwal series of Permo-Triassic age.
and Almora-Dudhatoli crystalline sheets of Precambrian age. Occurrence of base metals at Pokhari and Dhampur in Chamoli district are also prospective. The mineralisation in the Lesser Himalaya of Uttar Pradesh belongs to two geological ages. Copper mineralisation has also been located in Kangra district of Punjab, Dabari area, Udhampur district and Boniyar area, Baramulla district. Workable strike lengths have been established at Dikchu in Sikkim, Gorubatang in Darjeeling, Geneka in Bhutan and possibly Askote in Uttar Pradesh. So far there is only one small working mine at Bhotang near Rangpo, Sikkim. Such a large number of occurrences do suggest interesting possibilities. Quite a number of these have been mapped on a large scale and explored by bore holes and adits. But the level of success in proving workable reserves has not been high.

The problems in the Himalaya with regard to mineral exploratio are formidable, but at the same time the opportunities are attractive. Here there are vast sedimentary and metasedimentary sequences lying in thrust slices and dislocated by steep dipping transverse faults so that prospecting cannot be projected over any large tract, as in the case of stratigraphically well defined sectors, for fear of getting the drill trapped in one of the thrusts and faults. Moreover, the tectonic activity has fragmented most of the large ore bodies, as is perhaps the case with the lode at Askote, which results in the prospector running
up against a blank wall. Added to this are the technological problems. Airborne geophysical surveys cannot be conducted successfully in areas of steep slopes and photogeological interpretations pose problems in densely forested areas. Large landslides hinder systematic prospecting in many areas.

In the present work the task of summarising the geology of the Askote area from the structural and economic standpoint has been attempted. The scale of the work is small as compared with the magnitude of the subject, nevertheless, it is intended to give a preliminary idea. In the course of writing this report the author has consulted many texts. The emphasis laid on modern views, and the relative poverty of reference to the works of others, does not imply any disrespect to the latter.

The Askote area (29° 46' 10" : 80° 19' 40"), which has been taken up for the present investigation of its sulphide deposits, is situated about 50 km north of Pithoragarh at the Indo-Nepal border. It is connected to Tanakpur, the nearest rail-head, by an all weather road. Tanakpur is linked with the other major cities of India by broad gauge railways. The area has rugged topography as can be seen almost anywhere in the Himalaya. The altitude is generally between 1000 to 1600 mts above m.s.l.

The mineralisation, proved by the recent work of the Geological Survey of India, occurs below the surface and occupies
the top position of the schists in Askote Crystallines. The area shows polymetamorphism, progressive regional type being superimposed by dynamic and retrograde metamorphism. The Askote mineralisation is the only base metal occurrence of any significance in the U.P. Himalaya. The hydrothermal fluid produced extensive hornfelsisation of the sulphide zone and alteration of the wall rock. Attempt has been made to make a detailed study of the structures, petrography, and wall rock alteration of the host rocks of this base metal mineralisation.

Before attempting a detailed study in any part of the Himalaya it is of utmost importance to have at least a concise idea of the regional structural and tectonic setup. A summarised compilation of the upto date knowledge on this aspect is therefore attempted at the very outset. The portion of the text that deals with the tectonic and structural evolution of the Askote Crystallines is the outcome of field mapping during 1979 and 1980. The mapping was carried out on a scale of 4 inches = 1 mile. No statistical analysis of the structural elements has been attempted and hence the element of inaccuracy in the interpretations cannot be overruled.

The study of the alteration of host rocks is based on the investigation of sixty thin sections of specimen collected on a 15 meter grid over the mineralised zone. Some samples
were, however, available from the exploratory mine and the drill cores. The discussion of the paragenesis of ore minerals is based on an examination of twenty-eight polished sections. Most of the specimen were taken from the exploratory adit driven by the Mineral Exploration Corporation, a Govt. of India undertaking. Finally a synthesis of the structural, tectonic, and metamorphic history of the area and the history of mineralisation, as revealed by the present study, is presented.
Chapter -II

GEOLOGY AND STRUCTURE OF THE KUMAON HIMALAYA

The Himalaya constitutes the most mighty mountain system in the world. The Himalayan arc, as defined geographically, extends over a length of 2400 km, commencing from Nanga Parbat (8125 m) in Kashmir in the west to Namche Barwa (7755 m) in Assam on the east. The geological formations, however, take a sharp turn forming a hairpin bend at the eastern and western extremities of the arc, as if they were bend around pivotal points (Wadia, 1931) and continue southwards into the Baluchistan and Burmese arcs respectively. These two points of acute inflexion constitute the major syntaxial bends in the Himalaya.

The Himalaya are 200 to 250 km wide, generally limited by the upper courses of the Indus and Brahmaputra rivers on the north and by a narrow fringe of the Siwalik hills nearly all along the south.

According to Gansser (1964) the Himalaya may be subdivided into five geographical divisions from west to east:

Punjab Himalaya (including Kashmir Himalaya) 550 km long, from the northwest syntaxis to the Sutlej valley.

Kumaon Himalaya (including Garhwal Himalaya), 320 km long, from Sutlej to the Kali River.
Nepal Himalaya, 800 km long.
Sikkim and Bhutan Himalayas, 400 km long.
Nepa (North East Frontier Agency) or Assam Himalaya, 400 km long.
In the western corner the Salt Range is a southern prolongation of the Himalaya.

Longitudinally the Himalaya are classified into the following subdivisions from south to north:
The Sub or Outer Himalaya forming the foot hill zone.
The Lower or Lesser or Middle Himalaya.
The Great or Central or Higher Himalaya.
The Tethys or Tibetan Himalaya ending in the Tibetan Plateau.

Beyond these four zones are Laddakh and Kailash Ranges followed by the Trans-Himalayan Ranges (Figure 1).

STRUCTURAL BOUNDARIES:
The southward extension of the Siwalik molasse is marked by the large fans of Ganges alluvial deposits, whereas the northern edge is a clearly outlined tectonic feature —
The Main Boundary Fault, genetically linked to Miocene metamorphism in the Himalaya (Le Fort, 1975). Generally regarded as a steep northward dipping fault, it is more likely a thrust which flattens in depth. Valdiya (1978) is of the opinion that in the Kumaon region the Main Boundary Fault is exposed only in the
western sector between the Yamuna and Tons valleys, and that east of the Yamuna the higher Krol Thrust has overlapped the Eocene Subathu and has concealed the Main Boundary Fault completely. Hence it is the Krol Thrust which constitutes the boundary between the Sub and Lesser Himalaya of Kumaon. The Main Boundary Thrust is still very active and the measurements made by Singhal et al. (1973, in Valdiya, 1976, p. 5) demonstrate that the present day movement is of the order of 0.92 cm/year.

Between the Krol Thrust in the south and the Main Central Thrust of Miocene to Pliocene age (Le Fort, 1975) lies the stretch of the Lesser Himalaya (Gansser, 1964, Raina, 1978). The Main Central Thrust is a major tectonic feature of the Kumaon Himalaya and has brought the crystalline rocks of the Central Himalaya over the Younger sedimentaries. Valdiya (1978), however, takes a somewhat different stance on the northern limit of the Lesser Himalaya. The real boundary in his opinion is the place that separates the Precambrian granite injected metamorphics of medium grade (Munsari Formation) from the katatonial, very high grade metamorphics, making the bulk of the Higher Himalaya (Vaikrita Group). There is no thrust discernible between these two units which are considered by most workers to constitute the central crystalline zone. However, an abrupt and dramatic change in the grade of metamorphism is evident which reflects the presence of a thrust which Valdiya (1978) has designated as the
Veikrita Thrust defining the base of the Veikaita group (Figure 2).

In the Ladakh region of the Kashmir Himalaya, all along the Indus valley, is present a significant linear tectonic zone, well known as the Indus Suture. There is a lot of controversy regarding the nature and origin of the Indus Suture and the associated ophiolites and exotic blocks. One point of view considers this as a line of junction of the Indian and Asian plates, where the Indian plate is subducting beneath the Asian plate (Argand, 1924; Holmes, 1966) and that the flysch sediments are parts of the oceanic crust ab ducted during the collision (Gansser, 1966, 1973, 1974; Powell and Conaghan, 1973; Athavale, 1973; Le Fort, 1975). This concept has been strongly opposed by other workers (Petrushevsky, 1971; Meyerhoff and Meyerhoff, 1972; Crawford, 1974; Stonley, 1975; Sinha and Jhingran, 1975; Kaile and Hari Narain, 1976; Srikantia and Bhargava, 1978) who consider the northern boundary of the Indian plate along the very high seismic activity belt of Tian Shan mountains and the Indus Suture as being a deep fracture reaching up to the mantle along which Cretaceous onwards, flysch type sediments were deposited and volcanics and pyroclasts poured out and blocks of Alpine type ultramafics were emplaced almost in solid state (Vardrajan and Jhingran, 1977).
There is no sharp division in the Kumaun Himalaya between the Higher Himalaya and the northern Tibet or Tethys Himalaya. The fossiliferous sediments on the northern slopes, taken as the arbitrary boundary between the Higher and Tethys Himalaya is transitional from Cambrian into younger deposits. In the Tethyan zone the stratigraphic order is known to a great extent on account of the well preserved fossils e.g. *Productus, Ophioceras*, etc. On the other hand the stratigraphic order in the Lesser Himalaya is primarily based on structural setting and lithological correlation because of the stray fossil finds.

A bulk of evidence favours the existence of a barrier between the northern and southern sedimentary basins to which the contrast in sedimentary environment is assigned. This barrier was remarcated and termed by Saxena (1977) as the Central Crystalline Axis, which corresponds to the Central Himalaya. There is evidence of continuous Precambrian continental basement extending north of India through the Himalaya into Tibet (Saxena and Rao, 1973). It appears obvious that the sedimentation of the Himalaya took place in a sunken basement extending north of the Indian shield, which could have been in contact with the southern boundary of the Asian plate or the two might have been continuous. This basement formed the barrier between the northern and southern basins, thus
separating the two sedimentary environments in the form of an upthrust wedge. The fact that the Central Crystalline Axial zone is not younger than Lower Paleozoic supports this theory.

Comparing the stratigraphy of the Tethyan and Lesser Himalayan zone one fact becomes predominant, and that is in the Tethyan zone normally the metamorphics occur at the base of the sedimentary sequence, whereas, in the Lesser Himalayan zone the Simla Slates and their equivalents form the basement of the sedimentary sequence. In the Lesser Himalaya the sedimentaries are covered by the crystalline nappes and thrust sheets which are considered by many workers to have travelled far to the south of the Central Crystalline Axial zone which is considered the root zone of the crystalline thrusts.

TECTONIC EVOLUTION:

The tectonic history of the Himalaya is a much debated subject. Jhingran and Verma (1977) have deciphered four major tectonic events as follows:

a) The Daling (Precambrian or Lower Paleozoic)
b) The Kaman (Permian-Triassic)
c) The Himalayan (Early Tertiary)
d) The Siwalik (Neogene)

The Daling event is marked by medium grade metamorphism but intense deformation accompanied by both acid and basic
igneous intrusives. The Kameng event was characterised by moderate deformation along with basic igneous activity — mainly volcanic. On the other hand during the Himalayan event a strong deformation took place and post folding tourmaline bearing granites were emplaced with metamorphism being more or less absent. During the Sivalik event a mild to strong deformation occurred, apparently without any igneous activity or metamorphism.

According to Naha and Ray (1970) the E - W trending structures belong to the first and second events of deformation, but Bhattacharya and Miyogi (1971) regard the NW - SE trending structures as belonging to the first and second deformational events. The investigations by Merh (1966) in Kumaon and by Saklani (1971, 1972, 1973, 1975) in Garhwal seem to be similar. Minor variations in the trend can be accounted for by subsequent deformations.

Though there appears to be a general agreement as regards the number of tectonic episodes that have affected the Himalaya, there seems to be a great diversity of opinion as regards the dates of these episodes. Le Fort (1975) has recognised four main sets of deformation in the Himalaya. These can be followed throughout the entire range with the exception of the first event which is absent in the Sub-Himalaya and in the Krol Belt of the southern fringe, and in the Mesozoic
formations, mainly in the Tibetan Sedimentary Zone. Nearly all workers suggest the close relationship of the second event with the large scale overthrusting of MCT type. The first and second events are sometimes considered to be stages in a continuous deformation, sometimes separated by a large gap of time and metamorphism, especially when not coaxial. The early thrusts are consequently folded into broad undulations by the third and fourth tectonic event which are most conspicuous throughout the Lesser Himalaya.

Gibbs (1980) postulated that most of the present nappes acquired their present disposition after the first event and some of the deformation and metamorphism, and the granitic gneisses are relics of Pre-Himalayan tectonism. The main thrusting of the nappes took place in the second event. The last three deformational events are dated as Tertiary to Recent on structural evidences.

GEOPHYSICAL INVESTIGATIONS:

From a study of the gravity data Gureshi (1969) postulated that the Himalaya are underlain by a thick basaltic root and represent a block uplifted foreland. Nappes and recumbent folding might be the result of gravity gliding tectonics associated with the primary vertical movements. Large positive isostatic anomalies over the Middle Himalaya and large crustal
thickness reaching 60 km in places are interpreted to be mainly
due to thickening of a basalt layer or incorporation of heavy
material moving from depth into the crust (Gureshi, 1971).

Kaila and Hari Narain (1976) have deciphered a very high
seismic activity zone trending in a northwest-southeast direction
beneath Kedarnath and Askote in the Lesser Himalaya of Kumaon.
The highest seismic activity recorded in the Himalaya is just
east of Askote. Seismic considerations and field evidences
indicate that the seismic plane in the eastern Kumaon Himalaya
dips at an angle of 41° towards northeast. However, Holmes
(1966) postulates a low dipping thrust (0°-5°) to explain the
almost double crustal thickness beneath the Himalaya.

THE LESSER HIMALAYA OF KUMAON

The Kumaon Himalaya lying between the Kali river in the
east and the Sutlej in the west, include a 320 km stretch of
mountainous terrain. Much pioneer work was done at the turn
of the century (Griesbach, 1891; Hayden, 1904) followed by more
modern investigations between 1930 and 1940 (Auden, 1934,
1935, 1936; Heim and Gansser, 1939; Wadia, 1932, 1938; West,
1934, 1939).

The almost complete absence of fossils in the Lesser
Himalaya leaves many structural and stratigraphical problems
unsolved, since the correlation had to be based on lithology alone. This casts some doubt on certain tectonic interpretations.

The Kumaon Lesser Himalaya include a thrust bound sector delineated by two tectonic planes — the Krol Thrust to the south and the Main Central Thrust (or the Vaikrita Thrust) to the north. Existence of regional inversion of sedimentary pile has been postulated by many workers. There are two elongate sedimentary belts separated by an ESE - WNW trending Almora Crystalline zone. The outer sedimentary belt to the south of the crystalline mass is the Krol Belt while the inner sedimentary belt to the north constitutes the Debon - Tejam zone (Gansser, 1964). The following tectonic setup based on Valdiya (1978) for the Lesser Kumaon Himalaya is tabulated below:

<table>
<thead>
<tr>
<th>Vaikrita Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vaikrita Thrust</td>
</tr>
<tr>
<td>Munsari Formation</td>
</tr>
<tr>
<td>Main Central Thrust</td>
</tr>
</tbody>
</table>

| Almora Nappe and Askote & Baijnath Klippen |

| Almora Thrust |
| Chail-Barakot-Ramgarh Nappe |
| Ramgarh Thrust |
| Outer Sedimentary Belt |
| Krol Nappe |
| Inner Sedimentary Belt |

| Main Boundary Fault/ Krol Thrust |

Siwalik Group
INNER SEDIMENTARY BELT

This extends from the Garhwal region in the west to beyond the Kali River marking the eastern boundary of the Kumaon region. The oldest rock unit of this belt is termed the Hatsila Formation by Misra and Bhattacharya (1972, 1973). This formation is correlated with the Rautgara Quartzites (Valdiya, 1964) and Ramashwar Formation (Ahmad, 1975). The Hatsila Formation consists of slate, siltstone, subgraywacke prot quartzite, phyllite and limestone. The arenaceous beds sometimes show sedimentary structures.

The rock unit overlying the Hatsila Formation is termed the Kapkot Formation. Apparently, it is the same as the main calcareous unit of the Calc Zone of Pithoragarh (Valdiya, 1962; Misra and Banerjee, 1968; Misra and Valdiya, 1969), the Calc Zone of Tejam (Heim and Genasser, 1939; Genasser, 1964), and the kotaga Banali of Saklani (1971, 1978), as well as the Doya Dolomite (Misra and Bhattacharya, 1972) of Pugar valley and Jhatkvali Formation (Mehdi, et al. 1972). The Formation includes stromatolite bearing dolomitic limestone with magnesite, calc, chert, pebble beds and some slate/calcareous slate. Dolomitization and recrystallization are common features of the limestone.

On the basis of the discovery of stromatolites (Valdiya, 1969; Kumar and Tiwari, 1977, 1978; Kumar, 1978; Bhattacharya, 1976a),
a Middle Riphean age has been assigned to the stromatolite bearing rocks of this formation.

Overlying the Kapkot Formation, the Saling Formation (Bhattacharya, 1980) is the same as, or directly correlative with the Kanalichina Formation (Mehdi, et al. 1972) of the Pithoragarh District and the Betulghat Formation (Raina and Dungarakoti, 1973) of the Bhimtal – Bhowali area in Nainital District. The rock types include grey, green and black slates and phyllite with subordinate calcareous interbeds.

The topmost horizon of the Inner Sedimentary Belt is the Bering Formation which is seen surrounding the crystalline masses of the Almora, Askote, Bajnath and Karimpur units. The contact of the quartzites with underlying crystallines have been described to be tectonic by many workers. The lithology consists of fine to coarse grained massive quartzite, often sericitic and schistose with pebble beds, chlorite beds, and interbedded metabasites. Kumar (1978) has correlated the Bering Formation with the Kaimur Formation of Upper Vindhyan. Jain (1971) classified this unit as the Gadhwal Group. Based on field evidences, some workers (Valdiya, 1961, 1962, 1964, 1969, 1973; Misra and Kumar, 1968; Misra and Banerjee, 1968; Misra and Bhattacharya, 1972; Saklani, 1971, 1972; Jain 1971; Pachauri, 1972; and Bhattacharya, 1976 b) are
of the opinion that a thrust plane separates the Berinag Formation from the underlying units, and that the sedimentary sequence is inverted. Other workers (Heim and Gansser, 1939; Gansser, 1964; Mehdi, et al., 1973; Banerjee and Bisaria, 1975; Ramji, 1976; Kumar and Tiwari, 1977; Kumar, 1978 and Bhattacharya, 1980) maintain that the entire sedimentary pile is in normal position except for locally inverted sequences.

Structure

Lying between the MCT and the North Almora Thrust, the Inner Sedimentary Belt has been folded into a few E-W to ESE-WNW trending folds. In places there is strong evidence of thrusting and dislocation by a number of faults.

OUTER SEDIMENTARY BELT

Delineated in the south by the Krol Thrust and on the north by the Ramgarh Thrust, the Outer Sedimentary Belt includes a relatively less thick pile of sediments referable to the Krol Belt of the Garhwal Siwalik Himalaya. It occurs as a detached outliner which widens westwards and appears to extend up to Himachal Pradesh through Garhwal. Bhattacharya (1980) considers the Outer Sedimentary Belt to rest conformably over the Inner Sedimentary Belt. Hence the Outer Sedimentary Belt is considered the younger of the two,
The stratigraphic unit forming the base of the Outer Sedimentary Belt is the Nagthat Formation which appears to correlate well with the Berinag Formation (Valdiya, 1978). This consists of conglomeratic and pebbly protoquartzites, shales, slates and basic rocks.

Overlying the Nagthats is the Bhaini Formation which consists of two typical rock types; one is the boulder beds, the other the limestones, overlying the former. The rock association is not constant and often the boulder beds or the limestones can occur alone, or several horizons of boulder beds are found together with the limestones. These complications may be due to tectonic imbrication (Gansser, 1964).

The Infra-Krol Formation conformably overlying the Bhainis consists of grey to black slates and shales with siltstone and quartzite bands. Rarely blue limestone beds are seen. The Infra-Krols are overlain by the Krol Formation which has been divided into three sub-units viz. the Lower, Middle and Upper Krols. The Lower Krols consist of shales and slates with dolomitic intercalations, grey shales with intercalations of limestone, dolomite and minor red shale. The Middle Krols have green and red, medium to fine grained sandstone with shaly and silty intercalations. The
Upper Kroli include massive and thickly bedded dolomites, cherty and colitic dolomite and subordinate shale and quartzite interbeds.

Structure

Geiserer (1964) is of the opinion that none of the Kroli Thrust has actually been formed through large scale recumbent folding and there are numerous criteria which indicate normal sections and not recumbent "nappes". The strata of the Outer Sedimentary Belt have been folded into a syncline on an E - W axis, the northern limb of which is open as compared with the southern limb which is partly concealed beneath the Kroli Thrust (= MBF), while the northern one exposes all the rock units of the Outer Sedimentary Belt and is best exposed near Mainital (Bhattacharya, 1980) the Outer Sedimentary Belt has been affected by a number of tear and normal faults of varying dimensions.

THE CRYSTALLINE UNITS

The occurrence of scattered outcrops of older crystalline rocks is a typical feature of the Lesser Himalaya of Kumaon. The crystallines consist of Almorâ, Bajnath, Asutte, Dharmagadh, and Karimpur units and are characterised by a set of general features:
(1) Of the various younger sedimentary units, it is usually the youngest Berinag Formation that underlies these crystallines.

(2) Each of these units is dispersed in a synform, though severed by later folds, faults and thrusts.

(3) Each unit consists of meso to kate-grade of metamorphic rocks together with intrusive (?) granites.

(4) Generally metavolcanic rocks are seen at the contact of the crystallines with the sedimentaries.

(5) Augen granites and porphyries occur in the core of all these synclinal crystalline units.

(6) A zone of chlorite schists is quite common along the base of all these crystalline units indicating retrogression (to epi-grade).

The Almora crystalline unit is delineated along the two flanks by what is known as the South Almora Thrust and the North Almora Thrust. The rocks of the Almora crystallines and other lithologically correlatable units of the Bajnath, Askote and Amri units, have been considered by most workers, including some pioneers in Himalayan geology, to constitute
thrust sheets or nappes pushed over the younger rocks from the north with their roots in the Central Crystallines of the Higher Himalaya (Hein and Gansser, 1939; Gansser, 1964; Ghose, et al. 1974; Misra and Bhattacharya, 1976; Bhanot, et al., 1977). However, Misra (1972), Saxena (1974), Saxena and Rao (1975), Misra and Shama (1972), Misra et al. (1973), Bhattacharya (1980) suggest that the crystallines do not occur as nappes with their roots in the Central Crystallines instead they are authochthonous in nature with the root zone along the North Almora Thrust and their present disposition being due to vertical uplift. However, the various structural and tectonic considerations, supported by the correlation of radiometric age determinations of the granite-gneisses of the Central Crystalline Zone with those of the Crystalline sheets (Bhanot et al., 1977) indicate that a great nappe of crystalline rocks was pushed southwards over the sedimentary rocks of U.P. Himalaya. This crystalline sheet possibly extended as far as upto the Main Boundary Fault because the Amir Klippe is exposed very close to it. Saxena (1977) considers a Primo-Carboniferous age for this thrusting.

The South Almora Thrust is a very low dipping feature, and convergence of overlying and underlying formations of almost similar lithological units has made its recognitions and
delineation quite difficult. Some workers (Kumar et al., 1974; Saxena and Rao, 1975) dispute its very existence. Detailed structural studies by Mezh and Vashi (1965, 1976), Vashi and Mezh (1974), Ghose (1973), and other workers have conclusively established the existence of the South Almora Thrust which joins up with the North Almora Thrust at the northwestern nose of the vast plunging syncline in the western Nayyar valley, west of Dudlatoli massif. Valdiya (1988) and Bhattacharya (1980) are of the opinion that the metasedimentary sequence of the southern limb of the Almora synform is constituted of two thrust sheets, the upper one is called the Almora Nappe and the lower the Ramgarh nappe (Pande, 1950) overlying the Outer Sedimentary Belt. The Ramgarh Nappe is composed of mildly metamorphosed flyschoid rocks. The delimiting Ramgarh Thrust is not discernible in the northern flank, being overlapped by the rocks of the Almora Nappe with which the Ramgarh Nappe forms an imbricating pair. The base of the Almora Nappe is marked by sericite schists. However, Raina and Dingrakoti (1975) deny the existence of the Ramgarh Thrust.
Chapter -III

TECTONICS AND STRUCTURAL EVOLUTION
OF THE ASKOTE CRYSTALLINES

Structural Set-up

The metamorphics and associated granitic intrusives of the Askote Crystallines (= Didihat Crystallines, Kumar et al., 1976; Mahdi et al., 1972) form a syncline and are surrounded by the younger rocks of the sedimentary zone of Pithoragarh comprising two rock stratigraphic units, the one essentially arenaceous and the other argillo-calcareous. It represents a reversed sequence and probably the inverted limb of a recumbent fold. The transition of the arenaceous group to the physically underlying calcareous group is characterised by complete concordance without any suggestion of tectonic discontinuity or discordance. The Berinag Formation consisting of quartzites, sericite-quartz schists interbedded with chlorite schists and amphibolites, has been compared with the Nagthat and Jaunsar Series of the Garhwal and Punjab Himalaya (Valdiya, 1965) and with the Kaimur Formation of Upper Vindhyans (Kumar, 1978). The stratigraphic position of the Calc Zone of Pithoragarh, comprising dolomites, dolomitic, cherty and argillaceous limestones, shales and slates, may be placed anywhere between the Precambrian and Cambrian. Figure 3
represents a geological map of the Askote Crystallines, with the associated sedimentary zone of the Berinag Quartzites and the underlying Gangolihat Dolomites of the Calc. Zone.

The contact of the Askote Crystallines with the Berinag Quartzites has been considered a thrust contact (Gansser, 1964; Valdiya, 1962, 1965, 1978; Misra and Kumar, 1968; Misra and Bhattacharya, 1972, 1973; Bhattacharya, 1976; Ahmad, 1975). Some workers (Banerjee and Bisaria, 1975; Bhattacharya 1980) put forward the view that the contact is normal and the crystallines constitute an autochthonous unit and have not been transported from the Central Axial Crystalline Zone. Retrospective metamorphism in the form of chloritisation of garnet and biotite near the contact zone (Pl. 1, Fig. 1) and the restriction of the metamorphosed basic sills (amphibolite and Chlorite schists) within the Berinage Quartzites, however, speak volumes in favour of a tectonic plane separating the two groups, which is hereby referred to as the Askote Thrust.

The exposures of the crystallines die out towards east and west because of a double plunge of the axis of the synform towards its core. In the area under present investigation, the strike of the rock units is NW - SE to NNW - ESE. At the eastern closure the strike swings almost to N - E.
On a regional basis the Askote Crystallines are folded into a large synform together with the surrounding sedimentaries, the former occupying the core of the syncline which is asymmetrical and isoclinal in nature with a flat thrust to the south and a steep to vertical (locally overturned) northern border. The synclinal axis roughly trends NW-SE with minor variations up to WNW-ENE. This axis is itself folded imparting the syncline a double plunge. Along the contact with the crystallines, the Berinag Quartzites are highly sericitic. Amphibolites are generally noticed along the crystalline-quartzite contact. Riddled with secondary silica veins the occurrence of amphibolites is of much significance and may possibly be related to the thrusting event of the crystallines mass.

The occurrence of huge lenticles of quartzites within the lowestmost horizon of the crystallines and also in the amphibolite, is noteworthy. Megascopically and microscopically these quartzites bear close similarity with the Berinag Quartzites, and are possibly torn off pieces of underlying unit picked up during overthrusting of the crystalline mass.

The southward movement of the Central Crystalline Zone in the form of a nappe as suggested by Heim and Gansser (1939), Gansser (1964) and Valdiya (1976) may be responsible for the
**Table - 1**

**Lithostratigraphic Succession of Askote Crystallines with the Associated Sedimentary Zone**

<table>
<thead>
<tr>
<th>Layer Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biotite bearing augen gneiss</td>
</tr>
<tr>
<td>Chlorite-sericite-actinolite-tramolite-epidote-quartz schists</td>
</tr>
<tr>
<td>Biotite-muscovite-epidote-quartz schists</td>
</tr>
<tr>
<td>Garnetiferous biotite-muscovite-chlorite-quartz schists.</td>
</tr>
<tr>
<td>Quartz-sericite-chlorite-biotite-epidote schists, with lenticles of biotite bearing augen gneiss</td>
</tr>
<tr>
<td><strong>ASKOTE THRUST</strong></td>
</tr>
<tr>
<td><strong>THRUST (?)</strong></td>
</tr>
<tr>
<td>Amphibolite with Sericite-chlorite schists and lenticles of schistose quartzite.</td>
</tr>
<tr>
<td>White sericite-quartz schists and quartzites with bands of amphibolites, schistose amphibolite, biotite schists and Calc-chlorite schists.</td>
</tr>
<tr>
<td><strong>THrust (?)</strong></td>
</tr>
<tr>
<td>Thickly bedded dolomites and limestones with interbeded slates</td>
</tr>
</tbody>
</table>
supra sedimentary disposition of the Askote Crystallines, which may be described as a recumbent nappe, only the inverted limb of which is now exposed.

LITHOSTRATIGRAPHY

The Askote Crystallines consist of a variety of metamorphic rocks which include sericite-muscovite-, chlorite-, biotite schists, gneisses, para gneisses and granite gneisses. The tectonic sequence of the rocks around Askote including the sedimentary zone is given in Table 1.

The base of the crystallines is marked by a persistent horizon of sericite-chlorite-biotite schists, riddled with secondary silica veins and lenses, some as thick as 70 cms. Shear effects are evident around these lenses which are more abundant near the thrust contact, thus indicating profound shearing in this part. Moreover, the lowermost horizon of the crystallines contains large but impermanent lenticles of biotite bearing augen gneiss which may once have been a single unit but later broken up due to shearing.

The sericite-chlorite-biotite schists are overlain by garnetiferous biotite-muscovite-chlorite-schists which are highly crenulated and coated with ferruginous staining.
These in turn are succeeded by biotite-muscovite-epidote schists and then by chlorite-sericite-actinolite schists.

The rock unit overlying the schists consists of biotite bearing augen gneisses, granite gneisses and tourmaline gneisses which occupy the core of the syncline and consist of orthoclase, muscovite, quartz and micas. At the contact with the schists the gneisses are medium grained, with abundant muscovite and minor biotite. The gneissosity is poorly defined. As we go towards the top muscovite is substituted by biotite and the grain size increases progressively till the rock becomes very coarse grained augen-gneiss with large porphyroblasts of feldspars. These gneissic rocks are traversed by a number of quartz veins and show a good development of two sets of joints.

The Berinag quartzites underlie and surround the crystallines. Near the contact with the crystallines the quartzites are highly sericitic. This imparts a very well developed fissility to the rocks. The quartzites are fine to medium grained with muscovite and sericite and show mosaic texture. Magnetite occurs in minor amounts. In the uppermost horizon these quartzites are interbedded with schistose amphibolites which seem to bear their existence.
to the thrusting event. The Gangolihat Dolomites consist of thickly bedded limestones and dolomites interbedded with slates.

The lithology and metamorphic effects observed reflect the phenomenon of inverse metamorphism of the Askote Crystallines in which the rocks with low metamorphic grades occur at the base, while those with a higher grade lie higher up the sequence. The occurrence of sericite-chlorite schists at the base of this unit is of significance and it appears that mylonitisation along the thrust plane has brought down the grade of metamorphism.

MESOSCOPIC STRUCTURES

A. Planar Structures

The rocks are characterised by a number of well developed fissility planes of more than one generation. The original bedding \( S_1 \) is largely obliterated by later planar structures. The first deformation, particularly in the low grade rocks gave rise to the development of rock cleavage \( S_2 \) usually considered as axial plane cleavage. This is seen in the low grade schists. In thin sections such rocks are characterised by preferred orientation of platy minerals like mica, chlorite, sericite and a few flattened grains of quartz.
The general trend of $S_2$ planes bears close parallelism with the axis of the major folds striking NW/WW - SE/SEE. Sometimes $S_2$ planes tend to become parallel to $S_1$ indicating thereby an isoclinal or recumbent folding (Pl. 1, Fig. 2).

The next deformation caused superimposition of crenulation cleavages ($S_3$) on the earlier formed cleavages ($S_2$) due to puckering. Development of $S_3$ planes trending NNE - SSW is noticed in sericite and chlorite schists (Pl. 1, Fig. 3). Among the other planer structures there are two sets of joints trending NNE - SSW and ENE - WSW respectively.

3. Linear Structures:

The earlier tectonic impulses deformed the original $S_1$ planes to give rise to the first set of minor folds, the axes of which define $L_1$, the first lineation. Such folds are common in the schists and metamorphosed rocks of the Sedimentary Zone. The folds are generally recumbent and overturned isoclinal, with low plunges towards northwest, indicating a coaxial folding of the first generation.

The $L_2$ lineation is produced by the intersection of bedding planes ($S_1$) with $S_2$ planes. The $L_3$ lineation is developed by the recrystallisation of the constituent grains. This is confined to the $S_2$ planes and is marked by the preferred orientation of
prismatic and tabular minerals and linear alignment of quartz grains. \( L_4 \) linations are developed on \( S_2 \) planes and include axes of microfolds, puckering, corrugation and minor crenulations.

C. Folds:

Four generations of folds have been recognized in the rocks of the Askote Crystallines. The first generation \( (F_1) \) are mostly isoclinal with gently plunging axes trending NW/SE - SE/NE. The axial planes of these are recumbent to steeply inclined. They are well developed on \( S_2 \) planes. Coaxial refolding \( (F_2) \) of schistosity \( (S_2) \) is seen at many places which may be due to continued deformation along the same direction as \( (F_1) \). The third generation \( (F_3) \) include open and similar folds with SE - NW axes. These are developed in some beds of low grade schists. The fourth generation \( (F_4) \) include chevron type folds and monoclinal kinds. The axes of these generally trend NE - SW.

D. Fault

A NW - ESE trending fault is a major dislocation in the area. Occurrence of breccia at a number of places is an important criterion for the recognition of this fault. All along the Raunt is Gedi a number of evidences, e.g. intense crushing, pulverisation and silicification, random variations of
dip and strike, local shears and springs, slickensides and severe brecciation prove the existence of a fault, named as the Rauntis Fault. The fault can be traced for about a distance of 3 km in the area.

TECTONIC HISTORY

Based on systematic mapping of the area a tentative sequence of the structural evolution of the Askote Crystallines can be formulated as below:

A. Deformation due to vertical load: The rocks provide very scanty data on the earliest deformation which was obviously due to the weight of the overlying sediments. The only evidence in favour is the development of bedding ($S_1$) in these rocks.

B. Isoclinal folding: Orogenic movements folded the entire sequence into numerous isoclinal, inclined folds ($F_1$) showing steep northwesterly dipping axes. This deformation synchronised with the regional metamorphism and the main schistosity ($S_2$) marks the axial plane direction of the isoclinal folds.

C. Development of Askote thrust with drag folds ($F_2$): With the continued deformation, the isoclinal folding culminated into a major dislocation along which the older rocks of the Askote Crystallines were pushed over the younger Barinag Quartzites.
During this thrusting intense shearing along the Askote thrust developed a narrow zone of retrogressively metamorphosed phyllonite. These rocks show a strong shear cleavage paralleling the main schistosity ($S_2$), drag folds and boudinage structure in quartz veins and quartzitic layers. The axes of the drag folds ($F_3$) and $F_1$ folds have same orientation, indicating that isoclinal folding and the movement along the Askote Thrust constitute early and late stages of a single deformational episode as suggested earlier.

D. Symformal folding of the Askote Klippe ($F_3$): The Askote klippe was later folded into a symform. During the $F_3$ folding, the rocks developed extensive, subhorizontal and NW–SE trending crinkles and microfolds. Synchronously the rocks of the Berinag Formation were folded into a series of asymmetrical synclines and anticlines with axial planes dipping steeply towards northeast.

E. Open Folding ($F_4$): Partial twisting and refolding of the Askote symform to produce a double plunge is due to the superimposition of the fourth folding episode ($F_4$). During this episode the NNW–SSE trending syncline was folded on a NNE–SSW axis. This episode is responsible for minor folds, crenulations, development of
$S_3$ planes and $L_3$ lineations and perhaps the shearing of the rocks as noticed near Barjgaun where the schists of the mineralised zone have moderate to steep northeasterly dips. The reversal of dip is possibly due to coaxial folding with subhorizontal axes. The rocks are highly sheared (Pl.2, Fig.1) and consist of several NNE - SSW trending shear zones. This appears to be the last major tectonic event in the structural evolution of the Askote Crystallines.

**METAMORPHISM IN RELATION TO STRUCTURE**

The rocks of the Askote Crystallines show a gradual decrease in metamorphism towards the thrust while the underlying rocks show an upward increase in metamorphism. The area shows a striking relationship between the successive structural and metamorphic events and exhibits an excellent example of metamorphic convergence.

The sequence of metamorphic episodes in the Askote Crystallines are marked by both progressive and retrogressive phases. Lead metamorphism preceded the regional metamorphism and developed the bedding cleavage ($S_1$) which is now rarely visible in the rocks. The main metamorphism responsible for the development of garnetiferous mica schist coincided with isoclinal folding ($F_1$), as a result of which the main schistosity ($S_2$) developed along the axial planes of these isoclinal folds.
Injection of granites in the core of the nappes appears to have synchronised with the regional metamorphic episode which was followed by the thrusting of the crystalline mass over the younger sedimentaries. Bhanot et al. (1977) give an age of 1960 ± 100 m.y. for the granite gneiss of Askote.

The retrograde metamorphism of garnetiferous mica schist to sericite chlorite phyllonite due to overthrusting is the next metamorphic event giving rise to retrograde assemblages, mostly sericite and chlorite. The retrogressive metamorphism, mylonitisation and shearing are commonly seen in the lower horizons of the crystallines. The cataclastic effect decreases away from the thrust.

The synformal folding of the Askote Thrust mass produced crinkling of the foliation and development of strain slip cleavage and perhaps the formation of a new garnet and porphyroblasts of muscovite and biotite along the axial planes of crinkles.

The F₄ folding appears to have produced no metamorphic changes except partial twisting and refolding as described earlier (page 34).
Chapter -IV

PETROGRAPHY OF THE MINERALIZED ZONE AND WALL ROCK ALTERATION

In the area under investigation the host rocks are well foliated and folded micaceous schists. Approaching the sulphide lode from the fresh country rock side, the host rocks gradually lose schistosity and become hornfelsic. Phlogopite starts appearing without any apparent orientation and appears to be the sole representative of the mica group in the sulphide zone. Diffusion is noted to affect the country rock with progressive intensity towards the sulphide lode. The original textures are destroyed and at places amorphous mineral assemblages (? clay minerals) mark intense diffusion. This is due to the influx of hot hydrothermal fluids, bearing metals and other volatile matter. In the sulphide zone sericitisation and epidotisation are both very intense and the rock is completely recrystallised resulting in the production of hornfels. Away from the sulphide zone, the diffusion is associated with chloritisation, tourmalination, epidotisation, sericitisation and emplacement of fine-grained opaques. Still further, the alteration of the country rocks is restricted along the micaceous bands of schists and fractures.

PETROGRAPHY

In the fresh country rocks quartz occurs as almost
equidimensional, polygonal and irregular grains and becomes
inequigranular with extremely corroded, irregular and lobate
boundaries as the sulphide zone is approached (Pl. 2, Fig. 3).
This feature can be considered characteristic of recrystallisation.
Crystallisation of quartz is quite common everywhere. Remnant
quartz grains of large size occur as porphyroblasts, some of these
show strained extinction (Pl. 2, Fig. 3). In the altered zone
quartz is partly or completely diffused and recrystallised due
to the influx of hot metal bearing hydrothermal fluid.

Biotite is represented by both Mg and Fe end members.
The Mg end members (Phlogopite - estonite group) occur as
porphyroblasts and are more common towards the sulphide zone.
Near the sulphide zone the phlogopite becomes colourless while
further away it has a prominent brown colour probably due to
greater iron content. The Fe end members (amphibole-siderophyllite
group) generally occur as groundmass minerals.

Chlorite occurs as lamellae, tabular or basal flakes
and as fibrous radiating aggregates, intimately intergrown
with mica. Sometimes chlorite shows gradational contacts with
biotite. The alteration of biotite to chlorite is presumably
results in loss of potassium and silica and possibly some
magnesium, and addition of water (Schom and White, 1965, p. 1416).
Chlorite generally coats the quartz grains and other groundmass
minerals (Pl. 3, Fig. 1) in the diffused portion of the rock. Due to this peculiar nature of occurrence it appears to be an introduced mineral as a result of chloritisation.

Lamellar flaky and tabular crystals of muscovite occurs as fatty, flaky foliates within the micaceous bands and as porphyroblasts with random orientation. Muscovite also occurs as an alteration product of feldspars.

Sericite occurs as small colourless flakes and is mostly restricted to diffused areas. Introduced as a result of sericitisation, it increases in quantity towards the sulphide zone.

Almandine garnet is noted at every stage of the rock alteration. Three generations of garnet can be distinguished:

a) Large round crystals with inclusions of quartz, tourmaline, biotite and opaques, showing rotation and highly altered to chlorite, sericite, biotite and epidote (Pl. 3, Fig. 2).

b) Large skeletal fish-net crystals, irregular in shape and with inclusions of quartz. This garnet seems to be unaffected by alteration (Pl. 3, Fig. 3).

c) Small polygonal, euhedral crystals, free of inclusions. This type is generally unaltered except in the vicinity of sulphide zone where minor alteration to chlorite is noted.
Tourmaline is a common accessory mineral in the schists. Schorlomite occurs as stubby, broken, often corroded, prismatic crystals and fragments. Dravite occurs as small euhedral, prismatic crystals, confined to the diffused zones and is introduced due to tourmalinisation.

Epidote and clinozoisite occur as prismatic crystals in columnar aggregates. Epidote occurs as granular aggregates and is a product of saussuritisation. Clinozoisite, besides occurring in the groundmass as well, occurs as aggregates of small prismatic crystals within the diffused zone and appears to have been introduced as a result of epidotisation.

Clear, irregular patches of albite occur generally replacing the earlier constituents within the rock. The albite is a product of metasomatism, generally untwinned, though in many cases insipient polystylistic twinning has been noticed.

Plagioclase is rather rare in occurrence. When present, it is either completely saussuritised or highly altered to fine clayey sericitic mass and granular epidotes (Pl. 4, Fig.1). In the sulphide zone there are some fresh plagioclases generally filling the interstitial space between quartz, phlogopite and epidote.

Orthoclase occurs as highly cloudy grains in the
groundmass and also as porphyroblasts near the sulphide zone. In the sulphide zone proper, fresher orthoclase occurs in the groundmass in small quantity.

Pyrophyllite is comparatively rare and occurs as aggregates of very fine-grained foliated lamellae. Hornblende occurs very locally in the neighbourhood of the sulphide lode. Actinolite occurs as large acicular crystals without any orientation and intimately associated with phlogopite, quartz, epidote and chlorite (Pl. 4, Fig. 2). It is fairly abundant in the sulphide zone and the zone immediately adjoining it.

ALTERATION

Surface Expression of Alteration:

The Physical changes brought in the Schistose rocks as a result of hydrothermal alteration are extremely varied. The altered rocks are generally more porous and permeable than fresh rocks. Changes in colour are common in the alteration zone where the rocks are commonly bleached as compared with the unaltered equivalents, due to the abundance of light coloured minerals such as sericite, clay minerals, and quartz. Further, the colour changes are emphasized by the oxidation of ferrous minerals to limonite in the zone of alteration. At
places, a remarkable change of a dark grey rock (biotite-muscovite-quartz schist) altering to a green one is noticed as chlorite is developed. This in turn becomes greyish white as chlorite is replaced by sericite. This is assumed to be a progressive change, described by Kinlayson, (1929), for the Hauraki Goldfields, New Zealand, and by Anderson (1946) along mineralised fault zones in the Clark Fork district, Idaho.

Plagioclase feldspars are most susceptible to sericitic alteration (Moore and Nash, 1974, p. 437). Replacement of feldspar phenocrysts by clay minerals, sericite, pyrophyllite (?) etc. has resulted in an extreme diminution in grain size. Such alteration of plagioclase feldspars results in a release of silica, calcium and some sodium (Schoen and White, 1965, p. 1410). Quartz that has replaced earlier minerals is commonly cryptocrystalline. The original textures are completely destroyed in the sulphide zone. Fracturing and brecciation is conspicuous in the schists and becomes intense in the sulphide zone, thus providing the necessary permeability required for the high degree of hydrothermal alteration.

Mineralogical Changes:

It is widely accepted that the minerals formed during hydrothermal processes depend on four main factors (Schwartz, 1959): (1) composition of the original minerals and rocks, (2) Composition
of the fluid, (3) temperature, and (4) pressure. A fifth factor, time, is doubtless of some importance because it is evident that equilibrium is not commonly reached during hydrothermal processes and the stage at which action ceases is therefore important.

The feldspar, which form a minor constituent of the country rock, are altered to an aggregate of sericite, clay minerals and granular epidote. The alteration of feldspar to sericite has released some silica which is generally difficult to identify due to its fine grain size (Schwartz, op. cit.) Biotite has generally been altered to chlorite since it is one of the first minerals to be attacked and occurs as an alteration product of gamet. Primary quartz, very near to the sulphide lode, has recrystallised into larger and subhedral grains. A little quartz has actually been introduced into the country rock by hydrothermal activity.

On the basis of microscopic observation, the source of secondary silica in the altered rock can be attributed to (1) the breakdown of silicious minerals like feldspars, (2) leaching of the host rocks through which the solutions have passed, and (3) magmatic or other deep seated sources, from which the hydrothermal fluids originated.

Sericitic alteration is the most abundant, widespread
and significant, and does not seem to bear relationship with structural elements. Large areas of sacritic alteration are not readily related to specific structures (Moore and Nash, 1974). Sacrite replaces plagioclases in the early stages of wall rock alteration whence it is emplaced as small flakes (Pl. 4, Fig. 3). In the sulphide zone the hydrothermal alteration imparts a secondary foliation across the traces of the original schistosity.

Epidote, zoisite and clinozoisite are common in the altered rock but are rarely abundant, except epidote which is fairly widespread in the immediate neighbourhood of the sulphide lode.

Clear patches of albite are emplaced within the country rock replacing the original constituents. Albitisation is perhaps the result of concentration of sodium liberated by the breakdown of more calcio plagioclases (Meyer and Hemley, 1967, p. 178). Some crystals of tourmaline are widespread in the altered zone.

Chloritisation is prominent in the early stages of alteration. Pale green, non-pleochroic chlorite can be distinguished in and around diffused areas and is a result of chloritisation of the country rock. Chloritisation may have resulted due to large additions of magnesium and/or
iron to the alteration zone (Hayer and Hamley, op.cit, p.177)

Pyrophyllite closely resembles sericite in macroscopic and microscopic appearance and is probably present more often than identified. Nevertheless, it is a comparatively rare mineral and occurs as fine-grained foliated lemmas, generally associated with other micas, and appears to be the hydrothermal alteration product of feldspars.

ALTERATION-MINERALISATION ZONING

Effects of wall rock alteration that are visible in the field ordinarily extend only a few yards from the veins. Comprehensive investigation of the alteration has not been attempted, but a series of samples collected from the exploratory adit in Barigon show indication of the type and degree of change imposed on the host rocks.

Rock alteration in Askote area may be divided into five types which are distinguished from each other on the basis of mineralogy and distribution. These types of alteration have been designated stages 1 to 5, in the belief that they can be arranged in chronological order. Stage 1 represents the minor retrograde metamorphic effects observed throughout the area. The last four stages are believed to represent a continuous period of alteration due to the
invasion of metal bearing hydrothermal fluid. Stage 5 is represented by the sulphide zone proper while stages 2, 3 and 4 are arbitrary, in that they actually grade into each other.

Stage-1: This type of alteration is very widespread and represents a retrogressive metamorphic assemblage. At this stage, probably due to the effects of dynamic metamorphism and partly due to hydrothermal activity, the extensive alteration of post and syn-tectonic almandine garnet to chlorite, muscovitisation of calcic plagioclase and chloritisation of biotite took place. The rocks in this zone are well foliated schists showing well formed segregation bandings of micaceous and silicious components. Albition of the rocks is fair, probably representing the beginning of hydrothermal activity in the area. Very minor diffusion can be noted in a few instances.

Stage-2: The rocks are still well developed schists. Albitionisation and chloritisation are fair. Influx of hydrothermal fluids along micaceous bands and fractures has produced diffusion with partial destruction of schistosity. Albite, chlorite, tourmaline, clinocohrnite, sericite and silica have been conspicuously introduced into the host rocks by the hydrothermal fluids.
Stage-3: The rocks are highly diffused causing a high degree of destruction of schistosity. Minor hornfelsization is evident which is sometimes patchy and sometimes alternating with schistose bands. Mineral assemblage introduced by the hydrothermal fluids includes albite, chlorite, tourmaline, clinopyroxene, sericite, silica and phlogopite.

Stage-4: There has been thorough hornfelsization with the result that the schistosity is almost completely destroyed. Only a few scattered schistose relics can be seen. Quartz crystals are largely recrystallized. Large crystals of orthoclase and plagioclase develop and are rendered cloudy due to alteration along grain boundaries, cleavage planes and twin planes. Sericite and clay minerals are very abundant. Silicification is a little more important than in stage 2 and 3, phlogopite has increased remarkably in quantity and occurs as porphyroblasts.

Stage-5: This is represented by the sulphide zone proper which is occupied by a hornfelsic rock. There is no trace of schistosity. The texture is hornfelsic. Quartz is thoroughly recrystallized and has been considerably added to the country rock by the hydrothermal fluids. The hornfelsic texture is indicative of contact metamorphism. The mineral assemblage introduced by the hydrothermal fluids includes phlogopite, astinol epidote, quartz and minor albite.
Chapter - V

SULPHIDE MINERALISATION AND PARAGENESIS

MINERALISATION

Sulphide mineralisation in Askote area is restricted to a narrow zone occupied by the sheared schistose rocks occurring between granite gneisses on the southwestern side and amphibolites with schistose quartzites on the northeastern side. The schists are occasionally interbedded with biotite bearing augen gneiss and have most probably been affected by en-echelon shear zones parallel to the schistosity ($S_3$) and major structural trends of the tectonic province. Trends of the mineralised zone are almost parallel to the schistosity ($S_2$) suggesting thereby a distinct structural control of the sulphide ore bodies. There is no characteristic gossan zone exposed anywhere and this may be due to a higher rate of erosion in relation to the weathering in the immature topography of this terrain. The formation of a secondary supergene sulphide enrichment zone is hence very unlikely.

Sulphide minerals occur as veins, stringers, small pockets, and as disseminations within quartz-sericite-chlorite schists, containing minor biotite and garnet. The mineralisation has been brought about by two distinct phases, from the
same parent solution, separated by a period of very slow deposition rather than by a discontinuity. The first phase of deposition immediately followed a fracturing of the rocks—the pre-mineral fracturing (Table 2). This is considered necessary on the assumption that some channels were required for the introduction of the mineralising solutions. The first intra-mineral fracturing is presumed on similar grounds, in that the first intra-mineral fracturing, after the deposition of first generation sphalerite, galena, and chalcopyrite, reactivated old channels resulting in profuse deposition of the second generation minerals. During the second phase of deposition there was a second intra-mineral fracturing immediately before the introduction of second generation arsenopyrite. The replacement of second generation sphalerite by second generation galena along fracture planes is evidence of this fracturing (Pl. 5, Fig. 1). A third and less prominent fracturing is noteworthy just before the last chalcopyrite was deposited. This fracturing is most conspicuous in later quartz where the fractures are filled by bornite, chalcoite and chalcopyrite (Pl. 6, Fig. 3). The post mineral fracturing, characterised by minerals unaltered along such fractures, is most conspicuous in brittle minerals like pyrite and arsenopyrite (p. 5, Fig. 2).
There is no noteworthy difference in the mineral assemblage of the two phases and it is assumed that the channels through which the mineralising solutions moved were reactivated during the first intra-mineral fracturing so that the deposition which had started before the fracturing was carried to completion at a faster rate after this fracturing.

**CRITERIA FOR DETERMINING PARAGENESIS**

The criteria that are used in determining age similarity or diversity should be mentioned before dealing with the paragenetic relationships of ore minerals. Of the various criteria suggested by Bastin et al. (1931), only a few have been considered to be sufficiently diagnostic to be relied upon. Crystal boundaries have been considered in places as indicating successive mineral deposition. As suggested by Bastin (1941) this involves the assumption that a crystal with boundaries convex outwards is older than the surrounding minerals. Conversely a crystal with boundaries convex inwards is considered to be younger than the enclosing mineral. This can not be applied in case of exsolved minerals e.g. sphalerite stars in chalcopyrite (Pl. 7, Fig. 3) and spindles of pyrrhotite within cubanite (Pl. 8, Fig. 3) where the two minerals are considered to have been present simultaneously in the mineralising solutions. This crystal boundary relationship has not been used indiscriminately and the force of crystallisation has also been considered, for instance, cubehedral pyrite may develop either
simultaneously with, or later than surrounding quartz or chalcopyrite, in which case this principle would give invalid results. It has, however, been considered where supported by other replacement phenomenon e.g. pitting and corrosion. Depositional features in vugs and fractures, and veinlets with non-matching walls, where replacement of older minerals was clearly visible, have been used with confidence in determining successive deposition.

As suggested by Thomas (1949), "island to island" and "Island to mainland" relationship has been used as a supplementary evidence. This concept assumes isolated inclusions showing parallel orientation with each other and with a nearby parent mass, to be older than the surrounding minerals. It is very difficult to make direct determinations of simultaneous deposition, and the most reliable criterion is the occurrence of one mineral as exsolutions in the other. The occurrence of two or more minerals as adjacent segments of a veinlet filling has also been considered, with the realisation that this condition could also result from later replacements. Lack of data showing age diversity and lack of replacement between two minerals has also been considered to indicate simultaneity, which would mean that both minerals were available in the mineralising solutions
**TABLE 2**

**PARAGENESIS OF SULPHIDE MINERALS**

Vertical lines represent periods of fracturing, horizontal spacing indicates relative positions of minerals, not time units. Dashed lines indicate minor significance in occurrence.

<table>
<thead>
<tr>
<th>QUARTZ</th>
<th>ARSENYPRITE</th>
<th>SPHALERITE</th>
<th>GALENA</th>
<th>CHALCOPYRITE</th>
<th>MARCASITE</th>
<th>CUBANITE</th>
<th>PYRITE</th>
<th>PYRRHOTITE</th>
<th>BISMUTH</th>
<th>BORNITE</th>
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at the same time.

No single criterion has been taken to be indicative of a particular condition. Conclusions have been drawn only where several criteria could be applied and hence the accuracy of determinations is improved.

PARAGENESIS

Quartz is perhaps the first mineral which deposited from the mineralising solutions. Sphalerite began to be deposited almost immediately after early quartz. Two generations of sphalerite can be conclusively established, the first generation sphalerite occurs in minor amounts and is replaced by almost all other minerals, while the second generation sphalerite is the most abundant ore mineral in many polished sections, and apparently started depositing immediately after the first intra-mineral fracturing. Islands of first generation sphalerite can be seen in all other minerals including later quartz. The second generation sphalerite is replaced by second generation galena, chalcopyrite, pyrite, marcasite, cubanite and pyrrhotite. There is apparently no difference between the first and second generation sphalerite which may be explained best by the assumption that there was no difference in the nature of zinc containing solutions throughout the period of deposition.
Inclusions of first generation galena (Pl. 5, Fig. 3) and chalcopyrite (Pl. 6, Fig. 1) are abundant in second generation sphalerite. These vary from microscopic specks to blebs than can be seen with the naked eye. There is no uniformity in the orientation of these blebs which are more often scattered at random. These features are not indicative of exsolution and the presence of galena and chalcopyrite is therefore attributed to the effects of replacement.

Galena follows sphalerite in order of introduction. The first generation galena veins, corrodes and rounds crystals of early sphalerite, and is in turn replaced by arsenopyrite and sphalerite of the second generation, and chalcopyrite of both first and second generations. The second generation galena is seen to be profusely corroding sphalerite of first and second generation, arsenopyrite and chalcopyrite of first generation.

Blebs of chalcopyrite in second generation sphalerite are interpreted as replacement features, and the chalcopyrite is considered to be of the first generation, occasionally seen to be replacing first generation galena and sphalerite. Second generation chalcopyrite occurs as replacements along grain boundaries of sphalerite, galena, and in veins cutting
these and earlier minerals. Second generation chalcopyrite replaces cubanite along grain boundaries (Pl. 6, Fig. 2), cleavage planes (Pl. 6, Fig. 3) and also occurs contemporaneously with it (Pl. 7, Fig. 1).

Both generations of chalcopyrite are untwinned and show very weak anisotropy. Excellent exsolution lamellae of cubanite (p. 7, Fig. 2), stars of sphalerite (Pl. 7, Fig. 3) and spindles of pyrrhotite (Pl. 6, Fig. 1) are seen in second generation chalcopyrite.

Arsenopyrite is intimately associated with sphalerite, galena, chalcopyrite and gangue minerals and was introduced after the early quartz began to be deposited and then again before cubanite and second generation chalcopyrite. Cataclastic texture is very commonly observed in arsenopyrite, which is due to its early crystallisation and brittleness. In the first generation arsenopyrite only quartz occurs as inclusions while the second generation replaces sphalerite, galena, chalcopyrite and bornite. The introduction of second generation arsenopyrite closely followed the second intra-mineral fracturing.

Marcasite replaces galena and chalcopyrite of the first generation and at places it shows mutual boundary relationships with chalcopyrite. Development of marcasite
may be placed simultaneously to later than chalcopyrite of first generation.

Pyrite seems to have been deposited simultaneously with second generation galena but before cubanite. It typically developed crystal forms, and euhedral to subhedral intergrowths of quartz and pyrite are common. Second generation chalcopyrite and cubanite are seen to replace pyrite (Pl. 6, Fig. 3).

Crystallographic intergrowths of cubanite and second generation chalcopyrite indicate that the minerals are simultaneous in origin, but the replacement of cubanite along grain boundaries and cleavage planes (Pl. 6, Fig. 2) suggests that the deposition of cubanite ceased earlier than chalcopyrite which started replacing it. Exsolution lamellae of cubanite are noted in chalcopyrite, while that of pyrrhotite oriented parallel to each other, in cubanite. The individual lamellae have various thicknesses, often pinching and swelling (pl. 6, Fig. 2), and can be interpreted as exsolution lamellae. Cubanite rarely replaces pyrrhotite and the two minerals were deposited more or less simultaneously.

Bismuth was introduced after the first quartz began to be deposited. Its replacement by the first generation
galena (Pl. 5, Fig. 3) makes it one of the earliest ore minerals to be deposited. It was, however, again added to the mineralising solutions immediately after the third intra-mineral fracturing and is seen to be replacing along fractures in later introduced quartz (Pl. 6, Fig. 3) and being in turn replaced by second generation galena and chalcopyrite.

Presence of chalcocite and bornite are noticed as traces. Bornite occurs as thin veins within second generation chalcopyrite and chalcocite replaces both chalcopyrite and bornite as thin veins. The paragenetic positions are summarised in Table 2.
Chapter VI

DISCUSSIONS

Taylor (1973), based on studies of oxygen isotopes, considers it safe to conclude that all metallic deposits that are associated with intense hydrothermal alteration of the country rock, involving propylitisation, kaolinisation, sericitisation, silicification and/or albitisation, are formed from hydrothermal solutions that were composed of heated meteoric ground waters. The study of the petrography of the mineralised horizon at Askote proves that the area was subjected to polymetamorphism and hydrothermal wall rock alteration of propylitic (including albitisation and chloritisation), sericitic and potassium silicate types (see Chapter IV). The sequence of wall rock alteration suggests that silica and potash rich solutions accompanying sulphide mineralisation immediately followed propylitisation and magnesia metasomatism. The apparently lenticular sulphide deposits have been formed in a favourable structural locale in a chemically favourable host rock.

In Askote area, the nearness to metabasic amphibolite and granite gneiss suggests at least two periods of magmatism to have affected the rock types, but the restriction of the mineralisation to schists and large scale potassic alteration...
and silicification suggests a possible genetic relationship with the granitic rock.

Based on mineralogical and textural characters, Ghosh (1976) and Bhattacharya (1976) suggest that the mineralisation at Askote is syntectonic. Hydrothermal activity in the crystalline sheets of the Himalaya appears to be very widespread. Hair and Nithal (1976, p. 294) suggest a close proximity of mineralisation with the nappes zones in the Himalaya. Ashgirai (1977, p. 16) and Tiwari and Gaur (1977, p. 244) favour the concept that large deposits of magnetogenic type are usually located along the root zones of the crystalline nappes in the Lesser Himalaya.

The mineralisation of base metals in the Daling Series, Rangpo, correlatable with the crystallines of the Lesser Kumaon Himalaya are also considered to be epigenetic hydrothermal by Das Gupta (1968), and Mukherjee & Dhruva Rao (1974). Some workers (Ghosh, 1968; Sarkar and Banerjee, 1976), however, consider these deposits as contemporaneous with the deposition-diagenesis of the containing sediments. This concept is primarily based on the fact that no significant alteration of the wall rock is noticed.
Considering evidences from the field and laboratory investigations one fact becomes predominant, and that is, the mineralisation at Askote is epigenetic hydrothermal, and as suggested by earlier workers, syn-tectonic. Ghosh (1976) suggests that the hydrothermal activity took place after the $F_1$- folding but before the $F_2$- folding (see Chapter III). Accepting this fact we must look for the source of the hydrothermal fluids and its metal content in igneous activity in the area.

Granitisation has been shown to be an important process in altering schists to gneisses and, perhaps in extreme cases, gneisses to granite, but it is a significant fact that some examples of granitisation are conspicuously barren of ore deposits. The granitic rocks of Kumaon Himalaya have attracted considerable attention from a number of previous workers. Heim and Gansser (1939), Mathiyal (1941), Merh (1969), Powar (1972) and Agarwal et al. (1973) have regarded the granites of Almora to be of igneous origin, intrusive into the metasediments. On the other hand, the recent workers have invoked granitisation to explain the origin of these rocks. Gansser (1964) and Sarkar et al. (1965) have considered the Almora granites as the products of syngenetic granitisation. Similar views have been expressed by Merh and Vashi (1965),

Several investigators (Jensen, 1959; Jahans, 1955; Ramberg, 1948; and Schreyer et al., in Krauskopf, 1967, p. 22) have suggested that the process of regeneration or mobilisation of the more volatile constituents from rocks undergoing, for example, regional metamorphism may be capable of producing hydrothermal solutions. This process corresponds with Smirnov's (1968, p. 363) intermediate stage of geosynclinal cycle. Goodspeed (1952) supports the view that mineral bearing fluids may be derived from the breakdown of hydrous minerals during granitisation, when clay minerals alter to feldspars releasing the contained water, which can be as such as 16 percent. Under favourable circumstances, connate and meteoric waters enclosed in rocks may be set in motion and made chemically reactive by heat and pressure accompanying regional metamorphism (Shand, 1943). These metamorphic waters are regarded by many geologists as active ore carriers. During granitisation and its associated processes, the volatile and mobile constituents are activated (Parks and McDiarmid, 1964), and migrate towards cooler and,
in general, less deformed regions. Accompanying tectonic processes may provide avenues along which the metals and mineralising fluids travel producing a hydrothermal system, and are concentrated in areas of reduced pressure and/or temperature, or in areas of reactive wall rock. The composition of the solutions may differ only little, if at all, from what is presumed to be the composition of magmatic hydrothermal solutions. Magmatic hydrothermal solutions presumably become more and more concentrated and thereby homogenised in the latest crystallising phase of an intrusive igneous body. Metamorphic hydrothermal solution, on the other hand, might be derived from heterogeneous sources, but may undergo extensive intermingling before any locale of deposition or mineralisation is reached.

The consideration of the nearness of granitic gneisses to the mineralised zone at Barigaon and the large scale potassic alteration and silicification of the schists warrants a genetic relationship of the mineralisation with the granitic gneisses. The gradational contact of the granitic gneisses and the schists of the Askote Crystallines might be considered a positive evidence as to the anatetic origin of the granitic gneisses as suggested by many workers (see page 59). It is
merely a suggestion that the Askote mineralisation be classified as a metamorphic hydrothermal deposit and the homogeneity of the solutions be attributed to their being derived from one and the same rock — the Precambrian Crystallines. This process of mobilising solutions from the underlying rocks, however, might have been adequate to transport sufficient minerals upwards to the favourable structural and stratigraphic sites.

The sulphide zone is marked by hornfelsed schists, the development of which is indicative of contact metamorphism. Since no intrusive is located in the vicinity of the mineralised zone, it may be presumed that the hot hydrothermal fluids, which were above a temperature of 250°C as discussed later, acted as an intrusive body into the schists. These fluids are responsible for ore deposition and imparting a hornfels-like texture to the rocks of the sulphide zone. The presence of albite, epidote and actinolite suggest that the schists have undergone contact metamorphism at moderate temperature and high pressure to the albite-epidote-amphibolite facies (Turner & Verhoogen, 1951, p. 343).

The textural characteristics of the ore minerals contribute significantly towards the genetic interpretations
of the base metal mineralisation in Askote area. The
transformation of cubanite to chalcopyrite along grain
boundaries can possibly be attributed to the induction of
sulphur along grain boundaries, cleavage planes, etc. of
the earlier crystallised cubanite, during the latter part of
hydrothermal activity. This hypothesis is supported by the
fact that the boundary between cubanite and chalcopyrite
is not sharp, as is to be expected in the case of replacements,
but is gradational (Pl. 6, Fig. 2).

At high temperature much FeS is soluble in CuFeS₂,
producing chalcopyrrhotite, which, upon cooling, breaks up
as follows: ordinary chalcopyrite + Cubanite and chalcopyrite+
pyrrhotite. The unmixing with separation of cubanite occurs
at 250-300°C, with exsolved cubanite forming excellent
lamellae parallel to (111), provided the cooling is not too
rapid (Randohr, 1969). The existence of cubanite as exsolution
lamellae in chalcopyrite (Pl. 7, Fig. 2) shows thus in any
case that originally the temperature of formation must have
been over 250°C. Pyrrhotite is often present as spindles in
chalcopyrite (Pl. 8, Fig. 1). According to Stevenson (1951),
such pyrrhotite is an exsolution product in high temperature
chalcopyrite.
The presence of sphalerite stars in chalcopyrite (Pl. 7, Fig. 3) are generally to be interpreted as products of exsolution. Sphalerite stars are very much restricted to high temperature deposits (Ramdahr, 1969). At high temperature pyrrhotite can dissolve some CuFeS₂ and often exsolves this content not as chalcopyrite but as cubanite (Pl. 8, Fig. 2).

The textural characteristics permit that the Askota mineralisation may safely be classified as a mesothermal deposit formed at moderate temperatures and pressures. The presence of tourmaline in the zone of wall rock alteration, however, creates some doubt. As pointed out by Lindgren (1933, in Parks, & McDiarmaid, 1964, p. 290). Tourmaline being a high temperature mineral, is not supposed to be associated with mesothermal deposits. The only possible explanation for this would be that since the mesothermal zone is distinguished by both hypothermal and epithermal characteristics, the present deposit may have formed at the highest temperature of the mesothermal range, that is, roughly at 300° C. The epigenetic syntectonic mineralisation at Askota is thus mesothermal in nature.

Whatever be the origin of the granitic rocks at Askota, there is little doubt as to a genetic relationship
between them and the mineralisation of base metals. As suggested by Ghosh (1976), the ore body at Askote was emplaced at the time the crystallines were folded isoclinaly. This isoclinal folding synchronises remarkably well with regional metamorphism and granitisation, Panda et al. (1963) and Gaikwad (1975) assign a Tertiary age to the granitic rocks of Kumaon, while Sarkar et al. (1965), a Lower Oligocene age. Bhanot et al. (1977) have based their interpretations on whole rock Rb-Sr dating and give a Precambrian age.

More scientific investigations are required, particularly geochemical, to conclusively establish the origin of the granitic rocks and their relationship with the schists and the mineralisation of base metals. Isotopic age determinations of the galana samples and their age relationship with other gangue minerals (particularly biotite) and fission track dating of some minerals from the granites (muscovite and plagioclases) will throw light on the absolute age of mineralisation in relation to other geological events. Statistical approach to studying the structures will help delineate the various shear planes with respect to the direction and magnitude of displacement of the ore body and its present disposition.
Chapter -VII

SUMMARY AND CONCLUSIONS

The sulphide mineralisation at Askote is confined to a narrow zone in the Precambrian schistose rocks of the Crystalline Group, a northern outlier of the Almora-Dudhatoli thrust sheet. The zone of wall rock alteration surrounding the sulphide lode indicates that the ore body is lenticular in shape. The metamorphic rocks comprising gneisses and schists occur in the core of a NW- ESE trending doubly plunging synform which forms an overturned sequence. The Askote Crystallines have been tightly folded on a NW-ESE axis with the southern limb dipping gently towards north while the northern limb steeply inclined, and in the area of the present investigation, overturned (Fig. 3) so that the reversed sequence again becomes normal. The gneisses in the core of the syncline are surrounded successively by schists, amphibolites, quartzites and calcareous rocks. The schists are separated from the underlying amphibolites and quartzites of Berinag Formation by a thrust plane. The amphibolites are genetically related to the thrusting event of the Askote Crystallines, and the thrust plane is placed above the amphibolites.

The schists were subjected to metamorphism both prior and subsequent to thrusting accompanying polyphase deformation.
Based on structural mapping of the area four major structural events are recognised to have contributed to the structural evolution of the crystallines. The original pelitic sediments were subjected to load metamorphism resulting in the development of bending. The first tectonic event synchronised with the regional metamorphism and folded the crystallines into numerous isoclinal folds. The second event was a continuation of the first and resulted in a major dislocation along which the crystallines were pushed over the younger sedimentaries of the Berinag Formation. During the third event the Askote Klippe was folded into a synform on a NW - SE axis together with the rocks of the Berinag Formation. The fourth event resulted in the partial twisting and refolding of the syncline on a NNE - SSW axis to produce a double plunge. The crystallines were sheared during this event, with the shear planes trending NNE - SSW.

The crystallines show a gradual decrease in metamorphism towards the thrust, while the underlying rocks an upward increase in metamorphism. The sequence of metamorphic episodes to have affected the crystallines is marked by both progressive and retrogressive phases. The regional metamorphism is responsible for the development of garnetiferous mica schist. The isoclinal folding and resultant granitisation of the schists very closely followed the regional metamorphism.
The retrograde metamorphism of the schists was initiated in the form of chloritisation by the hydrothermal fluid generated as a result of granitisation and was later carried to completion by the overthrusting of the crystallines to produce sericite-chlorite phyllonite.

Widespread wall rock alteration in the form of propylitisation, sericitisation, chloritisation, biotitisation (formation of phlogopite), potassium silicate alteration and silicification preceded and accompanied the localisation of the epigenetic sulphide deposits.

The hydrothermal solutions responsible for the mineralisation and wall rock alteration bear their origin to the breakdown of the hydrous minerals during granitisation of the schists, when the volatile and mobile constituents were activated and migrated towards cooler and less deformed regions. The accompanying tectonic processes provided channels in the form of $S_2$ planes and fractures, through which the fluids travelled and laid down their metal content in areas of reduced temperature and pressure in the receptive wall rock. There has been a distinct structural control for mineralisation, in that the sulphide lode has been emplaced along the schistosity planes $S_2$, and is lenticular in shape.
The hydrothermal fluids acted as an intrusive body producing extensive wall rock alteration and bornfelsisation of the sulphide zone. Mineralisation was brought about in two different phases separated by a period of very slow deposition rather than by a disc ontinuity. The period of slow deposition is marked by a prominent fracturing which is believed to have reactivated old channels through which the ore bearing solutions were fed. The entire period of mineralisation was accompanied by moderate deformation which manifests itself in the form of intermittent fracturing of the ore and gangue minerals.

Principal sulphide ore minerals in paragenetic sequence are arsenopyrite, sphalerite, galena, chalcopyrite, cubanite, marcasite, pyrite, pyrrhotite, bismuth bornite and chalcocite. Two generations of arsenopyrite, sphalerite, galena and chalcopyrite have been recognised. The first generation minerals crystallised before the first intra-mineral fracturing and the second generation minerals afterwards.

From the mineralogical and textural considerations it has been interpreted that the original temperature of formation of the ore minerals must have been around 300°C and the mineralisation should be regarded mesothermal.
The metamorphic effects observed in the ores at Askote are mild. The presence of various exsolution intergrowths indicates that there has been no significant recrystallisation of the ore minerals (Edwards, 1965, p. 41). An unusual example of movements between mineralisation or between the intervals of repeated mineralisation affecting the ores is found. Brecciation of brittle minerals bears evidence to these movements. It can safely be concluded that the mesothermal epigenetic syntectonic ores at Askote have undergone very little metamorphic changes.
EXPLANATION OF PLATES

Plate : 1

Figure 1: Alteration of garnet (dark grey porphyroblast) to biotite and chlorite indicating retrogressive metamorphism. Thin section, Polarised light, 100 X.

Figure 2: S₂ planes parallel to S₁ except at the fold closures indicating an isoclinal folding of the schists. Thin section, polarised light, 30 X.

Figure 3: Crenulation cleavages (S₃) in sericite-chlorite schist on earlier formed cleavages due to puckering on S₂. Thin section, Polarised light, 30 X.

Plate : 2

Figure 1: Shearing in the Schistose rocks near Barigaoon as seen under the microscope. The direction of movement can be easily deciphered. Thin section, Polarised light, 30 X.

Figure 2: Inequigranular grains of quartz in the Schists adjoining the sulphide zone with extremely corroded, irregular and lobate boundaries characteristic of recrystallisation. Thin section, + nicols, 35 X.
Figure 3: Large quartz porphyroblasts that have survived granulation. These porphyroblasts show strained extinction. Thin section, + nicols, 35 X.

Plate 3:

Figure 1: Chlorite flakes overlapping quartz and other groundmass minerals indicate that chlorite is an introduced mineral. Note that the chlorite also forms sheaths around quartz grains. Thin section, polarised light, 35 X.

Figure 2: Garnet showing rotation and subsequent alteration to biotite and chlorite. The original schistosity still visible in biotite makes an angle with the foliation. Thin section, polarised light, 25 X.

Figure 3: Large skeletal fish-net garnet irregular in shape with inclusions of quartz. Thin section, polarised light, 30 X.

Plate 4:

Figure 2: Large grains of plagioclase highly altered to fine clayey sericitic mass. Thin section, + nicols, 30 X.
Figure 2: Long acicular prismatic crystals of actinolite intimately associated with phlogopite (small-elongate crystals), quartz, chlorite, and sulphide minerals (opaque). Thin Section, polarised light, 30 X.

Figure 3: Plagioclase showing twinning, appears sericitised along grain boundaries, cleavages, twin planes and partings. Thin Section, + nicols, 80 X.

Plate 5:

Figure 1: Galena replacing second generating sphalerite along fractures — evidence of second intra-mineral fracturing. Polished Section, polarised light, 225 X.

Figure 2: Post-mineral Fracturing in arsenopyrite. Note that there is no replacement of arsenopyrite along the fractures. Polished Section, polarised light, 120 X.

Figure 3: Inclusion of first generation galena (light grey) in second generation sphalerite (dark grey). The brilliant white mineral in galena is bismuth, apparently being replaced by galena. Polished section, polarised light, 350 X, oil imm.
Plate 6:

Figure 1: Inclusions of first generation chalcopyrite (light grey) in second generation sphalerite (dark grey). Note that the chalcopyrite contains inclusions of first generation sphalerite.
Polished section, polarised light, 250 X.

Figure 2: Chalcopyrite (white) replacing cubanite (grey) along its contact with the gangue (Black).
Polished section, + nicols, 350 X, oil imm.

Figure 3: Chalcopyrite (light grey) replacing cubanite (dark grey) along cleavage planes of the latter. Both chalcopyrite and cubanite replacing pyrite (white) along grain boundaries.
Polished section, + nicols, 350 X, oil imm.

Plate 7:

Figure 1: Chalcopyrite (white) replacing cubanite (grey) along grain boundaries and cleavage planes. Note that chalcopyrite shows post mineral fractures along which there has been no replacement.
Polished section, + nicols, 375 X, oil imm.

Figure 2: Exsolution lamellae of cubanite (white) within chalcopyrite (grey). Note that the exsolved cubanite is migrating along the cleavage planes towards the grain boundaries of chalcopyrite.
Polished section, + nicols, 375 X, oil imm.

Figure 3: Exsolution stars of sphalerite (dark grey) within chalcopyrite (light grey).
Polished section, polarised light, 2400 X, oil imm.

Plate 6:

Figure 1: Exsolution lamellae of pyrrhotite (grey) within chalcopyrite (light grey). Note that the pyrrhotite spindles have been bent, perhaps by later tectonic movements.
Polished section, polarised light, 350 X.

Figure 2: Exsolution lamellae of pyrrhotite (light grey) within cubanite (dark grey) oriented parallel to each other. The white mineral in the upper part is chalcopyrite.
Polished section, polarised light, 350 X.

Figure 3: Thin vein of bornite within later quartz, containing inclusions of first and second generation sphalerite, galena, and represents the third intramineral fracturing.
Polished section, polarised light, 250 X.
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