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**SULFIDE MINERALIZATION IN THE LEGA
DEMBI PRIMARY GOLD DEPOSIT, SIDAMO,
SOUTHERN ETHIOPIA**

**A Thesis presented
to
the Faculty of Science
Addis Ababa University**

**In Partial Fulfilment of the Requirements for the Degree of Master of Science
in Geology**

By
Worash Gétaneh

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ABSTRACT

Sulfides in the LDPGD are found in small quantity. The deposit is a low-sulfide-gold quartz deposit which specifically belongs to the pyrite-arsenopyrite-galena assemblage type of "Volcanic precious metals tellurides association" which is typical of volcanic to subvolcanic settings. It is hosted in volcano sedimentary succession metamorphosed to greenschist to lower amphibolite facies. It spatially coincides with the nearly N-S trending shear zone restricted to its hanging wall. Types and details of features of the enclosing rocks are discussed. Structures dominating in the area and their possible relation to the mineralizing process are described.

The ore zone and ore accommodating structures (fractures, veins, lenses, stringers and stockworks) are localized to the shear zone and generally trends parallel to major and minor structures in the area. The mineralization seems to be highly influenced by structures than lithology and other physico-chemical factors. Peculiarities related to the ore zone and ore bodies are elaborated.

Extensive metasomatic alterations are developed in the enclosing rocks. Their types, disposition and relations to the mineralized zone and mineralization process are explained.

Different ore minerals sulfides, sulfosalts, tellurides, tungstate and gold are identified. Their structure, texture, parageneses and zonal arrangement (especially the vertical one) are treated based on field and laboratory (using polished sections) studies.

Since sulfides are scarcely encountered, the treatment of geochemical data of sulfide forming metals was critical. This study was employed to systematically explain the nature of distribution of the sulfides. The most important sulfide forming elements (Pb, Zn, Cu, Ag, As, Sb, Mo, Co, Ni), their distribution (which can reasonably be explained by the presence or absence of their sulfides or sulfides of other metals which can host them) in relation to different lithologies and environments, their association in different environments and lithologies and their zonal arrangement along dip, strike and across the strike of the ore zone are explained. The distribution of the elements in relation to the distribution of the

sulfides, the significance of each element as a tracer or best associate of gold are given. The details about spatial distribution and character of gold and sulfide rich zones are treated in this work.

The mineralization is believed to be the result of regional metamorphism furnishing hydrothermal fluids which resulted in extensive metasomatic alterations and subsequent emigration, remobilization and redeposition of metals in the form of their sulfides. The reprecipitation was facilitated by the formation of low P-T regime within and around dilatant zones created by movements along the eastern shear zone.

Recommendations as what is to be done concerning further studies on the deposit and possible prospecting guides for gold in Adola area are suggested.

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1. INTRODUCTION

1.1 Previous works

The Adola area of Sidamo region has been a site of geological works and placer exploration since the late 1930s when the small placer gold occurrence was discovered and mined by prospectors in the Bedakessa valley. In the next five years the Italian geologists conducted placer exploration by sending different companies (COMINA - *Compania Mineraria Ethiopia* in particular) and groups of prospectors. But neither exploration nor reserve estimation has been made in those years.

The Adola gold potential was for the first time evaluated by T.G. Murdock (1945). J. Astrup (1948, 1950) tried to systematically explore the placers by making few traverses and geological mapping around Kibre Mengist town, within Awata-Mormora interfluve, Talew, Awata, Gayo, Adadikatu and Shakiso valleys. Similar prospecting works were carried out by N. Doorninck (1949) and G.H. Kemmer (1949-1954). Kemmer also gave an account for the Lega Dembi valleys which were reported to contain 20-30% of the whole estimated gold reserve of the Adola region. Tsegaye Desalegn and Holloway (1955) are also credited for the placer exploration of the area. In the period 1956 to 1965 the prospecting and exploration work for placer gold was getting more attention and the profound works have been performed by D. Jelenc. He evaluated the mineral potential of the Adola area and of the country as a whole. The first comprehensive effort to locate primary gold occurrences in the area and the whole Ethiopia was first made by this Yugoslav mining engineer in the same years. He studied different localities in the Adola area and estimated some of the placer reserves and proved the possibility of finding primary gold occurrences.

In 1958 Ohlschlager and P. Antolini carried out regional prospecting for minerals other than gold between Yavello and Hagere Mariam. The researchers tried to locate findings of quartz veins, with some assay values of gold, and mica pegmatites containing rutile.

Between 1960 and 1964 new placers were discovered in the region: Bentichaka (Feseha Tilahun, 1960), Lega Gora (Fiseha Tilahun and Getachew K/Mariam, 1960),

Kenticha (Sisay Dissassa, 1961), Sakaro, Bedakessa, Gayo, Shanka (Getachew K/Mariam, 1974) and others.

In 1961 - 1964 the specialists of the Ministry of Mines and Energy of Ethiopia carried out prospecting for nickel. Consequently nineteen occurrences (which were confined to serpentinite bodies) have been reported by the group led by D. Jelenc. Moreover, he was successful in finding molybdenite in Burjiji valley and chromite from Dubicha, Kenticha and Dermi Dama ultrabasic bodies. D. Levitte and G. Kent summarized the obtained data on nickel and recommended a number of targets for development.

Under the directory of UNDP (1967-71), V. Kazmin and I. Kent carried out geological mapping of Adola at scales 1:100,000 and 1:50,000 to outline the distribution of important occurrences of economic minerals. The map provided shows the results of stream sediments sampling for Cr, Cu and Zn for the central part of the area. Certain geochemical anomalies of elements have been detected which were later proved to be uneconomic.

Hamrla (1971) conducted placer prospecting and succeeded in estimating placer gold reserves in Kelecha, Burri and Shanka valleys.

A. Chater and C. Gilboy (1970-71) produced a geological map of Adola area at the scale 1:1,000,000. They described the geological features of the area, and advocated the very opinion of Holmes (1951) who proposed the region to represent the northern continuation of the Mozambique belt. These authors and V. Kazmin (1972) were the first to give the general reviews of the geology in Adola and to establish names and correlations to the three tectonostratigraphic complexes (Lower, Middle and Upper) out of which only two (Middle and Upper) were recognized in the Adola belt (EMRDC, 1985).

Companies from England ("Hunting Geology and Geophysics") and Canada ("Surveyor") have produced the photogeological maps of Adola in the years 1966-69 and 1972-74 using aerial photos at scales 1:500,000 and 1:250,000. This mapping did not provide enough and reliable information on the mineral potential of the area.

In the years between 1971 and 1978, search for primary gold and prospecting

works were done by the Ethiopian Institute of Geological Survey (EIGS). As a result of these works, gold-bearing quartz veins in Dermi Dama and Sakaro were found.

Senbeto Chewaka and Maartin J. de Wit (1981) gave a short account on the types of mineral deposits and their distribution in the Adola area and in the country as a whole. They also considered the mineralization in relation to plate tectonics model.

Woldai Gebreab (unpublished report, 1989b) treated the geological evolution of Adola and gave detailed data on composition, metamorphism and stratigraphy of the area. The author tried to show the relation of mineral occurrences to structure and lithology.

Hailu Worku and Kinetab Yifa (unpublished report, 1989) discussed the tectonic framework of Adola.

In 1989 W.H. Beraki et al. gave an account for the structure of the area and its metamorphic history.

The most important comprehensive works that revealed the economic importance of the area, the presence of both primary and placer gold and other minerals as well as the geological features of the area were conducted by Adola Mineral Exploration Project in 1979 - 81. This project covered an area of 7200 sq. km. As a result two major ore-bearing zones were identified: the Megado and Kenticha zones. The Megado zone is known for its gold mineralization and Kenticha for its rare metals. During these intensive prospecting and exploration works, the Lega Dembi deposit was discovered during follow-up work in 1979 when one of the prospecting line crossed a highly mineralized quartz vein. Since then, detailed prospecting was conducted: geological mapping at larger scale was done, types of rocks, their composition and structure and mineralization were ascertained. Subsequently, the Lega Dembi deposit was proved to be the first primary gold deposit in the Adola area and in the country. As a result of the aforesaid efforts the Lega Dembi primary gold deposit (LDPGD) is now under operation since 1990.

The different features of the rocks and grade of metamorphism were studied (EMRDC, 1985, 1987,1988).

Fiori et al (1988) described the paragenesis and possible evolution of the deposit.

1.2 Location and Accessibility

LDPGD is located in the southern Ethiopia, Sidamo region, 7 km south west of Shakiso which is 500 km from Addis Ababa, and is bounded by latitude $5^{\circ}37' - 5^{\circ}52'$ and longitude $38^{\circ}45' - 38^{\circ}55'$.

It is found within the southern slope of the Eastern Ethiopian Highlands along the transition to the Somalia Plateau. The area is near the eastern margin of the Main Ethiopian Rift.

Shakiso is accessible by 300 km asphalted and 200 km gravel roads. After Shakiso, the 7 km dirt road link Lega Dembi with Shakiso. By now unlike to other dry weather roads around Shakiso which are active only in dry seasons, this road is well accessible to vehicles. There is also air strip south-east of Shakiso which is sometimes active to air cargo. The highly vegetated character of the area surrounding Lega Dembi has limited the construction of readily usable transportation systems and consequently the accessibility of most of the Adola area.

1.3 Physiography and climate

Topographically, the area under consideration is mountainous with limited outcrops due to the dense vegetation cover which limited comprehensive and reliable geological mapping from outcrops. But at present, the active mining works excavated certain portions of the deposit to a level of 150 m below its original surface. The altitude varies from 1800 to 2300 m having a local relief of 150-300 m. The deposit itself is situated at an altitude of 2000 meters.

It is drained by the small intermittent river called Lega Dambi which is a tributary to the main perennial rivers (Awata and Mormora) that dissect the whole Adola area. These two rivers bound the Lega Dembi area: the Mormora in the west and the Awata in the east. Both youthful and mature river features like falls and rapids, and meanders, wide valleys, etc characterize most of the area.

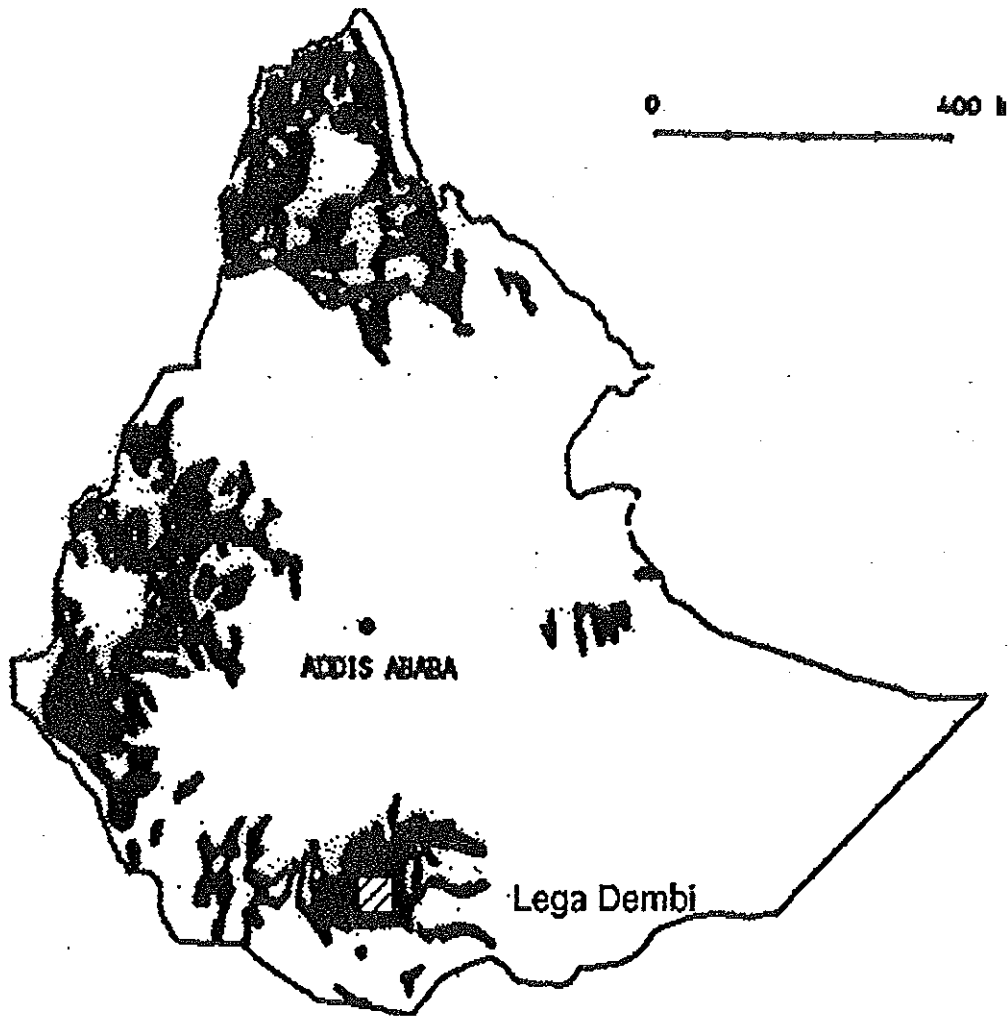


Fig. 1 Location map of Lega Dembi and areal extent of the basement rocks (modified from EIGS, 1975)

The area is of tropical to sub-tropical climate. According to the data collected at Shakiso and Kibre Mengist weather stations, the mean annual temperature varies from 15 to 20°C. The annual precipitation ranges from 814.6 mm to 1748.8 mm averaging 1150 mm. It exhibits four seasons in a year: Bega (summer: December, January, February), Kiremt (winter: June, July, August), Belg (autumn: March, April, May) and Tseday (spring: September, October, November). The highest rainfall is recorded during Bulg and Tseday. The most dry season is Bega in which the precipitation of 68.3 mm was recorded. The maximum daily precipitation is registered in November. The maximum monthly precipitation is 610.7 mm in October. During rainy seasons, the daily temperature doesn't exceed 22°C and it falls down to 12 to 10°C at night. In dry seasons (December to March), the maximum temperature varies from 29.7 to 31.0°C and the minimum from 0.2 to 4.9°C.

The vegetation cover is represented by evergreen tropical forest. Types of vegetation are very diverse and essentially varies from the lower bushes, underwoods and acacia to the very large eucalyptus, junipers and other trees up to 30 m high.

1.4 Purpose of Present work

After the discovery of the LDPGD, a lot of works have been conducted mainly under the directory of EMRDC. The target was and still is the exploration of gold. Some of the geologic implications of the deposit and its constituting minerals were given less attention. But past and present worldwide experiences gathered from mineral exploration prove and teach us that it is impossible or at least not worthy to explore a mineral deposit without the comprehensive study of all trace (minor) constituents. The study of their relationship in space and time with the main constituent (in this case gold) is essential in mineral beneficiation and other recovery processes. The use of these associates as indicators (pathfinders) help in discovering and developing a deposit at reduced cost and short period of time. This principle is especially applicable (important) in areas of similar geologic setting (evolution) like the Adola area which is assumed to have been evolved under the same and consecutive geological events. More over, associates of such kind have a bearing on

ore genesis. Hence, the detailed knowledge of the nature of gold associates in the deposit is critical for the continuation of prospecting and exploration of gold and other minerals in the belt and the country as a whole where the geology is alike.

Although many detailed works have been done on geology and ore minerals of the LDPGD, no detailed works were carried out regarding the nature, parageneses and zonal distribution of sulfides in the ore zone and country rocks. Moreover, the significance of sulfides in the exploration and prospecting for gold deposits was not considered.

Based on field observations and analyses of samples collected from selected bore holes and newly opened pit, the present work will try to characterize the mineralogical and geochemical zonation of the sulfides and their parageneses. Their economic significance will also be evaluated. Statistical treatments of data from the deposit are aimed to: a) Correlate the sulfide and gold distribution, b) Analyze the relation between the distribution pattern of the elements with respect to types of lithological units and environments (secondary vs. primary) and to assess which elements are associated with the gold-sulfide mineralization, c) Envisage the geochemical behavior and mode of dispersion of the elements in that very geochemical environment, and d) Deduce the control of the mineralization (whether it is structurally or lithologically controlled).

The work will also suggest the possible origin of sulfides in LDPGD.

1.5 Methods and Materials

In order to reach at the above mentioned objectives, different materials and methods were used. First of all field works were conducted on the deposit especially in the open pit so as to take check traverses to identify and describe the enclosing rocks, to collect grab samples for laboratory investigations, to study and describe the ore zone and ore bodies, to describe and characterize disposition of ore zone and ore bodies with respect to the different lithologic units and major structures.

Thin and polished sections (from drill cores and the pit) were prepared. Petrographic studies of host rocks were done with the help of petrographic

microscope to characterize their composition, structure and texture as well as the variation of these features within the different parts of the area under study. The polished sections were studied using ore microscope to determine type, structure, texture and parageneses of the ore minerals.

Geochemical studies were done using analyses results of eleven elements (Au, Pb, Zn, Cu, Ag, As, Sb, Mo, W, Co and Ni). The analyses were done using Atomic Absorption Spectroscopy (AAS) and Optical Emission Spectroscopy (OES). The AAS was used for gold while OES is for the rest of the elements. Samples collected in bore holes 623, 602 and 605 were analyzed for Au, Pb, Zn, Cu, Ag, Co and Ni using AAS. The AAS was done in Shakisso while that of OES is in Central laboratory of EIGS, Addis Ababa. The treatment of the core samples before the analyses is shown in the flow chart (Fig.2). The detection limits for each element and method is given in Table 1. The Analyses results were used to characterize the geochemical dispersion, association and zonation of the elements in the deposit. Application of different computers and statistical softwares (e.g. Lotus, Wordperfect, Statgraphics, etc) was critical to process the bulk data collected from the analyses.

Table.1 Detection limit (ppm) of elements for AAS and OES method.

	Au	Pb	Zn	Cu	Ag	As	Sb	Mo	W	Ni	Co
AAS	0.1	5, 0.1	5	5, 1	0.2	100	0.2,30	0.2	5	5	5
OES	10	3	100	3	0.3	100	100	1	50-100	5	1

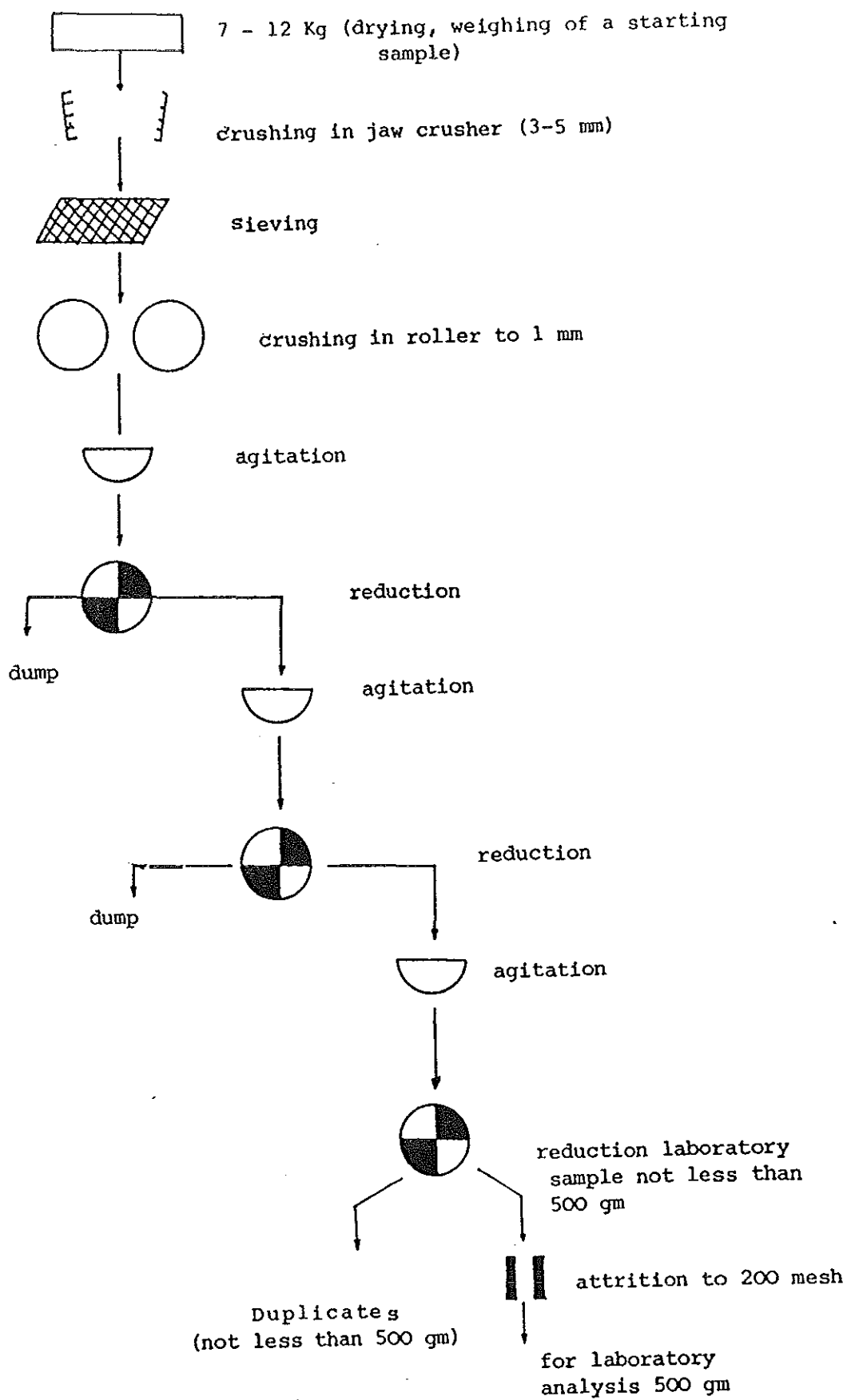


Fig.2 Flow chart of sample treatment for geochemical analyses

2. GEOLOGY

2.1 Regional Geology of Adola Area

2.1.1 *General geologic framework*

The geology of Ethiopia was first outlined by Blanford in 1860s. He was able to roughly explain the geology of the northern part of the country. Since that time, the geology of Ethiopia has been studied and described by different authors coming from different countries of the world (e.g. Dainelli, 1943; Mohr, 1971; Kazmin, 1972, 1975, 1978, etc). Based on the above studies, five main rock units have been identified in Ethiopia. These are from the older to the younger:

- 1) The basement-forming crystalline rock, referred to as 'Basement complex'- it is a series of metamorphic rocks varying in composition, degree of metamorphism and structures as well as intrusive rocks of granitoid to ultramafic composition,
- 2) Paleozoic and Mesozoic sediments,
- 3) Volcanic rocks of the Trap series formed in the Upper Cretaceous and Low Tertiary,
- 4) Post-Rift Volcanics- called Aden Series postdating the formation of the Main Ethiopian Rift Valley, and
- 5) Cenozoic and younger sediments.

The Basement Complex of Ethiopia is considered to be the northern extension of the Mozambique belt (Kazmin, 1972) which is a structural zone extending from Mozambique to Ethiopia, Sudan, Egypt and probably to Saudi Arabia.

This metamorphic unit is constituted by rocks that are intensely metamorphosed, folded, faulted, sheared, intruded and injected by igneous intrusions. The rocks have been subjected to repeated orogenic episodes since their formation. They consist of gneisses, schists of different kinds such as mica, talc, feldspar-amphibole, talc-tremolite schists and others, crystalline limestone, conglomerate and basic and acidic igneous rocks (granite, granodiorite, diorite, gabbro, pyroxenite, peridotite and serpentinite) and dikes or lenses of aplites and pegmatites (Molly, 1959).

Precambrian rocks of Ethiopia have been subdivided into three lithostructural complexes (Kazmin, 1972), viz., Lower complex which is assumed to represent the

oldest cratonic basement, Middle complex representing Lower to Middle Proterozoic platform cover and Upper complex assumed to be island arch assemblage (Kazmin et al., 1978). These three complexes are also subdivided into groups and formations by the same authors.

Gneisses of various composition (biotite and amphibole gneisses with minor feldspathic-quartz gneisses), migmatites, calc-silicates, amphibolites and metamorphic granites typify the Lower complex. This complex was documented in southern (Sidamo), western Ethiopia and in Harergie with restricted occurrences.

The Middle complex is constituted by metapelites and metapsamites such as biotite and quartz-muscovite schists, meta-arkoses and quartzites with subordinate marbles, calc-silicates and amphibole schists. These metasediments crop out in Sidamo (Wadera group rocks) and Harergie (Boye series). The same complex is represented by intercalations of amphibole schists and amphibolites in western Ethiopia.

The Upper complex is a succession of geosynclinal formations slightly metamorphosed (green schist to lower amphibolite facies), ophiolitic rocks, andesitic metavolcanics and associated metasediments, clastics and to less extent carbonate sediments.

When we consider the crystalline rocks of Ethiopia one fact becomes vivid; that is that exploited and economically important minerals occur in these rocks confirming the fact that the profound metallogenic history of the country is related to the geological/ structural evolution (history) of Ethiopia in the early to late Proterozoic (probably up to early Paleozoic) age. All known metallic minerals and certain nonmetallic deposits (such as beryl, mica, asbestos, talc) are exclusively associated with these rocks. Even if their economic exploitability is not proved, the many occurrences are documented in the Precambrian successions. Au and base metals in Tigray, Pt, Ni, base metals and Au in western Ethiopia (mainly Wolega), Nb-Ta-bearing pegmatites, Ni in serpentinites, Au and other metals in Upper Proterozoic rocks in southern Ethiopia (mainly Sidamo such as Kenticha, Sakaro, the known Lega Dembi and others) all are hosted in the basement complexes. All known

mineral occurrences (showings) and proved reserves, erected mineral processing plants and exploitation activities are concentrated or spatially overlap with the exposure of these basement rocks.

These three complexes are not equal in their mineral potential. Except some occurrences reported by D. Jelenc (1966), such as few indications of Cu- and Fe-sulfides (Gimbi-Wollega), heavy minerals like rutile (between Harerge and Jijiga) and pegmatites which are extensively developed especially in Sidamo for Nb-Ta, quartz, feldspars, micas, garnets, Li, Be, U, Th, Mo, W, Ti, the Lower and Middle complexes are subordinate (have negligible economic mineral contents) to the Upper one with respect to their enrichment in economically exploitable minerals. Probably, the upper Proterozoic rocks owe their importance due to the low grade of metamorphism of the associated volcano-sedimentary formations, greater aerial extent of the basic-ultrabasic units and the effects of granitoid intrusions creating favorable conditions for formations of deposits. Hence, among the three complexes so far documented, the Au and other economically important minerals are associated with low grade metamorphic rocks of the Upper Proterozoic age which (according to the accepted classification of the basement) belongs to the Upper complex. It is thus worth mentioning about the nature of mineralization of gold which ranks top in its importance in the country. The most important Au deposits in the country is wholly associated with this Upper complex. The general occurrences of gold in Ethiopia is in either of the following forms, especially in reference to the Sidamo region as it has been given by Solomon Tadesse (unpublished report, 1991). These forms of occurrences are:

a) in auriferous hydrothermal quartz veins, lodes, stockworks and silicified zones associated with sulfides or alone. These are confined to the lower part of the Chakata Formation which belongs to the Upper complex. The veins are usually disposed parallel to the foliation and other rock structures in the formation. The known Lega Dembi and Sakaro belong to this group, b) in quartzites, c) in conglomerates, meta-arkoses of Kajimiti beds, d) auriferous quartz veins in gneisses and e) as elluvial/alluvial/deluvial placers whose source is assumed to be the near-by

crystalline rocks which are not necessarily rich and may not be profitable to work. The placers are the most profoundly exploited and are still important and are found in Sidamo province, western and certain parts of northern Ethiopia.

The regional geological setting of Adola area was previously described by Chater and Gilboy (1970), Kazmin (1972, 1975, 1978) and a number of other authors. Most extensively and in a very detailed manner, it was treated by EMRDC (1985, 1987). The area is assumed to be the northern extension of the Mozambique orogenic belt which forms a portion of late Proterozoic intracratonic trough initiated on an ancient consolidated basement within Mozambique Baikalian geosynclinal fold belt (Holmes, 1951; Kazmin, 1972; Warden, 1984; EMRDC, 1985 and others). This belt is considered to be vestigial facets or rejuvenated basement of the Pan-African orogenic evolution (Clifford, 1970). This is represented by the high-grade gneissic terrain which has undergone repeated episodes of orogeny and rejuvenation and is intruded by syn- and post-tectonic granitoids. Overlying this is the geosynclinal volcano-sedimentary sequence which is assumed to have been deposited on the crystalline basement gneiss through crustal extension / rifting in a back arc environment (Woldai, 1989b). UNDP (1972) in Woldai (1989b) considered the Adola belt to represent a subduction-related obducted slices. Worku and Yifa (1989) considered the belt to have undergone extensional faulting with basin development into which volcano-sedimentary sequences and associated ultrabasic suits were deposited, later compression leading to the development of thrust and in the latest stage of tectonism N-S-trending ductile strike-slip shearing.

Among the different suggestions circling around the two main ideas (i.e. whether complete rifting took place with development of the real oceanic basin and later closing of the ocean with subsequent collision of crust giving rise to magmatism and sedimentation, or it is an aborted rift with only crustal thinning (without real breakage of the continental crust) before the development of the proper oceanic crust into which volcano-sedimentary rocks have been deposited), no consensus is reached. Hence, it is still open to discussion.

Whatever model is applied to the area, under the general scheme of the

stratigraphy, lithology and metamorphic features of the Ethiopian basement and other rock units outlined above the Adola area is represented by (from oldest to the youngest): Upper Proterozoic volcano-sedimentary and intrusive rocks, Paleogen volcanics and a cover of Quaternary superficial deposits. The ore-bearing Adola Greenstone belt is represented by two nearly N-S-trending zones: the Megado and the Kenticha zones which are at maximum 12 and 10 km wide respectively (EMRDC, 1985). These zones are bordered by gneissic terrain in eastern and western part.

According to different authors (Gilboy, 1970; Chater, 1971; Kazmin, 1972; EMRDC, 1985), the metamorphic units of the Adola area belong to the Middle complex (Mormora group rocks) and Upper complex (Adola group rocks). The Middle complex is the main geosynclinal unit of the Baikalian orogenic cycle (110 to 650 my) and represents two major cycles of sedimentation. The first cycle of sedimentation is represented by the Awata group of rocks and the second one is recorded by the rocks of the Mormora group. The Upper complex was formed in a narrow trough initiated upon the already consolidated Middle complex during the late Proterozoic orogeny (620 to 500 my) (Gilboy, 1970; Chater, 1971; Kazmin, 1972; EMRDC, 1985). The rocks of the Middle complex are metamorphosed to amphibolite facies and the Upper complex to the greenschist to lower amphibolite facies. In Adola, the Mormora group are represented by Aflata and Kenticha formations while that of Adola group by Chakata and Finkilcha formations.

Structurally, the Adola area is constituted by three linear nearly N-S-trending blocks called the Eastern, Central and Western ones (EMRDC, 1985). The eastern and western blocks are covered by rocks of the Middle complex while that of central block by Upper complex. The central block is called the Megado Graben (MG). It is the main structural unit of the area and is bordered in its eastern and western parts by nearly N-S-trending shear zones (suture zones) which are marked by intrusions of basic-ultrabasic rocks metamorphosed into talc and serpentinites. Amphibolite bodies and volcanics are also other associates of the structures. With reference to these faults, the MG represents the downthrown part of the fault system which, as it has been mentioned above, runs in N-S direction. The fault systems

affecting the area form three sets: N-S-trending deep faults, diagonal faults trending NW and younger faults of NE strike. The NW and NE faults are local and recent with respect to the N-S faults which are more extensive and older. The intersection places of these differently oriented fault systems are supposed to be the most favorable sites for post-tectonic magmatism and ore formation (EMRDC, 1985). The general stratigraphic succession of the Adola area is summarized in Fig.3.

The characteristics of these rocks are presented below as revised by Kazmin (1972); Kazmin et al. (1978) and EMRDC (1985).

2.1.2 *The Middle Complex*:- the Middle complex of the area is represented by the Mormora group consisting of rocks metamorphosed to high grade (up to amphibolite facies) metamorphism and lithologically consisting of biotite-hornblende and amphibolite gneisses and migmatized micaceous schists. The rocks of this group crop out to the east and west of Megado graben that is filled with the Adola group rocks which are the most important ore-bearing formations. EMRDC (1985) divided this group into Aflata and Kenticha formations.

i. *Aflata formation*: these rocks are assumed to be the oldest of all rocks in the area. The outcrop is restricted to the upper part of the formation as identified in the Sidamo province. Petrographically, it is constituted by migmatized gneisses of quartzo-feldspathic, biotite, biotite-quartz composition interlayered with amphibolites.

The biotite gneisses range in thickness from 800 to 900 m and dip at 70-75° to the west, the strike being almost N-S. The color varies from gray to dark-gray and they are medium to fine-grained displaying a well developed banding due to the migmatization process. It is interlayered with lenses or seams of quartzo-feldspathic composition. Microscopically it is lepidogranoblastic to a lesser degree inequigranular due to increasing proportion of larger feldspar crystals. The mineralogical composition is feldspar (50-70%), quartz (20-35%), biotite (10-20%), epidote (3-5%) and chlorite (1-3%). Accessories are apatite, tourmaline, garnet and magnetite. The biotite gneiss is also interlayered with a continuous layer of kyanite-muscovite-quartz schists having a thickness range from tens to hundreds of meters. Color is light, medium-grained, thinly to coarsely banded and display linear features due to parallel

SYSTEM	COMPLEX	GROUP	Thickness (m)	Lithological description
PALEOGENE			475	Olivine basalts with rhyolites and tuffs in the upper part.
UPPER PROTEROZOIC	UPPER COMPLEX		600	Kajimiti Beds. Merasandstones and metaconglomerates
		ADOLA GROUP	1100	Finkilcha Formation. Metamorphosed siltstone interbedded with graphite phyllite. lower part. phyllite graphite interbedded with amphibolite, biotite gneisses and metasandstone beds.
			850	Chakata Formation. amphibolite, chlorite-schists, chlorite-actinolite schists, graphite phyllites, quartzites.
	MIDDLE COMPLEX	MORMORA GROUP	2400	Kenticha Formation. leucocratic gneisses with marble beds, graphitic schists, mica schists, hornblende gneisses, amphibolite quartz-feldspathic gneisses and biotite gneisses.
	2000		Aflata Formation. biotite gneisses and biotite-hornblende gneisses with interbedded amphibolite	

FIG.3 STRATIGRAPHIC COLUMN OF THE ADOLA AREA (SIMPLIFIED FROM EMRDC, 1985)

to subparallel arrangement of micas and kyanite.

The amphibolites are greenish to dark gray, schistose, fine- to medium-grained with porphyroblastic texture having a thickness of greater than 700 m and dipping 50-70° to the west. The strike is the same as the schists. The texture is nematoblastic and the composition is feldspars (30-45%), amphiboles (30-45%), quartz (5-10%). Accessories are represented by sphene and garnet. The amphibolites appear more or less uniform in texture and composition. The overall thickness of Aflata formation within the MG is about 1600 m.

ii. Kenticha Formation: These rocks border the MG. They are very variable in composition consisting of: biotite, biotite-muscovite gneisses and towards the upper part by quartzite intercalations with micaceous schists. In the western part which is dominated by the biotite and biotite-muscovite gneisses and where the whole succession of the formation is well displayed, the rocks dip at 65-80°E. Their contact with Aflata formation is conformable but at some places they have tectonic contact. These gneisses are fine- to medium-grained, bedded and gray to dark-gray in color. The texture is both granoblastic and porphyroblastic. Biotite and muscovite laths are segregated in parallel to subparallel arrangement giving a bedded appearance to the rocks. Composition is quartz (25-30%), feldspars (20-25%), biotite (15-25%), garnet (10-15%), staurolite (10-12%) and muscovite (up to 3%). Minerals of subdued amount are tourmaline and opaque minerals. This member consists of numerous thin beds and interbeds of 30-50 m thick, fine-grained amphibolites, biotite and garnet amphibolite gneisses.

Quartzites having average thickness of 100 m are cryptocrystalline, light-gray, massive, lepidogranoblastic and fine-grained. They are constituted by quartz and chalcedony aggregates with laths of muscovite, iron hydroxides and reddish-brown hematite.

The whole Kenticha formation is topped by a thick (up to 500 m) members of graphite schists unit. In the eastern part of MG, these rocks are represented by quartzo-feldspathic gneisses faulted against the Aflata formation. They outcrop as a continuous, of nearly north-south trend, banded and dipping at 30-70°W. In

handspecimen they are pink to pinkish-gray, coarse- to medium- grained rocks with gneissic texture.

They form rugged exposure forming steep slopes and ridges. They are sometimes weathered and disintegrated. Under the microscope they are porphyroblastic with lepidonematoblastic groundmass. Porphyroblasts are represented by feldspars. Groundmass is represented by quartz (up to 35%), microcline (up to 45%), plagioclase (up to 20%), biotite (5-7%), epidote (up to 1%) and individual grains of hornblende, muscovite, sphene, garnet, leucoxene and opaque minerals. The textural and structural features of the rocks are impersistent. Near the LDPGD, the quartzofeldspathic gneiss is topped by interbeds of leucocratic biotite and biotite-amphibole schists.

The overall thickness of the Kenticha formation in the western part of the MG reaches 1800-2000 m and in the east 600-700 m.

2.1.3 Upper Complex:- The Upper complex consists of low grade metamorphic rocks represented by volcano-sedimentary units of the Adola group and Kajimiti Beds. The rocks form 5 to 12 km wide and about 120 km long synclinal area in almost N-S direction. The Upper complex rocks are separated from the Middle complex rocks of the Mormora group by extensive fault zones. The Adola group and Kajimiti beds possess unconformable contact. According to EMRDC (1985), the Adola group rocks are represented by Chakata and Finkilcha formations.

i. *Chakata Formation*: These rocks constitute and/or fill the MG hosting the most important mineralization zones/auriferous quartz veins. They are thick succession of exceedingly complex variation with lateral and vertical changes in composition, types, structures and textures. Two nearly N-S-trending shear zones marked by the development of ultrabasic bodies (mainly talc) bound the Chakata formation in the east and west. The formation in question is separated from the Kenticha formation of the Mormora group by the eastern deep fault that strikes N-S and dips at 65-80° W and supposed to control, in space and time, the emplacement of the ultrabasic masses. The formation as a whole has a thickness of 2-2.2 km. This formation strike in N-S direction and dip at 50-70° to the west. Its variation along strike and dip is

displayed by the presence of thin to thick lenses or veins of different schists, quartz veins and stringers, sulfides and even graphitic materials that are evenly to irregularly distributed and sometimes forming patches and pockets. It includes the following rock types: graphitic, graphitic-quartz-mica, tremolitic, amphibolite, chlorite-actinolite, sericite-chlorite, micaceous, and quartzo-feldspathic schists, and graphitic quartzites (localized at two places, Chuba-Jibota and Megado; Roldugin et al., 1985).

The lower part of this unit is well exposed in the eastern limb of the MG. This lower part is constituted by the graphitic and graphitic-quartz-mica schists (300-800 m thick) which are greenish, brown and red-brown when weathered and dark-gray, thinly foliated when they are fresh. Quartz veins and stringers as well as sulfides as fissure fillings and along schistosity planes are common features of the rocks. Compositionally, they include quartz, different types of micas (muscovite, sericite, biotite laths), graphite, feldspars, quartzo-feldspathic aggregate of groundmass with sericite, chlorite and impregnations of sulfides. Accessories are represented by tourmaline, rutile, sphene, leucoxene, apatite and garnet. The graphite-quartz-mica schists are supposed to be derived from fine-grained sandy marine sediments. These schists also include interbeds of actinolite-tremolite rocks.

Next to the graphite-quartz-micaceous schists, there appear the amphibolites (1000-1200 m thick). These are represented by fine- to medium-grained, massive, schistose to nematogranoblastic and porphyroblastic (with porphyroblasts of plagioclase and hornblende) amphibolites. The amphibolites and micaceous schists are gradational both vertically and laterally. Compositionally, they are constituted by hornblende, plagioclase (albite and andesine), quartz, clinozoisite and some biotite crystals. Accessories like leucoxene, sphene and magnetite are common. Due to its microlayering feature and presence of detrital material, it is assumed to be derived from sedimentary rocks (Roldugin et al., 1985). The rocks are also seen to be associated with metasediments (phyllites). The massive one is derived from metavolcanics. Interbeds of chlorite-actinolite, sericite-chlorite and micaceous schists are common.

ii. *Finkilcha formation* marks the end or close of the metamorphic succession in the

MG and has a thickness from 100 to 120 m. It has very limited exposure localized to the southern extreme cropping out in a pinching fashion to the north. It overlies the Chakata formation schists. The contact between them is conformable. The rocks are metasilstones with intercalations of graphitic phyllites. Compositionally, they consist of sericite, biotite, quartzo-feldspathic aggregates and accessories like magnetite and rare crystals of zircon. The rocks are fine-grained, schistose and sometimes with porphyroblastic nature due to the development of large crystals of biotite.

2.1.4 The Kajimiti beds are constituted by metasandstones and metaconglomerates. They have restricted occurrence and have unconformable contact with the Adola group rocks in the MG. The thickness of the succession reaches 1000 m (EMRDC, 1985).

2.1.5 Intrusive and Extrusive Rocks- The intrusive rocks occurring in the Adola area are of three age groups:

1- The metamorphic granites of the Garriboro ultramafic complex. These represent the oldest of all intrusives and have, as determined by Rb-Sr method, an age of 680 ± 30 my (Gilboy, 1971).

2- The Adola magmatic series which consist of volcanics of the Adola group and associated subvolcanics of ultrabasites and gabbros emplaced during the formation of the Upper complex (500-550 my).

3- Post-tectonic intrusions of leucocratic granites, quartz diorites, quartz-bearing gabbro and norites. Their age is 505 ± 10 my (Gilboy, 1970; Chater, 1971). Postorogenic intrusions are characterized by a discordant relations to the surrounding rocks and by absence of evidence of metamorphism (EMRDC,1985). Besides, young basalts and subordinate rhyolite lavas lie in the north western part of the area. The lava flows are assumed to belong to the Trap series of Pleocene-Miocene age (Kazmin, 1972). The thickness of the Paleogene volcanics amounts to 400 m.

2.2 Geology of the LDPGD

2.2.1 *General:* The geology of the deposit is discussed based on the observations conducted in the actively being-mined open pit which covers what EMRDC called Upper Lega Dembi (ULD), Northern Lega Dembi (NLD) and Central Lega Dembi (CLD), and based on the available publications. The thick forest and soil cover to the north, south, east and west of the open pit prohibit easy access and direct observation of the host rocks without workings (trenching and pitting).

The LDPGD is confined in the Chakata formation of the Adola group which belongs to the Upper Proterozoic volcano-sedimentary sequence. It is located in the central part of the Adola Goldfield. It is to the west of the eastern deep fault (shear zone) separating the Kenticha formation of the Middle complex and Chakata formation of the Adola group (Upper complex). The rocks of the deposit consist of low- to medium-grade metamorphic rock units (greenschist to lower amphibolite facies) of the Adola group overlying high-grade metamorphic rocks (amphibolite facies) comprising biotite, hornblende gneiss (Mormora group - Middle complex).

The rocks cropping out in the area comprise the following lithostratigraphic units (from bottom to top or from east to west):

- a) biotite-feldspar-quartz gneiss,
- b) biotite-feldspathic-quartz schists,
- c) carbonaceous-quartz-mica schists, and
- d) amphibolite.

The whole succession of the area is topped by amphibolized gabbro. In addition to gabbro other intrusive bodies in the deposit include metamorphosed ultrabasic rocks transformed into talc and talc-tremolite schists. All the rocks exposed in the area strike almost N-S (NNE-SSW, NNW-SSE) and dip at angle 60-85° to the west.

The stratigraphy of the rocks of the deposit is given in Fig.4. The descriptions of the different units listed above are the following.

2.2.2 The Gneiss unit:- This unit is found to the east of the shear zone and of the

gold-sulfide deposit. It consists of quartz (40-60%), plagioclase (albitic to oligoclase, 1-5%), K-feldspar, mainly microcline (20-30%), and biotite (1-5%). In small quantities carbonates (mainly calcite), epidote, muscovite, actinolite and pyrite are found.

It is pink, dark to dark-grey when fresh and yellowish to pinkish-white when weathered. At the surface it is almost completely weathered to a fine-grained clayey material (most probably kaoline). Alteration is intense and extends to great depth near the shear zone (i.e. its contact with the schists). Rocks are highly deformed to the extent of development of pygmatic folds. Barren quartz veins with a thickness range of less than a cm up to 3 cm are found displaying a pinch and swell feature (Fig.5) and usually incorporate (are crossed) by flakes of micas (muscovite and biotite). Quartz is milky-white and coarse- to medium-grained which becomes fine-grained in the surrounding schists. Due to the development of iron oxides and hydroxides due to the oxidation of iron-containing minerals, reddish to reddish-brown tint (coloration) covered the gneiss. At places gneisses are coated by impregnations and nests of sulfides (mainly pyrite). The prevailing rock exposed is homogenous biotite gneiss with fine-grained, dark to dark-green amphibole schists as interbeds, intercalations and continuous to discontinuous lensoid bodies, their thickness ranging from less than a cm to 1-2 m. The rock as a whole is foliated or banded due to alternation of biotite and sometimes hornblende and quartz- and feldspar-rich layers.

Microscopically, the gneiss is of granoblastic polygonal texture consisting of equant grains of quartz and feldspars. Foliation is represented by parallel flakes of micas, elongated quartz and rods of feldspars. The layering (banding) is most probably the result of metamorphic differentiation (segregation of light- and dark-colored components with increasing degree of metamorphism). Some of the micas are randomly oriented accentuating the fine, incipient foliation of the stretched quartz, feldspars and the micas themselves. Microcline is perthitic and found as coarse-grained porphyroblasts set in matrix of plagioclase, muscovite and biotite. Feldspars are seen to be sericitized and kaolinized in some of the thin sections (section Gn-14) as well as in outcrops. Based on its lithological composition,

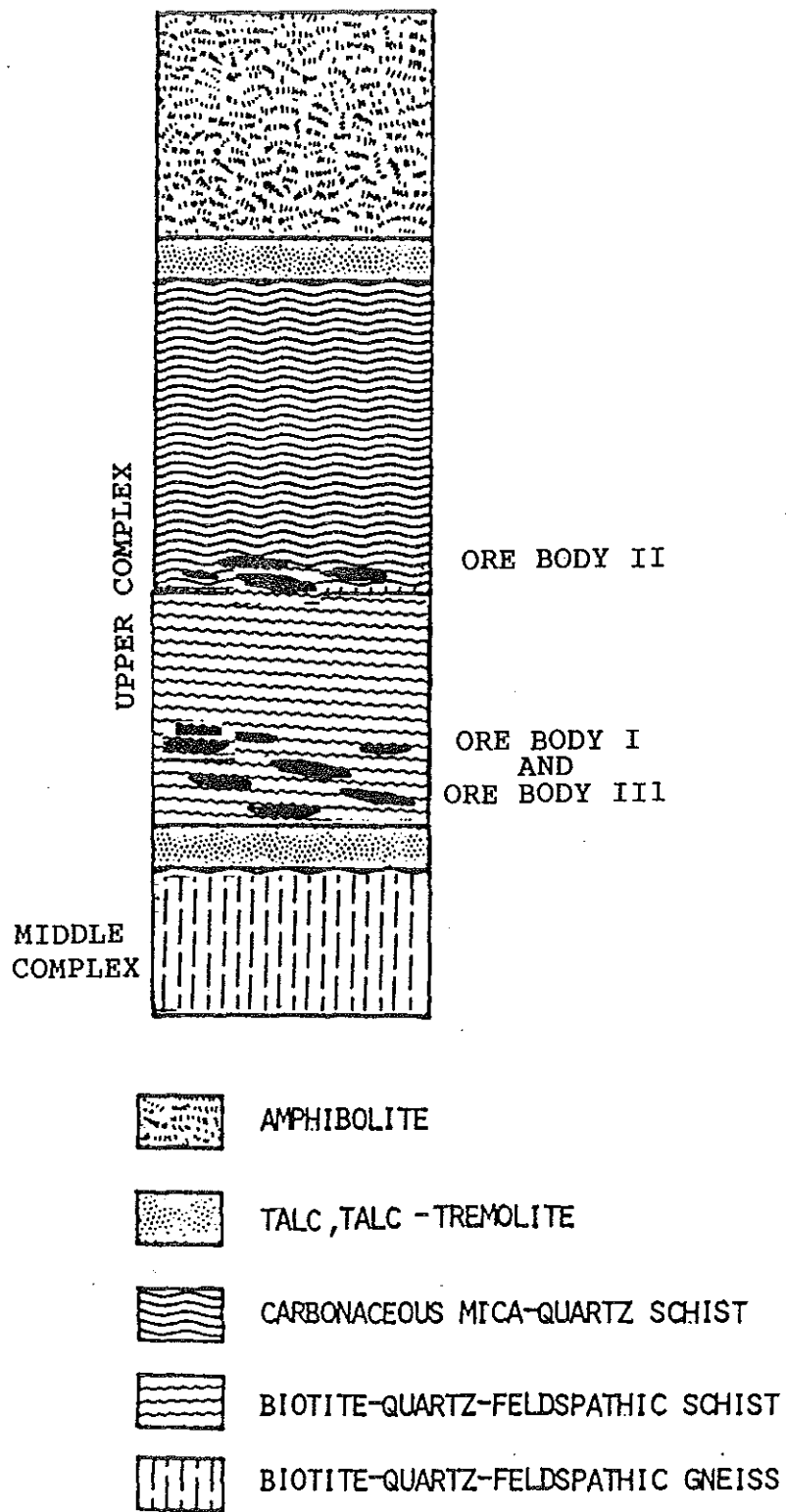


Fig.4 Stratigraphic column of the Lega Dembi deposit (modified from EMRDC, 1985).

structural style and degree of metamorphism, this unit is correlatable to the Kenticha Formation of the Mormora Group (Middle complex). Such correlation is also confirmed and adopted by EMRDC (1985).

2.2.3 Biotite-feldspathic-quartz schists:- This unit is composed of complex intercalations of different schists which are intricately interlayered grading one to the other. The intercalated schists here include: biotite-feldspar-quartz (dominant), talc, talc-tremolite, tremolite-actinolite, chlorite-tremolite-actinolite schists and veins, stringers, lenses, swarms and nests of quartz invading the whole rock. The thickness of the unit ranges from 50 to 300m.

It is light-grey to milky-white, fine- to medium-grained, thinly foliated (schistose) and consists of quartz (50-70%), plagioclase (albite to oligoclase, 20-30%), biotite (1-5%), and muscovite (4-10%). Minerals of low quantity are calcite, chlorite, sulfides, carbonaceous matter (graphite), sericite, epidote and microcline. Talc, tremolite-actinolite and chlorite are also found forming lenses and intercalations of talc, talc-tremolite and chlorite-tremolite-actinolite schists. The schistosity of the rocks is defined by parallel orientation of micas, elongated quartz grains and prisms of feldspars. Some of the rocks attained granoblastic polygonal texture at places. The original schistosity shows bending (folding) due to later coming deformations. Bending is also displayed by quartz veins. The bending at some places is complicated and two orientations of bending (deformations- M1 and M2) were identified (section Ls1-39). Quartz is found both as vein former in which case it is coarse-grained and part of the schists in which it is fine grained relative to the one composing the veins. Quartz veins have different orientations, but only two systems crossing each other at obtuse angle were observed (section Ls1-39). Quartz in one of the veins is stretched parallel to the schistosity of the host rocks, fractured and has wavy extinction while the quartz in the younger veins is equidimensional and homogenous. Flakes of micas are found interspersed in the quartz veins and usually are concentrated along quartz grain boundaries. Some quartz grains are recrystallized filling voids and open spaces in the schists and are secondary in origin.



Fig.5 Pinch and swell structure of quartz veins

Fig.6 Two generations of quartz veins

2.2.4 Carbonaceous-quartz-mica schists:- It conformably overlies and gradational to the feldspathic-quartz schists and has a thickness of 300-400 m.

It is ashy-grey at the surface and dark to dark-grey at depth. It is an intercalation of micaceous quartz, mica and amphibole (biotite-actinolite) and actinolite-tremolite schists. The unit is finely schistose having pseudolamination feature which is the mimetic growth after a sedimentary rock.

Compositionally, it consists of quartz (30-50%), muscovite (10-20%), biotite (20-30%), sericite (1-5%), graphite and small amount of calcite, feldspars, sulfides and chlorite. Rare occurrences of sphene, apatite and tourmaline are also observed. The intercalated biotite-amphibole schists are dark to dark-green constituted by actinolite, quartz, plagioclase, apatite and epidote (sometimes chlorite).

Their similarity in lithology, metamorphism and structural setting enable us to prove that the units described in (b) and (c) are parts of the Chakata Formation of the Adola group (Upper complex).

2.2.5 The Amphibolite forms the western part of the deposit and has a thickness of 100-300 meters. Amphibolite is yellowish to yellowish-brown (weathered part) and dark to dark-green (when it is fresh). Slight foliation is observed. Compositionally it consists of hornblende (40-50%), plagioclase (albite to oligoclase, 25-30%), quartz (10-30%), biotite (3-10%) and subordinate amount of chlorite, calcite and very minor impregnations of sulfides. Alterations (specially silicification) is evident at places.

2.2.6 Intrusives:- These include the gabbro amphibolite which is coarse- to medium-grained, dark to dark-green, massive with incipient or no foliation and is composed of hornblende (50-70%), augite (5-10%), plagioclase (labradorite, 25-30%), quartz (10-15%) and trace amounts of biotite, garnet, orthoclase and sulfide coatings.

Metamorphosed ultrabasites (talc, talc-tremolites and tremolite-actinolite schists) are also found as intercalations in schists and along the shear zone (faults, mainly along those ones that strike in near N-S direction).

Talc schists represent the eastern deep fault (separating the gneiss and the schists) and other N-S trending faults. They are grey to yellowish-grey, friable (loose), fine-grained and sheared rocks ranging in thickness from 1 to 6 m (when

intercalated with other schists) as measured at the northern Lega Dembi.

Mineralogical studies conducted on the enclosing rocks of the LDPGD show the following mineral assemblage: hornblende, biotite, muscovite, chlorite, sericite, quartz, K-feldspar (microcline), plagioclase (albite, oligoclase and labradorite), talc, tremolite, actinolite, epidote and garnet. This mineral association is characteristic of metamorphism of greenschist to amphibolite facies. The gneiss unit being amphibolite facies rock and the schists are greenschist to lower amphibolite facies.

The above mentioned and described rocks are deformed (folded, faulted and regionally metamorphosed). According to Chater (1970), metamorphism is of regional dynamothermal type characterized by a rise in pressure and decrease in temperature.

2.2.7 Structures:- Tectonically, the rock units of the area as a whole, including the mineralized ones, are subdivided into two structural stages - the lower and the upper ones; differentiated from each other by petrography, degree of metamorphism and type of tectonic deformations. The lower structural stage is developed in the eastern part of the Lega Dembi mineralized area and is made up of rocks of the Kenticha formation gneiss. These were resulted from the early event of regional metamorphism (630-680 my, Gilboy, 1972). The metamorphism of this unit reached an amphibolite facies. The upper structural stage is composed of volcano-sedimentary rocks of the Chakata formation schists formed during the late phase of the Baikalian orogeny (620-500 my, EMRDC, 1987). The rocks of the Upper complex are metamorphosed into the greenschist facies.

In the studied area three sets of faults are found. One set strikes N-S and is marked by ultrabasic rocks now represented by talc, talc-tremolite and talc-chlorite schists. Among these faults the eastern deep fault separating the gneiss unit (Kenticha formation) and the schists (Chakata formation) is the main one in the area. The fault itself is accompanied by highly sheared, shattered and mylonitized as well as metamorphosed ultrabasic units. It seems to extend for a long distance. The exposure of this sheared talc body has a thickness of from 5 m to 20 m. Its exposure is covered by thick forest and mantle of weathered material. The fault dips at 70 to

85° west. The displacement of the rocks can't be determined due to the lack of markers. Certain faults seem to splay from this fault (such as what EMRDC called the Chakata fault) which runs through the Chakata Formation schists. The second and the third (younger and diagonal) sets strike NE and NW respectively. These later faults cut the packet of rocks squeezed between the near N-S-trending faults into several blocks among which the largest corresponds to the sections defined by EMRDC (1985) as the Upper Lega Dembi (ULD), Northern Lega Dembi (NLD), Central Lega Dembi (CLD) and Southern Lega Dembi (SLD). The near E-W-running local faults are also important in the area. They have been evidenced by dragging of veins, fractures and joints. EMRDC reported the nature, amount of displacement, dip angles and directions of these faults. Information were gathered from pits, trenches and assay data collected during the mining of the open pit. Emelyanov et al. (1985) reported that these faults played a role in the spotty and erratic distribution of the mineralization within the ore zone and its pinch out characteristics. Even if these E-W-striking faults complicate the morphology and attitude of the ore bodies, the displacements along these faults are small.

3. MINERALIZED ZONE, ORE BODIES AND ALTERATION OF WALL ROCKS

3.1 Ore zone and Ore bodies

The mineralization is confined to the lower part of the Chakata formation which is highly altered and saturated with quartz veins. The zone of mineralization is bounded by two impervious bounding structures - the eastern deep fault and the amphibolite capping the rocks of the deposit. These structures seem to have played the role of screening or blocking spilling or dissipation of the mineralizing fluids out of this zone. It means that the amphibolites seem to have been more impervious and have effected "damming" and accumulation of the mineralizing fluid.

The boundary between the ore zone and the biotite gneiss is distinct. It is marked by the eastern N-S-trending fault and is visible when the dark-grey talc-tremolite schists grade into the light-grey biotite gneiss. The upper boundary of the zone is not clear but runs through the monotonous carbonaceous quartz-mica schists and it may be defined by means of sampling where assay returns of gold is taken into consideration.

The thickness of the ore zone vary from 50 to 80 m in width. Along its strike it is expected to run for about 2 km (from southern to upper Lega Dembi). The depth continuation was traced up to 250 meters from surface. Deep drilling of three bore holes (Nos. 602, 605 and 623) was conducted and it is possible to find rich ores at greater depths. From ore mineralogy study, pyrrhotite, pyrite and chalcopyrite were detected at great depth from samples of bore holes Nos. 602 and 623. But low temperature sulfides of gold associates were not detected; instead, wolframite is found in good proportion around a depth of 245 m in which it accounts for 20% (polished section C38), 50% (section C33) and 40% (section C32). Assay data of gold and its indicator elements were collected and found to be promising up to the depth of about 350 m. Up to this depth rich ore zone with average grade of 1.13 g/t gold in quartz veins and actinolite-biotite schists was encountered. In bore hole No. 623, average gold content of 5.15 g/t in quartz veins and feldspar-quartz-mica schists was encountered. In case of bore hole No. 605 average gold grade of 8.6 g/t was detected

around the same depth. Hence, the above observations are encouraging to conduct systematic detailed study as to depth continuation of the deposit.

Based on types of host rocks, mineral parageneses, enrichment variation in sulfides and gold (based on assay data) and their position in the area, three ore veins arranged in an echelon fashion are detected (Emelyanov et al., 1987). The ore bodies exhibit no clear-cut geologic boundaries and are outlined only on the basis of sampling. They are separated by barren or uneconomic zone which contains gold below the cut-off grade and subdued amount of sulfides. Ore bodies 3 and 1 are found in the mica-feldspar-quartz schists in which ore body 3 extends from CLD to NLD and ore body 1 is contained within NLD, some part entering into CLD. Ore body number 2 is hosted in the graphitic-mica schists and runs from NLD to ULD. The parageneses of these ore bodies are almost the same being gold associated with Fe-Cu-Pb-Zn-sulfides, sulfosalts and tellurides.

Ore body number 1 comprises eight branches, ore body number 2 has four branches (lenses) (EMRDC, 1988) while ore body 3 consists of two branches. Distinctions by mineralogical composition between ore bodies 1 and 2 were made by Fiori et al. (1988) based on microprobe and microscopic analyses. Ore body 1 is characterized by free gold with little silver content associated with the mentioned base metal sulfides, tellurides, ullmanite, breithauptite and nisbite were detected; galena has a low Te content and Te occurs as free tellurides (hessite, altaite, petzite). In ore body 2 gold and electrum are found associated with sulfides together with rare tellurides, Ag-tetrahedrite, boulangerite and bournonite while galena shows a high Te content (decreasing when tellurides appear, which are very rare). Ore bodies 1 and 2 have long been mined and are still being mined. Ore body 3 is recently (1992) opened. According to EMRDC's report (1987), ore body 1 has the greatest part of the Au estimated in the northern section of the deposit. This mineralized belt extends for a distance of 520 m along strike. The ore zone as a whole shows variation in width and thins towards the north. The saturation with gold and sulfides is inversely related. The grain size and grade of gold and its associate sulfides increase to the north. The pick is registered in the NLD along exploratory

line EL-8 (see part 5-4).

Ores are stuffed in veins, lenses, stock-works and stringers of quartz invading the different intercalated schists which are themselves mineralized, especially the silicified ones. Analyses of gold distribution in relation to different lithologies show that the actinolite schists interbedded with mica-feldspar-quartz and carbonaceous quartz-mica schists are the most favorable for gold mineralization.

Ore-hosting structures are aligned almost parallel to the N-S-trending structural suture and are disposed concordantly with foliations and contacts of the host rocks. The veins, stringers and lenses vary in thickness from less than a millimeter up to tens of meters and the length varies from tens to hundreds of meters along strike and down dip. Brecciated quartz veins, especially at contacts of different types of the rocks, permeated by micas and amphiboles are also observed especially in the weathered zone. Veins, lenses and stringers have different orientations. Some of them are parallel, others are inclined (crossing) even to a less extent perpendicular to the schistosity, contacts of different rock types and each other. The crossing of the veins may indicate different but more than one generations of veins resulting in various stages of mineralization characterized by different mineralogy, chemistry and parageneses (this fact is evidenced in the ore mineralogy part by at least two types of pyrite and chalcopyrite). They usually occur as continuous veins extending for long distance uninterruptedly with more or less uniform thickness. Some appear as pinches and swells with some discontinuities and bends (thin section Ls1-14). Others still show up themselves as patches and nests or as swarms of veins, lenses and stringers branching, re-branching and invading the whole rock mass as well as grading and coalescing into massive and thick pure quartz veins with subordinate micas and amphiboles. Sometimes they are densely populated to the extent that the whole rock seems to be quartzose and some are sparsely dispersed. The patches and nests are less mineralized than the continuous, pinches and swells. Most of the quartz veins show a bend when they reach a fracture or joint which shows small displacement along the fractures causing dragging of the veins. This enables one to say that the fractures are local faults that don't extend beyond a single rock type but cause

complications of the shapes and spatial distribution of the veins. The extent of distribution, thickness and abundance of quartz veins decrease to the west (i.e., when one recedes from the shear zone), especially in the graphitic schists and amphibolites.

Essentially two types of ores are identified in the deposit both in polished sections and hand specimen. These are ores dominated by schists (banded schistose ores) and ores dominated by massive quartz gangue (non-schistose ores).

The banded schistose ores are constituted by hydrothermally altered schists of different composition (actinolite, biotite-quartz-feldspar and carbonaceous quartz-mica schists) hosting thin veins and stringers of quartz in which sulfides are concentrated along schistosity planes almost in parallel to subparallel arrangement. Schistosity is rendered to the ore due to the preferred arrangement of platy minerals like micas. Gangues are represented by amphiboles (actinolite-tremolite and hornblende), micas (biotite, muscovite and sericite) and few grains of feldspars. Talc, carbonates and graphitic materials are not uncommon.

The massive ore is characterized by the dominance of quartz with subordinate light-colored micas, which are found in the interstices between quartz grains, actinolite and lithologically different schists. Sometimes salvages of quartz veins comprise brecciated ores of fine-grained quartz composition with minor sulfides. Sulfides are usually more abundant and coarse in the massive ore than in the schistose one. Sulfide mineralization is distributed quite irregularly. Generally, sulfide occurrences are mostly localized:

- 1) in contacts between different rock units, 2) as films, impregnations and coatings in quartz veins and schists in which sulfides are partially or completely oxidized where they are in the zone of oxidation, 3) along schistosity planes of the different schists, and 4) along fractures in which partial or complete oxidation took place.

As it has been shown, the economic pay lodes, veins and stringers are found near the eastern deep fault (lower part of mica-feldspar-quartz schists). The high degree of deformation leading to fracturing and jointing of the differently intercalated schists which have contrasting physico-chemical behavior and competence favored the

saturation of the near fault units. The fracturing of the Chakata schists induced by the shearing seems to extend up to the gneiss which contains barren quartz veins deposited at dilatant sites triggered by stress associated with the shearing. The high role played by this fault in creating favorable conditions for the mineralization is evidenced by barren nature or decrease in degree of mineralization of the host rocks when one recedes from the fault to the west. The role of this fault reaches to the extent that even some faults that splay from it like Chakata fault has a role in controlling the mineralization. This fact is shown by the inverse relation between the distance of separation of the two faults and the saturation of rocks with quartz veins, lodes and stringers (i.e. gold and sulfide mineralization). Hence, the different ore-controlling features of the rocks (fractures, joints, dilatant veins to which the mineralizing solution damped its mineral content and the small faults with their drag folds) are the direct consequences of this fault. The double role played by the shear zone is also implied by virtue of its function in serving as channel way in the migration of the mineralizing solution from great depth (see part VI). Rich ores are spotty, irregularly distributed and located at the intersections of N - S - trending and diagonal - faults (EMRDC, 1987). The ore bodies are stratabound epigenetic (contained within the mica-feldspar-quartz and quartz-mica schists).

As usually encountered in most of the world known deposits carbonaceous matter aids as a catalyst and absorbent of metals in the precipitation of gold and other ore minerals. But in the case of Lega Dembi the reverse happened; the noncarbonaceous mica-feldspar-quartz schists are more mineralized than the graphitic schists. This may be due to the structural factor. The mica-feldspar-quartz schists are near the shear zone. They are also constituted by different schists having different physico-chemical properties. This property might have favored fracturing and formation of dilatant veins. These veins are most favorable for deposition of metals from hydrothermal ore-bearing solutions because it is in this sites that decrease in P-T condition is encountered. Therefore, precipitation took place before the solution reached the graphitic schists. Considering these facts we can say that the structural factor played the highest role in controlling the mineralization. But, since the pay lodes are

confined only to single formation (i.e., feldspar-mica-quartz and the lower part of the carbonaceous-quartz-mica schists), not in gneiss and amphibolite, the mineralization is also lithologically controlled. Hence, one can say that it is controlled both by lithology and structure (degree of competence of host rocks), though structure seems to play more role than lithology.

3.2 Alterations of Wall Rocks

Alterations were studied and described based on field observations and studies of twenty five thin sections collected at different parts of the deposit.

The metasomatic alterations developed in the enclosing rocks are extensive. They include sulfidization, sericitization, propylization, feldspathization, phyllitization, actinolitization, biotitization, chloritization, carbonatization, argillic alteration and by far the most important one is silicification.

In the altered wall rocks, complex ion exchanges might have taken place whereby some constituents were removed, others are added, and still others are merely redistributed. These alteration processes and effects are evidenced by changes which rendered the rocks many physical and chemical changes. Among the physical changes which are typical in the wall rocks of LDPGD are bleaching (which usually results from argillization, reduction or hydration, Schwartz, 1959; Park, 1975), development of porosity, permeability and other changes. The chemical and mineralogical changes would have been very complex even difficult to characterize in this work; but all displayed themselves by the formation of the aforementioned minerals. Recrystallization would have possibly taken place during the alteration of wall rocks, especially associated with the formation of coarse grained calcite and dolomite crystals (in sections Us1, Ls-27, A35-T). These resulting chemical and physical changes are an interplay between the composition of wall rocks which seems to have exerted a strong influence especially on the early stage of alteration (it directly refers to the susceptibility of the wall rocks to reactions or alterations) and composition of the solutions which usually play greater role in the late stage of the process by virtue of such factors as Eh, pH, vapor pressure and degree of hydrolysis (Schwartz, 1959;

Park, 1975; Barnes, 1967, 1975).

In schists where silicification is less important, micas, pyrophyllites, actinolite-tremolite and other hydrous minerals are dominant suggesting the higher activity of water.

Silicification (development of tectosilicate, in this case represented by quartz) is closely related with the development of quartz stringers, veins and quartzose schists in which gold mineralization is significantly higher than in others. This mode of occurrence of silicification and its association was also noted and described by EMRDC (1985) which is proved now in the present work. Essentially, this alteration covers the whole rocks found in the deposit but at various degree decreasing outward from the mineralized veins. Quartz in the silicified rocks might have been originated from: a) primary quartz, b) breaking down of siliceous minerals such as orthoclase and albite (desilication), and c) leaching from rocks through which the solutions passed (desilication) and redeposition.

Development of various amphiboles is represented mainly by actinolite and tremolite which form their own units: actinolite schists, actinolite-tremolite schists and hornblende schists. These schists are disposed as lenses and thin beds of a centimeter to a few meters of thickness.

Carbonitization is evidenced by the development of calcite and dolomite (ankerite is expected to occur but not observed), in association with the talc-tremolite schists. This alteration has very small extent and was observed in the graphitic schists and in limited number of sections (Us1, Ls-27, A35-T) which are constituted by talc, actinolite-tremolite, calcite and dolomite.

Sulfidization occurs as films and impregnations of sulfides (pyrrhotite, pyrite, chalcopyrite and others) in rocks. This alteration, especially pyritization, implies the addition of sulfur to the host rocks containing Fe-bearing minerals (Mackinstry, 1957). This alteration, like silicification, is associated with gold mineralization denoting their genetic link. Sulfidization is more evident along schistosity planes what applies also for all kinds of alterations (EMRDC, 1988). The decrease in extent of sulfidization outward from the gold pay lodes (veins) is noted.

Chloritization is common especially in the carbonaceous quartz mica schists distal to the ore zone and might have been developed on the expense of biotite and hornblende. The occurrence of chlorite in the peripheral zone of the altered wall rocks of LDPGD is in agreement with the theoretically established fact of Park (1975) and observations of Sainsbury (1960) in the Lost River tin mine, Alaska.

Sericitization and biotitization is developed all over the deposit. Sericitization is well developed in and around quartz veins in which hair-like sericites are observed along quartz grain boundaries. Sericite would have been formed by replacing plagioclase in the early stage, but, as noted by Schwartz (1959) and others, as the process continues, it can replace ferromagnesian minerals commonly with chlorite as intermediate product. Sericite is also expected to be produced from argillization process in which clay minerals form in the early period of alteration. The latter minerals usually are converted into sericite in the late stage of the process (Schwartz, 1955). Biotite is well developed in most part of the deposit. It is also common in quartz veins as coarse flakes interspersed between quartz grains. Biotite in the altered wall rocks of LDPGD is most probably found as both alteration product and primary one. The behavior of biotite during alteration, as given by Schwartz (1959), is such that it is one of the most susceptible minerals to be attacked in the early period of alteration but it is also found less commonly as product of later alteration processes. The potassium of sericite and biotite might be furnished by orthoclase.

Development of talc is common in all rock types. It usually dominates along schistosity planes of the major types of schists especially of actinolite-tremolite schists in which talcization is more intense. This alteration is conspicuous in near fault formations but restricted only to the hanging wall side.

Even if the different types of alterations are assumed or expected to have taken place simultaneously or at least with a considerable range of overlap in space and time, since conditions of temperature and chemistry usually differ at various distances from the mineralized veins (zone), different zones of alterations disposed laterally away from the zone could be distinguished. In case of the LDPGD, alterations are restricted within and to the hanging wall of the deposit. Hence, any zonation study

of alterations will detect the asymmetric nature (Fig.7). But since the wall rock alterations are complex and extensively developed, there is no such well-defined zonal arrangement of alteration products. Hence, unless extensivity of the different types of alterations is taken into consideration, there is no a zone that does not contain all of the mentioned alterations. This means that all types of alterations are developed in every part of the area. Therefore, when we say a zone of silica alteration, it does not mean that only silicification is present but means silicification is dominant and others are subordinate. In fact there are certain alterations restricted to a specific area. Among these are chloritization (found only to the low temperature side of the deposit, i.e., in the outscurt) and argillization (found in the carbonaceous quartz-mica schists).

Silicification and sulfidization with subordinate amount of actinolitization, biotitization and sericitization are extensively developed in the mineralized zone. In places, the wall rocks around veins are altered to fine-grained aggregate of silica, sericite and to a lesser extent feldspars. This alteration is bordered by sericitic alteration followed by argillization which usually dominates in the impervious carbonaceous quartz-mica schists. The impervious nature of these schists is most probably the result of the argillization process which is evident in these rocks. The most difficult problem which needs careful observation is the identification of clays that result from hypogene alteration and weathering. Chloritization and carbonization are also found in these schists. Sulfides in the zone of mineralization are found as individual grains but they become films and impregnations in the host rocks outside the ore zone. Chloritization with other hydration alterations (i.e., development of amphiboles) occurs in the outer fringes of the whole alteration zone that grades outward into relatively fresh rocks (gabbro-amphibolites). Generally one can envisage the following grossly established zones outward from the zone of mineralization: silica-feldspar-sulfides, sericite-biotite-actinolite and chlorite-sericite-carbonates zones.

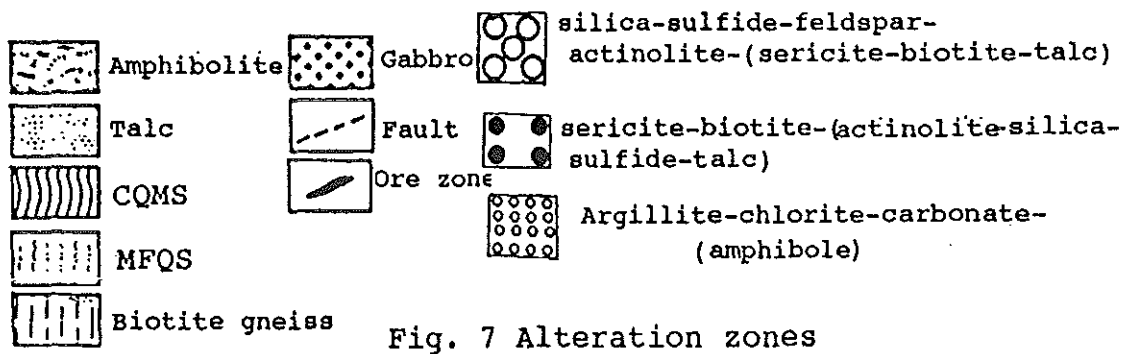
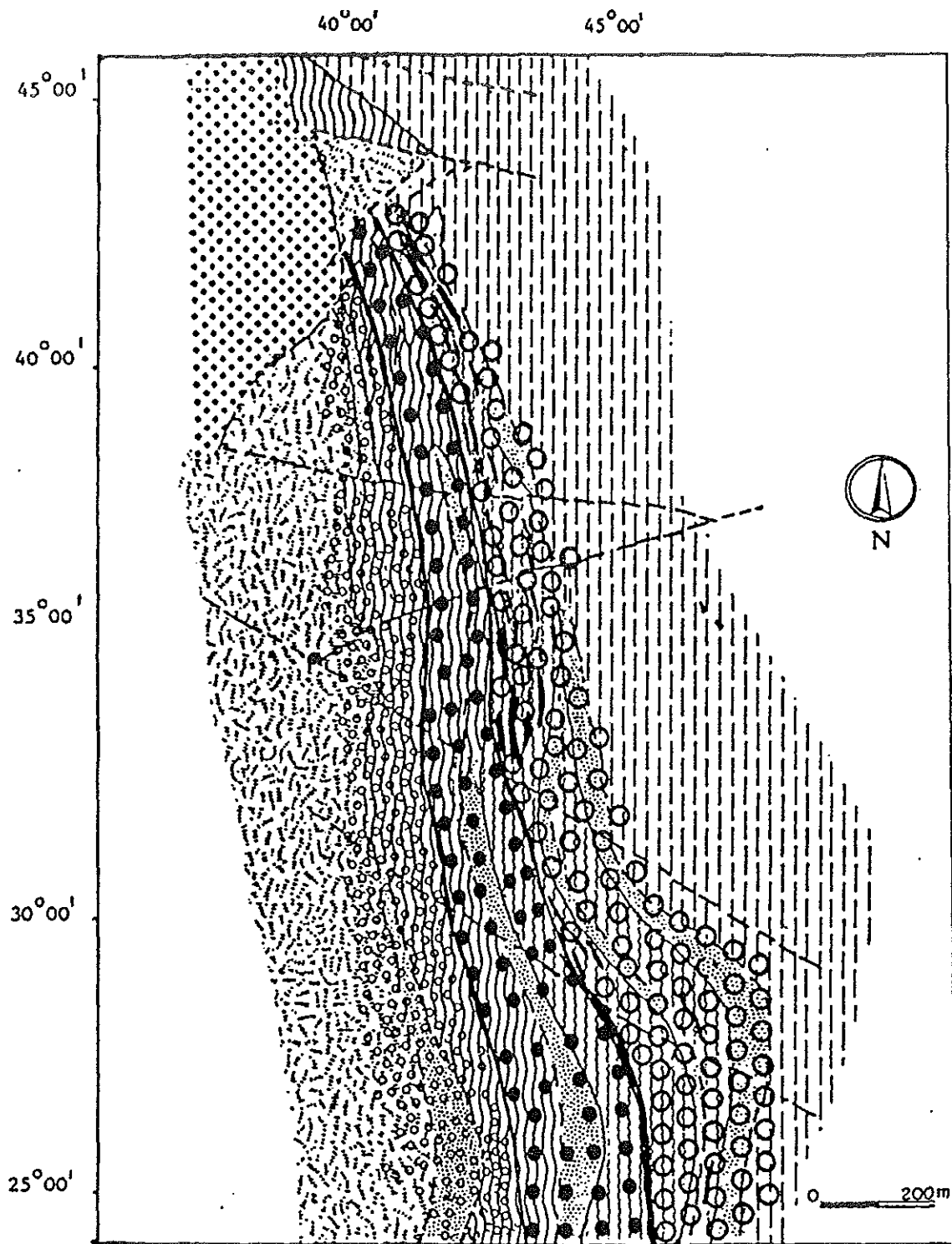


Fig. 7 Alteration zones

This type of arrangement of alteration products is most frequently encountered and described by different researchers. Schwartz (1956, 1959) stated that it is normal for epigenetic ores to be bordered by altered rock that fades into unaltered rock away from the ore zone. From the different illustrations of most of the world deposits, such as Butte, the common zonation generally is quartz and sericite accompanied by pyrite and copper sulfides near the vein or center of mineralization grading outward to clay minerals. He also noted the possible extension of chloritic or propylitic alteration beyond the argillic one, but it is assumed to be local rather than consistent over large areas, the case noted in the altered wall rocks of LDPGD. Sales and Meyer in Mckinstry (1957) demonstrated the loss of sulfide forming base metals, especially iron, from the argillized wall rocks (at the fringe of the deposits in Butte, Castle Dome - Arizona "a porphyry copper deposit" and Chuquicamata) and its concentration in sericitic zone. This could be taken as a proof for the dominance of sulfidization process in the ore zone of LDPGD.

Apart from the hypogene alterations described above, alterations of secondary origin that result from oxidation and/or weathering are conspicuously developed to a depth of from 20 to 60 (70) meters (as deduced from geological sections of EMRDC, 1985), with production of kaolin-rich material, staining rocks and development of limonite and other secondary minerals such as malachite, azurite, copper oxides, manganese oxides (as black coatings) and others that result from the decomposition of sulfides. The quartz at the surface is fine- to medium-grained, sugary-white, jointed with frequent coatings and grades to compact milky quartz at depth. This change in the characteristics of quartz is accompanied by the variation in the associated minerals: at surface, secondary minerals that result from dissociation of hypogene minerals and in depth primary minerals and minerals of the secondary sulfide enrichment zone that result from leaching and redeposition of metals from the zone of oxidation. Fragments of the host rocks and other gangue minerals are altered into clayey material and quartz-mica aggregates. An association of pyrrhotite and brownish film which is oxidation product of iron sulfides including

pyrrhotite itself along schistosity plane is observed and this association is ascribed to partial oxidation of sulfides. The latter is also seen in polished sections where they are found as nucleus of secondary minerals. Pyrite, flakes of mica and recrystallized quartz grains which are secondary precipitate are concentrated in the gneiss unit along the contacts between barren quartz veins and the host rock.

4. SULFIDE MINERALS AND THEIR PARAGENESES

4.1 Ore Minerals

The mineralogical associations, type and distribution of the LDPGD was investigated using ore microscope. The minerals identified are pyrrhotite, pyrite, arsenopyrite, galena, sphalerite, melnikovite-pyrite, covellite, chalcocite, marcasite, chalcopyrite, wolframite and trace amount of gold (detected in sections dominated by low temperature lead and copper sulfides), molybdenite, tellurides and sulfosalts. The prominent gangues are amphiboles, micas, feldspars, carbonates, small amount of talc and graphitic material. In primary ores the above-mentioned sulfides and associated gangues are dominant while in the oxidized ores, hydrous ferric and manganese oxides, clay minerals and other oxidation products of the hypogene minerals are most significant.

The samples of rocks and ores (fresh as well as weathered) were collected from the pit and core drills (from ULD, NLD and CLD). The sampling interval was not constant due to some limitations (lack of rock samples with sulfides at a desired interval) but representatives for the different depths of the bore holes (especially the vertical distribution of the samples) was done systematically. From the mineralogical study, the lower part of the deposit is dominated by wolframite and the high temperature iron sulfides like pyrrhotite; but the low temperature sulfides, like galena to which the most economically important mineral (gold) is usually associated, have subdued amount or they are absent at all (sections CR-26, CR-23, etc). Previously prepared sections at 100 m depth (adit No.1) were used to compare the results and to obtain a reference level.

As it has been described in the other part of this paper, the mineralization is found in quartz veins containing flakes of micas and amphibole and in schists which have undergone intensive alterations and replacement as a result of which the ore minerals are supposed to be formed. Sulfides are found in good proportion in samples at depth but they are represented by their oxidation products staining the host rocks in near surface (pit) samples. Sulfides were detected in varying amount in almost all 45 polished sections investigated. Their distribution is such that they are

more abundant and coarser in quartz veins (non-schistose ore) than in schists (banded schistose ore). This may be related to the mode of deposition of the ore minerals. The original open space (dilatant portion of rocks which is now represented by quartz veins) into which sulfides and silica were deposited, was relatively wide allowing free and uninterrupted growth of crystals in abundance and larger crystal size. But sulfides in schists are deposited as a result of replacement and impregnation along planes of weakness like schistosity planes and minor fractures which are narrower than the tectonic dilatant veins and hence limiting free growth of crystals into big size. The sulfides (especially the tabular and elongated ones like arsenopyrite, wolframite and others) in schists show a well preferred parallel arrangement to the schistosity of the host rocks (e.g. section C90). They are disposed along schistosity planes, fractures (usually parallel to foliations) and more concentrated along the contact between schists and quartz veins. Sulfides in the banded schistose ore are found in quartz stringers (which are penetrating and invading the host rocks) and the schists themselves as impregnations and/or well developed fine-grained crystals. All of the sulfides found in the deposit have a patchy relationship or an intergrowth. Some of them show deformation structures like granulation and fragmentation (arsenopyrite and pyrite in section Ls1-17). Subdued amount of sulfides especially pyrite is detected from the gneiss unit both in handspecimens and sections. Pyrite here is coarse-grained, euhedral and isolated (i.e. not associated with other sulfides). Schists containing ore minerals (sulfides and gold) are highly affected by alteration especially silicification (development of swarms of quartz stringers and lenses).

The different optical properties, associations, textures, structures and distribution of the identified ore minerals are given below.

Pyrrhotite ($Fe_{1-x}S$)

Pyrrhotite is the most abundant and through runner of all of the sulfide minerals present in the LDPGD. It is widely distributed in the unweathered part of the deposit while it is represented by its alteration and/or oxidation products in the secondary environment. The alteration products include secondary sulfide minerals like

marcasite, melnikovite-pyrite, iron-hydroxides (mainly limonite) and pyrite displaying the characteristic "bird's eye texture". As can be observed from the approximate percentage of pyrrhotite in the different polished sections collected at different depths, high percentages are concentrated in core samples at considerable depth in comparison to samples from the pit. It is not unique when one considers the generally established fact concerning the susceptibility of pyrrhotite to oxidation/alteration at or near the surface (Einaudi, 1971; Burke, 1972; Ramdohr, 1967, 1980; Stanton, 1972). Einaudi (1971) recognized the preferential replacement of the hexagonal rather than the monoclinic modification of pyrrhotite by an intermediate alteration product in the deposits of Cerro de Pasco and Cobriza. He ascribed this to the relative stability difference of the two forms; the monoclinic one is more stable than the hexagonal variety under the conditions of formations of the intermediate product (due to partial oxidation) which is confirmed by the author to be low temperature and pH. The absence or reduced amount of pyrrhotite in samples of the pit (samples No. Ls1, Ls1-2, Ls1-17, Ls-8) and its high percentage in samples from depth (sections Cr23, Cr26, C75, C34, C38) are clear evidences to the already mentioned observations and facts.

At depth, pyrrhotite is found as fresh and free of any alteration signatures. In the zone of oxidation (from samples near the surface), it is highly altered, surrounded by advancing alteration rims (oxidation coronas), fragmented, fractured, intruded by chalcopyrite, fine powdery aggregate of marcasite-pyrite-melnikovite-pyrite. It is found as relics, rounded to subrounded remnants and inclusions in chalcopyrite and other minerals. It is well known that the replacement, alteration or oxidation is accelerated (facilitated) along cracks, fissures, openings or other zones of weakness and grain boundaries which serve as channel ways for replacing solutions and accelerates the action of the invading solutions. In section Cr22, there is an intergrowth of pyrrhotite with marcasite (Fig. 16) which shows some replacement phenomenon. This may not be ascribed to secondary processes as it is at depth which is far from oxygen laden solutions. This marcasite thus may not be of supergene origin but a normal paragenetic association due to different stages of crystallization from a solution that

was potentially rich in constituents that could precipitate marcasite and pyrrhotite.

In some of the pyrrhotite grains a brown film is so extensive and thick that it reached to a level of masking the anisotropic nature of the mineral. This brownish film is due to the tarnishing and/or air etching by incipient oxidation of polished surfaces. Reflectivity, in most of the sections, is significantly reduced from its theoretical value which may be due to: a) the brown oxidation film, b) poor polishing, c) bireflectance, and d) variation in chemical composition (admixture of chemical impurities). The bireflectance/ reflection pleochroism is observable in some of the grains at least along grain boundaries especially for fresh samples but not visible for samples collected from the secondary zone where alteration effect masked it. Pleochroic effect is displayed by change in reflectivity. The anisotropism of pyrrhotite, in some of the grains, is appreciably reduced and is visible only under high illumination.

Fabric:- Due to the fact that most of the pyrrhotite grains do not develop in to open space, they form allotriomorphic, xenomorphic to hypidiomorphic, granular aggregates, compact masses and less commonly idiomorphic grains. No grain orientation was observed. Simple twinning sometimes lamellar is not uncommon (Ls1-29). In some sections the grain boundaries (where grains are very coarse grained and at depth - section C1) define a triple junction type of arrangement which enables one to say that they exhibit granoblastic polygonal texture, a term related to the petrographic description of rocks. These grains, due to their coarse grained (1-1.5 cm) and partly idiomorphic nature, suggest the precipitation or deposition of pyrrhotite into open spaces at least in some part of the deposit. The grain boundary relationship between pyrrhotite and associated minerals varies from mutual, serrated, irregular to interpenetrating relationship. These relations enabled to construct the paragenesis except in the case of mutual boundaries. Lobate appearance of xenomorphic grain aggregates is also detected. Cleavage is inferred from altered pyrrhotite in which the plane is traced by the alignment of the alteration products which are mostly fine grained, powdery and smoky aggregate of marcasite, pyrite and melnicovite pyrite. The grain size is highly variable from minute crystals up to coarse

grained varieties of 2-3 cm (this is measured in hand specimens but in microscopic observations the size range is from less than 0.02 mm up to 3 mm).

Association:- the pyrrhotite is found as intergrowth of the different phases (monoclinic and hexagonal) which may be attributed to exsolution. But the distinction in ore microscope was not easy as it needs some structural etching. However, the association here was guessed from different susceptibility of the two phases to air etching (incipient oxidation and formation of brown film, peculiar to the monoclinic phase; Stanton, 1972; Ramdohr, 1980). The most frequently encountered association, especially at depth, is between pyrrhotite and chalcopyrite. In this association chalcopyrite is intruding, penetrating and replacing pyrrhotite starting from grain boundaries, cracks, fissures and openings towards the center; sometimes mutually associated each other. The chalcopyrite inclusions in pyrrhotite are sometimes oriented and some times irregularly distributed. Chalcopyrite grains inside pyrrhotite at some places are rounded to subrounded blebs which may suggest exsolution features. The frequent and intimate association of the two minerals in almost all sections may suggest either the breakdown of pyrrhotite to chalcopyrite or their simultaneous or at least certain overlap of deposition, but the most probable and easily seen relationship is replacement which is evidenced by preferred disposition of chalcopyrite in zones of weakness and its preference to grain boundary fillings between pyrrhotite and other minerals. The other associations observed are arsenopyrite, pyrite, marcasite, melnikovite-pyrite and wolframite. Except wolframite which has exclusively mutual relationship, the others have a replacement relationship with pyrrhotite (denoting their later origin).

Alteration/Replacement:- The hypogene replacement is represented by chalcopyrite. Only a single replacement of pyrrhotite by marcasite-pyrite association (intergrowth) in the primary zone is observed (section Cr22). Pyrite is also observed replacing pyrrhotite peripherally (section C1 and Fig.11). This hypogene replacement by pyrite and marcasite may indicate the increase in the S:Fe ratio in the course of crystallization (Ramdohr, 1980). As it has been described before, pyrrhotite is the most susceptible to alteration especially in the secondary zone and even below the

water table. It is well evidenced in the sections by the total disintegration and alteration of the grains whose former presence is shown only by remnants found as inclusions or fragments in the alteration aggregate. In sections collected at 100 meters depth, pyrrhotite is found as remnants/relics, rounded to subrounded sometimes skeletal inclusions in chalcopyrite and galena. The formation of marcasite in the colloform and "bird's eye" texture is striking, wide spread and denotes the feature of the then mentioned mineral in the zone of weathering. The extremely fine grained, black, powderish aggregate along cracks, grain edges and cleavage planes/fissures is constituted by minute, highly birefringent grains which may be marcasite. Pyrite and limonite are also part of the aggregated complex.

Pyrite (FeS₂)

This mineral, next to pyrrhotite, is found widely distributed through out the deposit. It is found as both primary (hypogene) and secondary (supergene) mineral. In the case of the secondary type, it is the result of decomposition of pyrrhotite in the formation of the colloform pyrite-marcasite-melnicovite pyrite association. Unlike to the other sulfides except pyrrhotite, it was possible to collect pyrite crystals even in handspecimen from the gneiss unit. These pyrites are, unlike to the one in the schists and quartz veins, very coarse grained (up to 3-4 cm). It is related to the increase in size of sulfides distributed in metamorphosed rocks with increasing intensity of metamorphism (Stanton, 1972).

Most of the grains observed show weak anomalous anisotropic effect. But as one of the cubic minerals, it has been regarded as optically isotropic. Beside this fact, the observed anomalous anisotropic effect can probably be ascribed to polishing methods and lattice distortion/strain due to chemical impurities, thermal changes and others rather than intrinsic quality of the crystal. However, Stanton (1972) after analyzing 350 pyrite specimens representing a very wide natural depositional conditions, suggested that the anisotropism is real in the case of pyrite. He elaborated this phenomenon by spectrographic studies which confirmed the phenomenon not to be induced by impurities or heating as the anisotropy was not irreversibly affected by temperature up to 570°C.

Fabrics:- Being one of the early minerals formed and its high formation energy in relation to its associates (Uytenbogaardt et al., 1971; Ramdohr, 1980), even if it crystallizes simultaneously with the associated minerals, it generally develops idiomorphically to subidiomorphically, coarser grains showing rectangular or square outlines. Other mode of occurrence is coarse grained aggregates of crystal fragments, fine grained idiomorphic, fine grained spherical to subspherical (rounded) inclusions and free crystals. The secondary pyrite occurs in fine grained aggregate with marcasite and melnicovite. Even if there is no guarantee to say that chalcopyrite blebs found in pyrite are exsolution blebs, some of the pyrite grains have incorporated such features which may be due to residuals from replacement process or later infiltrations. This feature gave the ore minerals poikiloblastic textural feature. Deformations caused by tectonic stress produced breakage, cracking and fragmentation of pyrite grains. Some of the irregular cracks are the site of replacement of pyrite by chalcopyrite. The pyrite crystals are veined and pressed apart by the crystallization pressure of the invading chalcopyrite precipitating solution. In contrary to these fragmented pyrite grains, one can find a number of pure and undeformed pyrite without any breakage or replacement feature. The presence of these two types led to the suggestion that there were probably two generations of pyrite before and after certain stage of tectonic deformation the first stage pyrite being cracked, fractured, fragmented into pieces (cataclastic texture) and deformed due to the brittle nature of pyrite which doesn't allow it to flow plastically during any stress action. The size is highly variable and ranges from 4-5 cm 0.1-4 mm. Twinning and zoning were not observed. But in some grains there is observation of twinning features by different angle of extinction of different portions of a single grain in crossed nicols. However, there is no concluding evidence to say that it is intrinsic property of the grains. It may be ascribed to stress induced feature. Grain boundary relationship of pyrite with each other and grains of other minerals is usually straight and some times curved. But pyrite in the secondary environment is surrounded by advancing front of alteration corona giving a sutured boundary.

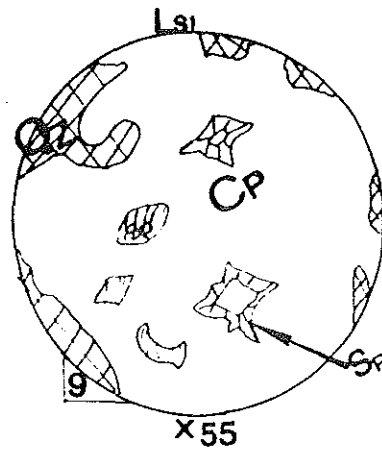
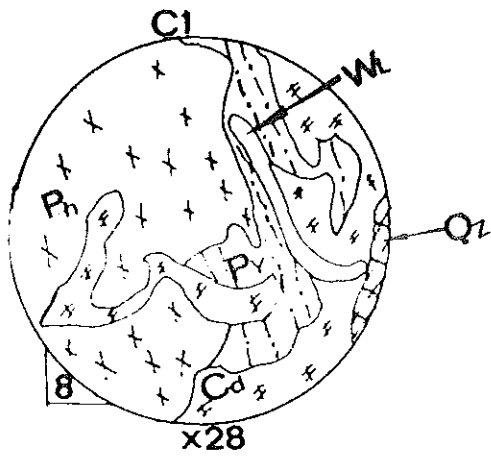


Fig.8 Relation between pyrrhotite (Ph), pyrite (Py) and wolframite (WL).

Fig.9 Starlets of sphalerite (Sp) in Chalcopyrite (Cp).

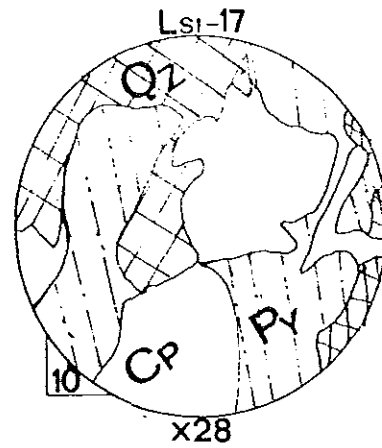
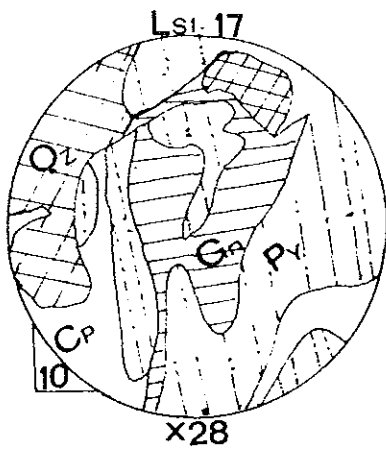


Fig.10 Pyrite (Py) grains fragmented by later precipitating chalcopyrite (Cp) and galena (Gn).

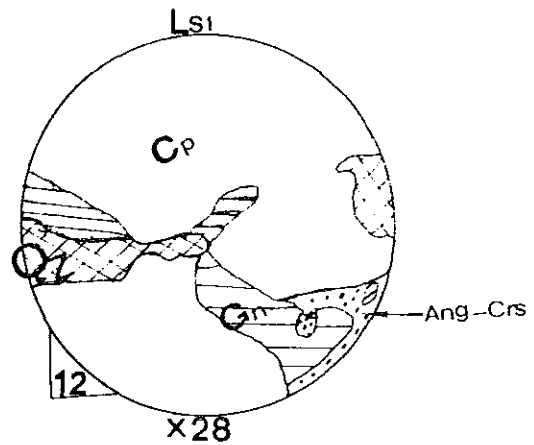
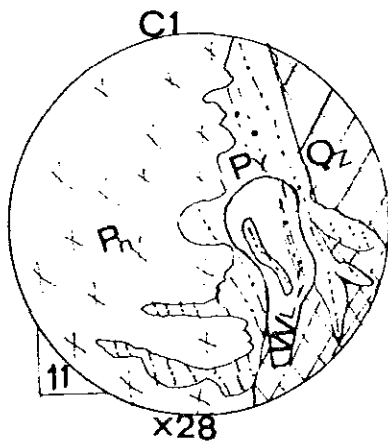


Fig.11 Pyrrhotite (Ph) being intruded by pyrite (Py). Pyrite laths are found in wolframite (WL).

Fig.12 Chalcopyrite (Cp) penetrated by galena (Gn) which inturn oxidized into anglesite-cerussite (Ang-Crs) along cracks and grain boundaries.

Alteration/Replacement:- Pyrite is viable to replacement by ascendant and descendant solutions in any mineral deposit containing pyrite. The replacement is usually facilitated by cataclastic cracks which serve as channel ways for replacing solutions and accelerates the action of the invading solutions (here chalcopyrite-precipitating solutions). According to Ramdohr (1980), replacement is also shown in undeformed pyrite grains and this is ascribed to the position of pyrite in the electrochemical series of minerals and its early formation which gives rise to the greatest chance for subsequent replacement. The replacement observed here is represented by chalcopyrite (most frequently) and galena which was invariably induced by hypogene solutions. The replacement is more evident along cleavage cracks, veinlets and sutured grain boundaries. Most pyrite grains in the zone of weathering incorporated minute, birefringent and anisotropic secondary marcasite grains which probably formed in the first stage of the oxidation of the deposit as a whole.

Associations:- Most frequently pyrite is found as independent separate grains. However, an intergrowth with marcasite and arsenopyrite is observed in some sections (e.g. section Cr22). The following associations are observed:

- *pyrite-chalcopyrite-galena,
- *pyrite-chalcopyrite,
- *pyrite-pyrrhotite-chalcopyrite-wolframite,
- *pyrite-pyrrhotite-chalcopyrite-galena-arsenopyrite,
- *pyrite-arsenopyrite-pyrrhotite, and
- *pyrite-chalcopyrite-galena-sphalerite.

Chalcopyrite (CuFeS_2) is observed in all sections in variable quantities. It shows a distinct vertical variation in relative percentage (upward increasing pattern).

habits:- Chalcopyrite is found in compact crystals, as independent grains or associated with other sulfides such as sphalerite and pyrrhotite. It also occurs as acicular and lamellar crystal exsolved from sphalerite along different directions. Blebs of chalcopyrite in pyrite, sphalerite and others are not uncommon. Some of the more irregular shapes observed are due to the effect of impingement induced by the growth of neighboring minerals or may be due to the irregular features of the cracks

or spaces into which chalcopyrite precipitated. Mostly, when it is in association with other minerals, it occurs xenomorphically/allotriomorphically filling grain boundaries and cracks. The size is highly variable and the measured limits for the sections is from less than 0.02 mm up to 3 mm. It has irregular, sutured to curvilinear grain boundary relationships with other minerals. It also displays mutual as well as penetrating relationship with galena, pyrrhotite, pyrite and other associates. Interlocking of grains are not uncommon. Twinning is very common and occurs in different shape, size, orientation and distribution. The frequently observed lamellar twinning is sharp, very fine to broad, evenly to unevenly distributed (spaced) and less frequently curved. Some of the twins have the characteristic spindle shape. Both twins have different orientations (at least three systems were observed). Both types of twinning may show, according to Ramdohr (1967, 1980): 1) exsolution of high temperature chalcopyrite with decreasing temperature, so they represent transformation structure, 2) later tectonic deformation, or 3) simple growth twinning. The observed mode of occurrences of chalcopyrite are:

- 1) enclosed in pyrrhotite as elongate, xenomorphic crystal, 2) in intimate intergrowth with sphalerite as exsolved phase and in its turn containing starlets of sphalerite, 3) filling grain boundaries between the associated minerals and between ore minerals and gangues, 4) as coarse to fine, rounded to subrounded dot like separate and interspersed grains in the gangue and sulfides (e.g. blebs of chalcopyrite in pyrite), 5) as cracks-, cleavage cracks-, veinlets- and fissure-fillings in pyrite, pyrrhotite and arsenopyrite grains and enveloping the grains of these minerals, and 6) intruding, fragmenting and projecting from edges towards the center of the already mentioned minerals of the earlier generation, but mostly pyrite and pyrrhotite.

As a result of exsolution it shows inclusions of sphalerite (usually star-shaped and irregularly to evenly distributed) worm-like bodies which probably be the tetrahedrite-tennantite group minerals. Chalcopyrite is also found as fine, oriented, needle-shaped to lamellar inclusions in sphalerite. From this relationship, we can suggest that there were two periods characterized by various concentration of the two

minerals. First, abundant precipitation of chalcopyrite with less amount of sphalerite, latter excess sphalerite with reduced chalcopyrite as inclusions in sphalerite.

Associations:- It frequently shows an intimate intergrowth with sphalerite. Other associations are: *chalcopyrite-galena,

*chalcopyrite-pyrite-pyrrhotite,

*chalcopyrite-pyrrhotite,

*chalcopyrite-arsenopyrite-pyrrhotite,

*chalcopyrite-pyrite, and

*chalcopyrite-covellite-chalcocite.

Alteration/Replacement:- Hypogene replacement is mostly represented by galena (Fig.13) which intrudes into and peripherally replaces chalcopyrite. Replacement by sphalerite is also observed. In the zone of oxidation and zone of secondary sulfide enrichment, the alteration and replacement is different. In the weathering zone, it is usually replaced along grain boundaries and cracks by a fine, powdery, blackish to bluish aggregate of its carbonates and hydroxides (malachite and azurite) and limonite. It is usually surrounded by corrugated grain edges which represent alteration rims/coronas. The other important product especially in the cementation zone is covellite (see under covellite). It is found along grain boundaries and as irregular inclusions within the chalcopyrite grains.

Galena (PbS) shows a distinct vertical zonation; scarce or absent at depth and increased relative abundance towards the surface. The overall abundance is limited and is concentrated, like chalcopyrite, in sections collected from the ore zone. In the secondary environment, the color of galena is not the usual one but highly modified by differently (variegated) colored films due to the alteration process. The reflectivity is high except in the weathered varieties in which it is reduced. Concerning the anisotropic effect; as it is cubic, one doesn't expect it. But weak anomalous anisotropism is sometimes observed and it may be due to poor polishing quality, mechanical deformation or chemical impurities.

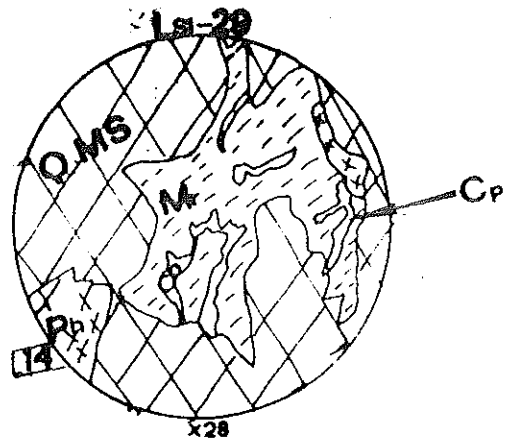


Fig.13 Galena (Gn) penetrating chalcopyrite (Cp) which contains fahlores (Fh). Cv (covellite), Qz (quartz).

Fig.14 Veinlets of chalcopyrite (Cp) along cracks and grain boundaries of marcasite (Mr). Ph (pyrrhotite), QMS (quartz-mica schist).

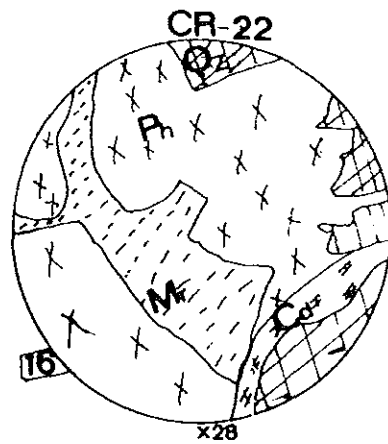
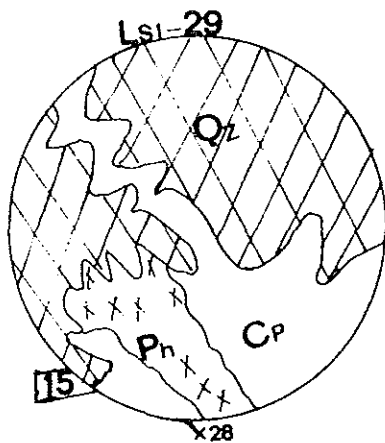


Fig.15 Sulfides (chalcopyrite, Cp and pyrrhotite, Ph) penetrating quartz (Qz) denoting their later origin.

Fig.16 Marcasite (Mr) veining pyrrhotite (Ph). Cd (siderite), Qz (quartz).

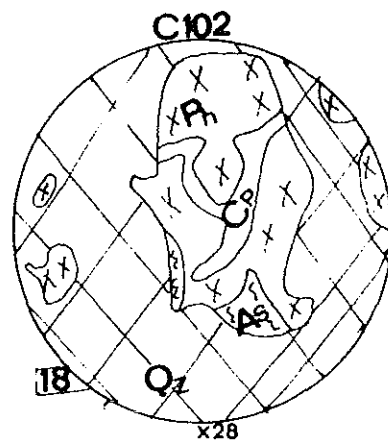
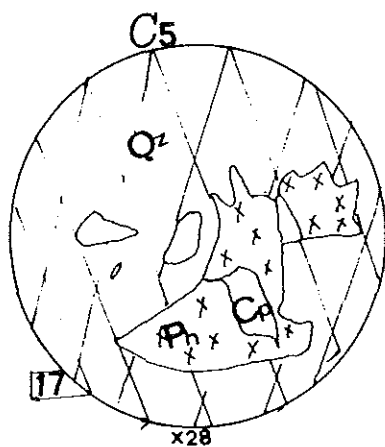


Fig.17 Chalcopyrite (Cp) intruding pyrrhotite (Ph).

Fig.18 Pyrrhotite (Ph) being intruded by both chalcopyrite (Cp) and arsenopyrite (As).

Fabric:- The grains occur as xenomorphic to hypidiomorphic compact mass, granular aggregates and as skeletal crystals (Ls1-17). Straight, irregular, reticulated, sometimes curved grain boundary relationship with the associated minerals is observed. The relation with chalcopyrite is sometimes mutual, with quartz curved, somewhat intruding one to the other allowing paragenetic sequence determination, with chalcopyrite, pyrite, pyrrhotite, arsenopyrite and marcasite, penetrative as well as mutual relationship (galena intruding and replacing the listed minerals). The size is variable ranging from 0.6 mm up to 0.01 mm. Usually it is found as boundary, fracture, vein and fissure fillings within the earlier formed and fractured minerals like pyrite and chalcopyrite.

Intergrowth with chalcopyrite and pyrrhotite, arsenopyrite and pyrite is observed in some of the sections. At least from the sections examined, galena is out of inclusions except its alteration products and relics of earlier existing minerals. But white, worm-like droplets are usually observed and these are most probably altaite. Since galena flows plastically into grain boundaries and fractures of brittle minerals like pyrite (Gill, 1969; Burke et al., 1971; Barnes, 1967, 1975; Ramdohr, 1967, 1980), deformation features are not easily observable except twinning, anisotropic effect and bending of cleavage planes. However, except the anomalous anisotropy, there was no sign of deformation. But the fractured nature of the associated minerals (e.g. pyrite) whose fracture is filled by galena itself and other minerals demonstrate the effect of deformation on both minerals. Gill (1969) conducted experimental deformation and annealing of sulfides and reached at the following conclusions. Plastic flow occurs very quickly in galena and chalcopyrite at temperatures within the range recognized for rocks of the greenschist and amphibolite facies under confining pressure less than 1700 bars. Under these conditions, sphalerite may adjust by minor twinning or fracture while pyrite fails by fracturing. His result confirmed that if mixtures of galena, chalcopyrite, pyrite, pyrrhotite and sphalerite were treated in the same manner, galena could be forced mechanically into cracks in the other minerals. Galena, chalcopyrite and pyrrhotite could penetrate pyrite and sphalerite. The later ones could be granulated and the grains would be spread out by plastic flow of

galena and chalcopyrite - a case demonstrated by this work in sections and where pyrite grains are pushed apart by veinlets of chalcopyrite and galena. The other to mention here is that had the deformation took place and the temperature high enough, galena would have been recrystallized, but no recrystallization is seen.

Alteration/Replacement:- Galena is one of the susceptible mineral to weathering or alteration in the zone of oxidation and enrichment. But due to the fact that the alteration products especially anglesite are highly insoluble, once the decomposition commences, it will immediately be protected from further decomposition by the enveloping film or aggregate of these products. This fact is well observed in the samples from the zone of oxidation and cementation (Ls-5, Ls1-2, Ls1-20). Most of the galena grains are encrusted, enveloped, blanketed or surrounded by thick crust of an aggregate constituted by very fine grained, even difficult to identify, anglesite, cerussite and limonite. Galena is zonally and peripherally replaced by cerussite and anglesite. They are excellently developed along the cubic cleavage cracks, fissures and boundaries (grain edges).

The association (aggregate) is also constituted by very fine grain covellite and chalcocite precipitates which normally show intimate association with anglesite, cerussite and galena itself. In some part of the sections (e.g. Ls1), the replacement is almost complete and only traces of irregularly distributed relics of galena are found in a matrix of very fine grained aggregate of covellite-chalcocite-limonite-marcasite.

The formation of covellite and chalcocite is related to their precipitation on galena grains in the zone of oxidation and most frequently in the zone of secondary sulfide enrichment zone due to the release of trace amount of Cu from copper containing minerals like chalcopyrite by weathering and formation of acidic compounds like sulfuric acid (Sato, 1960; Stanton, 1972; Ramdohr, 1980).

Arsenopyrite (FeAsS) is found both in hypogene and supergene environments as primary and secondary mineral. The secondary arsenopyrite is the result of decomposition of mostly pyrrhotite. The relative abundance is subordinate to the other sulfides (especially pyrite, pyrrhotite, chalcopyrite and marcasite).

Fabric:- Usually idiomorphically developed, in many cases, with characteristics

rhomb-shaped; also as skeleton-shaped, hypidiomorphic granular and elongated (when it is found as inclusions). Grains have straight to slightly curved boundary relations with their neighbors. It is found in association with pyrrhotite, pyrite (in intimate intergrowth), marcasite, galena, chalcopyrite and sometimes with sphalerite. It intrudes and projects towards the center of some pyrrhotite grains (section C90). Sometimes enclosed in pyrite and pyrrhotite (section C34). Occurrences between pyrrhotite and gangues mainly quartz as boundary fillings are also observed (section Ls1-29). Independent and isolated crystals interspersed in the surrounding gangue are not uncommon. Arsenopyrite in schists, like pyrite, shows a well developed parallel to subparallel arrangement to the schistosity of the host rocks. The size of grains is variable, less than 0.02 mm up to 0.5 mm. Lamellar twinning (in one direction) is commonly observed in grains especially in the primary environment. Fragmentation (cataclastic texture) is observed in some of the grains like pyrite (sections Ls-5, C100, C90). This is simply due to its early crystallization and brittle nature.

Alteration/Replacement:- Due to the fact that most of the grains are found isolated and separated, determination of alteration and replacement is very difficult. Hence, these phenomena are not as extensive as in the other sulfides. It seems to be replaced by galena and chalcopyrite, but there is no any concluding textural relationship that denotes replacement phenomenon. In its part, arsenopyrite replaces pyrrhotite. With pyrite it has mutual relationship which prohibits inference of replacement feature. In the secondary environment and zone of cementation, it is replaced by very fine grained aggregate of galena, marcasite and covellite.

Marcasite (FeS₂) has restricted distribution but detected from both at depth and surface. It is more abundant in the pit samples than samples from the primary environment. Since marcasite is the low temperature form of FeS₂ and forms under acidic conditions (Stanton, 1972), it is not strange if one finds more frequently in the secondary zone where the temperature is low and acidic conditions are set by the formation of H₂SO₄ from primary pyrite. In addition to this, marcasite is added by the decomposition of pyrrhotite (since it is the low temperature alteration product of pyrrhotite).

Fabric: Marcasite occurs less frequently as idiomorphic to hypidiomorphic crystals. But the most important occurrence is in the colloform and bird's eye texture, as encrustation on pyrite and pyrrhotite, as fracture (vein) filling in pyrrhotite and pyrite, as swarms of very fine grained crystals invading pyrrhotite and pyrite and as alternating layers with pyrite, covellite, melnikovite-pyrite and chalcocite aggregate in the alteration product of pyrite and pyrrhotite. It is usually observed irregularly replacing pyrrhotite. The size is extremely variable from very minute crystals which are even below the resolution power of the microscope up to independent crystals of 0.5-1 mm. Usually forms intergrowth with arsenopyrite, pyrite, melnikovite-pyrite and less frequently with covellite.

Covellite (CuS) is usually confined only to the zone of secondary sulfide enrichment and is exclusively associated with chalcopyrite as enclosed grains or around margins and some times with the associated galena grains. No even single grain was observed from samples at depth. Hence hypogene origin of covellite is improbable or not possible in this deposit. The occurrence of covellite in the zone of cementation and oxidation is related to decomposition of pyrite and other iron sulfides giving sulfuric acid and ferric sulfate (Baumann, 1976). Surface water enriched in these components may attack copper bearing minerals like chalcopyrite and produce CuSO_4 solutions. The solutions percolate deeper into the ore body and further attack primary material producing chalcocite and covellite (Sato, 1960; Takahashi, 1960; Evans, 1980; Stanton, 1972). Hence, covellite here is associated to supergene origin.

Fabric: The rare occurrence and small grain size of covellite prohibited observation of detail nature of the mineral (shape, arrangement, twinning, etc). The possible explanation from what is observed are the following. Grains under crossed nicol show subidiomorphic granular aggregation; rarely a tendency to idioblastic development is seen. Lamellar to lobate nature are not uncommon. Grain size is highly variable from minute fine aggregation to individual grains of about 1 mm size. The exclusive association of covellite with chalcopyrite (within chalcopyrite grains replacing in an irregular fashion or around their boundaries with other minerals) is in support to the decomposition of chalcopyrite, which is the common originate of covellite, to give the

mineral in question in the zone of cementation or at the base of the weathering/oxidation zone. It shows an intimate intergrowth with chalcopyrite, some times galena and very fine aggregate of chalcocite, marcasite, limonite, malachite and azurite. In this association, one observes the degeneration of chalcopyrite into chalcocite-covellite-marcasite aggregate due to the secondary processes. Chalcopyrite, which may originally be single grain, disintegrated giving rise to a coarse-network of covellite and limonite as well as innumerable holes. The replacement of chalcopyrite by covellite is quite irregular, without any relation to the forms of the chalcopyrite. Burke (1972) and Ramdohr (1967, 1980) described the different possibilities of occurrence of covellite in the secondary sulfide enrichment zone. In some particular cases the chalcopyrite may have disappeared completely and only the arrangement of the covellite lamellae in loose lattices can prove its former existence. In rare cases the disintegration of chalcopyrite will create a mixture of covellite and marcasite.

Chalcocite (supergene) is found in fine-grained ground mass, like what Ramdohr referred to "sooty chalcocite" composed of chalcocite and covellite intergrowth disposed around chalcopyrite and galena as a reaction rim or corona. Since there is no any perceptible isolated chalcocite grain, exact determination of properties of the then mentioned mineral was not possible.

Melnikovite-Pyrite is secondary mineral that resulted from decomposition/weathering of pyrite and pyrrhotite.

It has variable color, yellowish white, brownish, dark powdery and sooty. Reflectivity is low rarely moderate, at places approximating that of pyrite / marcasite. Bireflectance / reflection pleochroism and anisotropism were not observed.

Fabric:- It occurs as concentric colloform aggregate, rhythmically layered as fine, porous, blackish powder and sometimes as pure crystalline. Xenomorphic or skeletal grains set in the powdery porous matrix are also common. It surrounds relics pyrite grains as advancing front of weathering giving a sutured grain boundary. In the powdery porous matrix, the minute birefringent marcasite crystals are very common. The concentric layers and rhythmic colloform textures (section Ls1-20) of the marcasite-melnikovite-pyrite association is striking and it may suggest rhythmic

precipitation and/or the effect of weathering on pyrite (probably also pyrrhotite, but no relics of this mineral was observed in association with melnicovite-pyrite) giving rise to this association. The melnicovite aggregate and the pure crystalline grains are seen to predate and intrude galena, form a film between galena, quartz and pyrite. The association as a whole is an indication of the low temperature origin (Einaudi, 1971; Ramdohr, 1980).

Sphalerite (ZnS) has very restricted distribution. The already observed grains are small in size prohibiting property determination in microscope except certain crystals. It is the least common sulfide. Rarely isolated, more often associated with other sulfides especially with chalcopyrite whose relationship is a type of exsolution either stars of sphalerite in chalcopyrite or droplets and needles of chalcopyrite in sphalerite. Sphalerite associated with galena especially along grain boundaries with chalcopyrite is observed.

Internal Reflection was not well represented except some grains. According to Burke et al. (1971) at about 10% of iron, the zinc sulfide becomes opaque and internal reflections can no longer be observed. So, the rare observation of internal reflections will be ascribed to this fact.

Fabric:- Xenomorphic to hypidiomorphic, rounded to subrounded and some of the grains approximate polygonal outline. Usually associated with chalcopyrite, sometimes between grains of chalcopyrite and pyrite, chalcopyrite and galena, chalcopyrite and pyrrhotite and between chalcopyrite and the associated gangue minerals commonly quartz. Size is very small rarely up to 0.1 mm. They show intergrowth with chalcopyrite, irregularly to regularly distributed starlets of sphalerite in chalcopyrite. In its turn, sphalerite contains droplets and needles of chalcopyrite usually without systematic disposition and sometimes regularly distributed. Sphalerite is thus assumed to have different generations starting from high temperature (when they are found as starlets of sphalerite in chalcopyrite) up to low temperature range.

Other minerals

The other minerals observed as free or isolated crystals distributed in the gangue or as accessory rock-forming ones are ilmenite, sphene and magnetite. Wolframite

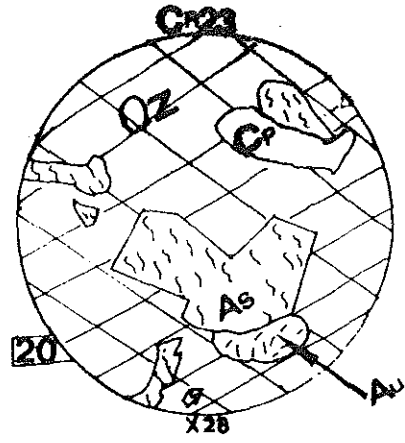
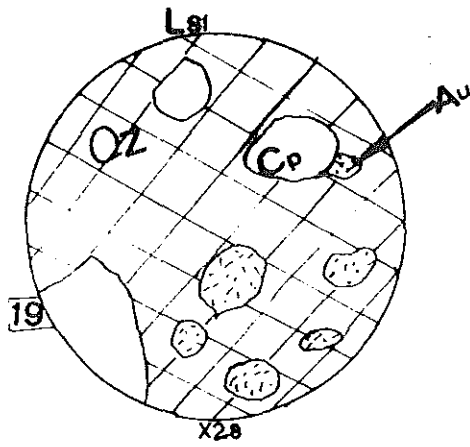


Fig.19 Relation between gold (Au), quartz (Qz) and chalcopyrite (Cp).

Fig.20 Relation between gold (Au) and arsenopyrite (As).

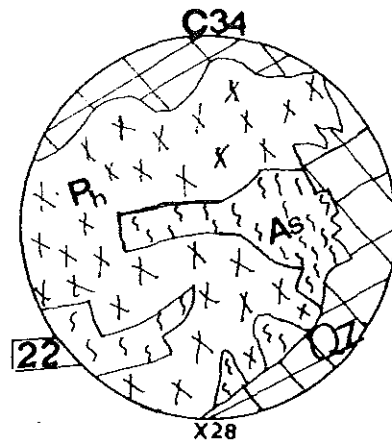
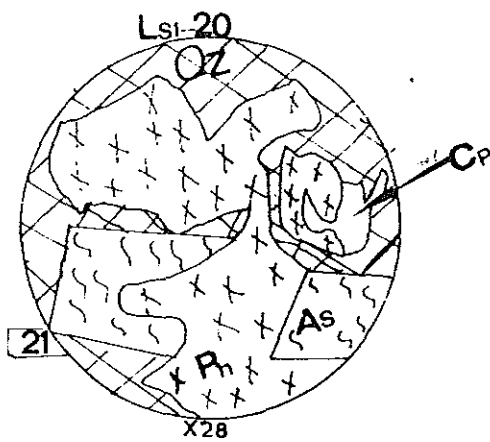


Fig.21 Pyrrhotite (Ph)-arsenopyrite (As)-chalcopyrite (Cp) relationship.

Fig.22 Arsenopyrite (As) penetrating pyrrhotite (Ph).

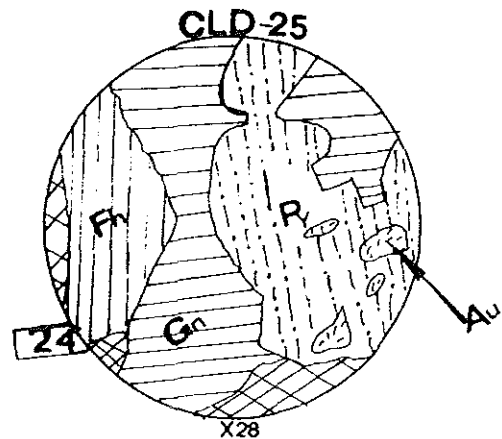
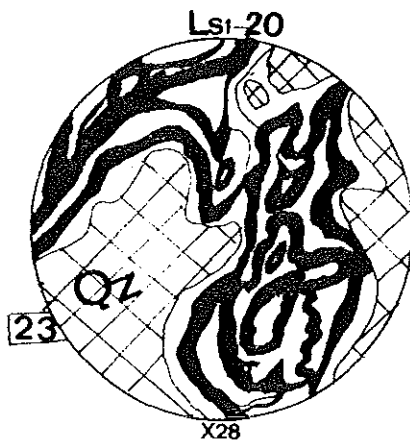


Fig.23 Colloform and bird's eye texture of melnicovite-pyrite.

Fig.24 Gold (Au) locked in pyrite (Py). Gn (galena), Fh (fahlore), Qz (quartz).

is somewhat found in good proportion and sometimes associated with pyrrhotite having mutual boundary relationship. Wolframite occurs as idiomorphic, columnar (tabular), lath-shaped to xenomorphic, rounded to subrounded and sometimes reticulated grains. Size is variable from less than a millimeter to 1 mm. It is strongly anisotropic, reflectivity is low and frequently twinned (lamellar). It sometimes shows alteration crowns surrounding it as enveloping coronas. The alteration is also displayed at the center of grains as intergrowth of wolframite and the alteration product.

Gold was also found in samples dominated by chalcopyrite and galena (sections C84, Ls1, Ls1-5, CLD-25). Here, it is found as very fine grained (less than 0.02 mm up to 0.3 mm), isolated and interspersed, rounded to subrounded crystals in the gangue mineral (quartz). Sometimes, in addition to the mutual grain boundary relationship, it forms as inclusions inside chalcopyrite. It is also found associated with galena (section C84) and arsenopyrite (section Cr23). In both cases it has mutual boundary relationship (Figures 19 and 20). Gold is also observed as rounded to subrounded elliptical grains of up to 3 mm size locked in pyrite grains (Fig.24).

Fahlöre group minerals are also detected in association with chalcopyrite and galena forming exsolution (as minute droplets and lamellae) type intergrowth constituted by tetrahedrite-chalcopyrite-pyrite and arsenopyrite. The tetrahedrite-tennantite group minerals are also found isolated but most frequently with chalcopyrite. These minerals, in the zone of cementation, show rhythmic intergrowth (especially along the peripheries of grains) with covellite-chalcocite aggregate which shows the disintegration and subsequent deposition of the former.

Sulfosalts of lead (jammessonite-boulangerite series) are commonly developed. They usually occur as compact, sometimes needle like, strongly twinned (probably jammessonite) crystals most frequently associated with galena. Jammessonite-fahlöre association is also observed.

4.2 Mineralogical Zonation

The study of zonation at regional, district or ore body scales has been one of

the principal focus of exploration geologists. This study attracted their attention due to the fact that it is applicable for locating or predicting promising areas, to systematize the result of exploration of a given deposit, for development of mineral deposits and even to prospect in areas of similar geologic features as well as inferring blind ore bodies. Zonality study of ore bodies has a bearing in saving money and time expenditure in blending and/or mining of barren rocks which usually intervene rich zones (Park, 1975; Evans, 1980 and Barnes, 1975).

In accordance with these views, the mineralogical zonation of LDPGD is outlined based on analysis of polished sections collected during the study. Due to the low sampling density, there is not enough and comprehensive data in comparison to the extensivity of the deposit to characterize the zonation, especially the lateral one. Hence, this aspect of the zonation problem is treated in the geochemical part where relatively a good number of data is available for reasonable concluding remarks. Considering the quantity of samples as a limiting condition, the mineralogical zonation study will therefore be a general work and delineation of the different zones is not specific (exact), instead the zones are defined grossly simply by their sequential order of occurrence in which one or two minerals are dominating in a given zone.

More than 90% of the investigated samples come from the ore zone. Therefore, this zonation study is applicable, with a reasonable degree of fairness, to the ore zone. But samples from the wall rocks were not sufficient to characterize the zonation in them. This aspect will be illustrated in the geochemical part in which the geochemistry of the most important sulfide-forming metals like Pb, Cu, Zn, As, Mo and Ni are treated using their assay data.

Examination of the polished sections and plotting of the data on geological cross-sections at their respective position revealed the presence of four zones. These are (from the top to bottom): zone 1 (marcasite-melnicovite-pyrite zone), zone 2 (covellite-chalcocite zone), zone 3 (galena-sphalerite-chalcopyrite zone) and zone 4 (pyrrhotite-wolframite zone). The zones and their characteristic mineral assemblages are as follows. In all of these zones pyrrhotite and pyrite are present in different proportion. The zones are defined based on the relative percentage increase /

decrease of pyrrhotite, presence or absence of galena and sphalerite and occurrence of secondary minerals like covellite.

Zone 1 (marcasite-melnikovite-pyrite zone):- it covers the whole of the oxidation zone up to level 2075. This zone is totally dominated or constituted by secondary minerals that result from the decomposition of hypogene sulfides, viz., galena (anglesite and cerussite), chalcopyrite (oxides, oxycarbonates and hydroxids of copper and iron like malachite, azurite and limonite), and pyrite and pyrrhotite (secondary marcasite and pyrite, melnikovite-pyrite, oxides and hydroxides of iron like limonite and jarosite).

In main, in zone one, oxidation and / or disulfidization are at their zenith but irregularly developed. Almost all sulfides, if present, are observed as relics or inclusions that have been preserved in the central part of the supergene formations. It is hard to find pyrrhotite. All the weathering products are characterized by irregular granular structure, zonally banded (such as bird's eye textures and colloform melnikovite), fine to coarse veinlets predating the formation of hypogene minerals, as nest-like segregation, 'jackets' on quartz and other gangues, and as fine dissections along the cleavage planes of layered rock-forming minerals. In case of gangues, the most important non-ore constituents of the primary banded schistose ores (actinolite-tremolite, biotite, muscovite, sericite and carbonates, mainly calcite and ankerite) are reduced significantly on account of an increase of the content of kaoline and micaceous aggregates representing a mixture of fine grained segregation of oxides and hydroxides of different metals.

Zone 2 (covellite-chalcocite zone):- this zone is a subzone to zone 3 and has a very narrow vertical extension below the ground water table. It represents the zone of secondary sulfide enrichment. We call it the zone of covellite and chalcocite, even if they are trace constituent, because they are characteristically developed only in this zone as it has been confirmed theoretically (Ramdohr, 1980) and observed practically from the sections studied during this work. Covellite and chalcocite account for 5-6%, marcasite 5%, pyrite 20%, pyrrhotite 15%, chalcopyrite 10%, galena 5% and small amount of malachite, azurite and melnicovite-pyrite. Chalcopyrite, which was originally single grain, is disintegrated giving rise to a coarse network of covellite-

chalcocite aggregate and limonite as well as innumerable holes. Hence, covellite in this zone occurs as decomposition product of chalcopyrite and as a precursor to the actual disintegration of the later in the upper zone (zone of oxidation). In fact, as it has been explained in the ore mineralogy part, covellite is found as grain boundary filling between chalcopyrite and galena showing some replacement phenomena. According to Ramdohr (1980), the replacement of galena by covellite must have been preceded by replacement of galena by chalcocite in which the later is in turn replaced by covellite.

Zone 3 (gold-galena-chalcopyrite zone):- even if the relative percentage of pyrrhotite and pyrite is greater than that of galena, sphalerite and chalcopyrite, it is preferable to call this zone as gold-galena-chalcopyrite zone and treat as a separate zone because of the fact that the peak of the abundance of the latter minerals is registered in this zone. Chalcopyrite in zones 4 and 1 has very low concentration whilst that of galena and sphalerite were not detected in zone 4 and have subdued amount in zones 2 and 1. Towards the bottom part of this zone, pyrrhotite is found as separate, independent, relatively fresh mineral but becomes disintegrated and seen as relics and inclusions in chalcopyrite and pyrite showing its replacement by the aforementioned sulfides. Its relative percentage decreased from 80% (in zone 4) to 20% (zone 3). Gold is found as isolated grain in quartz and in association with galena and chalcopyrite displaying mutual grain boundary relationship. Gold locked in grains of chalcopyrite and pyrite is also observed. Gold-galena and gold-chalcopyrite association is typical here while in zone 4 association is with high temperature sulfides like arsenopyrite or as isolated grain, in zone-1 (oxidation zone) gold is set free by the weathering process and is found mostly as individual free crystals. The most important gold pay lodes corresponds with this zone having an assay value of gold 1-60 g/t. Zone 3 contains almost all hypogene minerals detected in ores and include: galena (17%), sphalerite (1-5%), pyrrhotite (20%), pyrite (24%), marcasite (5%), arsenopyrite (8%), chalcopyrite (20%) and wolframite (1.5%). Here, distinction from the other zones is blurring as it contains minerals of all zones, except some, and this may be due to the telescoping effect which occurred due to the steep

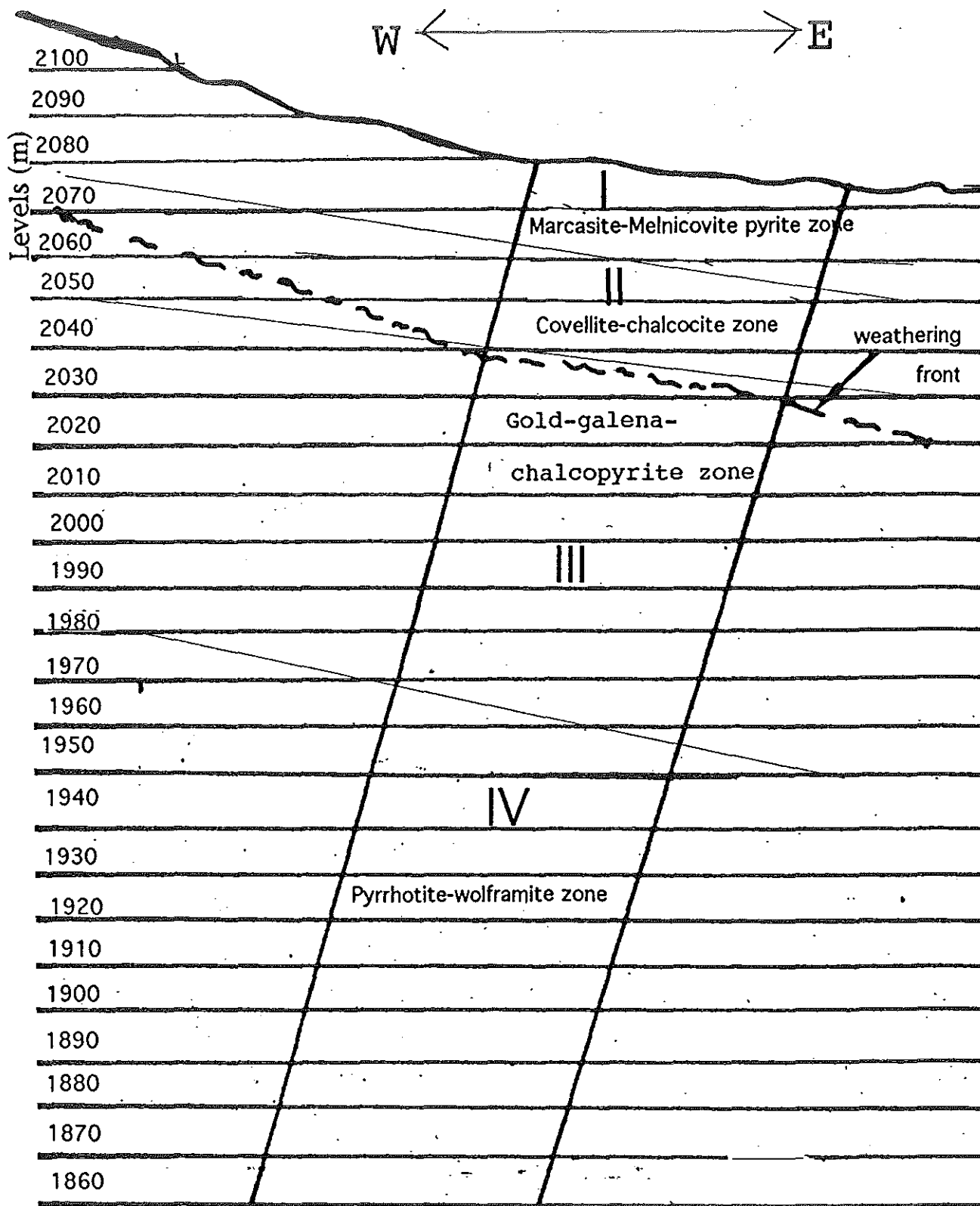


Fig.25 Vertical zonation of ore minerals from LDPGD

gradient of pressure and temperature causing rapid deposition of the ore minerals (Park, 1975). This low temperature effect is also confirmed by the retrogressive nature of metamorphism in the host rocks. Had the precipitation proceeded slowly, there would have been further differentiation of the ore minerals and the low temperature sulfides like galena would have been concentrated further up and this zone dominated by high to medium temperature sulfides like arsenopyrite and pyrrhotite. In contrary to this zone, zone 4 is constituted by limited number of minerals largely by pyrrhotite, wolframite, pyrite and marcasite with trace amount of chalcopyrite. This is probably due to the gentler gradient of pressure and temperature causing slow deposition of minerals and effecting a well defined separation of the high temperature minerals.

Concerning the mineral associations which are typical to this zone, we can only say that the observed assemblages are very diverse. Even if the pyrrhotite-chalcopyrite association is still important, it is shared by chalcopyrite-galena and chalcopyrite-sphalerite which are prominent in this zone. The relative proportion of chalcopyrite is increased and changes in its properties are noted. In chalcopyrite starlets of sphalerite exsolutions, lamellar to spindle shaped and "Oleander Leaf" lamellae which are supposed to be twin lamellae of a former high temperature chalcopyrite (Ramdohr, 1980) are vivid and extensively developed in this zone than they are in zone 4.

The pyrrhotite-arsenopyrite association of zone 4 which is to some extent penetrative (arsenopyrite wedging into pyrrhotite) is changed to arsenopyrite-pyrite intergrowth (section C90) in which pyrite seems to be a later generation mineral and pyrrhotite-arsenopyrite which is less abundant and characteristically mutually related. Observed changes on pyrite is concerning its deformation features. Pyrite in zone 4 is not deformed but in zone 3 some of its grains display fissured and cracked appearance (Ls1-17). This may suggest the presence of two types of pyrite. Wolframite is found isolated and interspersed in the gangue.

The other, probably the most important, difference between zone 4 and zone 3 is with respect to gold associates. In zone 4 gold is observed associated only with

arsenopyrite This assemblage is changed to the typical gold-galena and gold-chalcopyrite and gold-pyrite associations; in fact presence of isolated gold grains is common to all zones. In both cases gold has mutual boundaries relationship with the respective sulfides. Other than these, galena-arsenopyrite-pyrite, galena-pyrite-chalcopyrite, pyrite-galena, sphalerite-chalcopyrite-galena and chalcopyrite-pyrite are common assemblages.

The approximate vertical extension of this zone is from level 1980 m up to the base of the oxidation zone (level ~2075 m). This depth extension includes zone 2 which is considered to be the top most part of this zone.

Zone 4 (pyrrhotite-wolframite zone):- in this zone the leading mineral is pyrrhotite averaging 80%. Also present are wolframite (~9%), pyrite (6.2%), arsenopyrite (1.4%), marcasite (2.2%) and chalcopyrite (1.8%). This zone covers the deepest level of the deposit. In this zone gold is observed to be associated with sulfides other than galena most probably with chalcopyrite and the already observed one is the clear mutual relationship between gold and arsenopyrite (section Cr23, Fig.20). In case of chalcopyrite except its presence no association with gold was observed. Pyrrhotite is unaltered (fresh) except the hypogene replacement by marcasite and pyrite which is supposed to be the result of increasing S:Fe ratio during progressive deposition of ore minerals (Ramdohr, 1980). The possible tentative upper boundary of this zone could be level 1980. The usually encountered associations in this zone are pyrrhotite-arsenopyrite in which the later penetrates the former, pyrrhotite-chalcopyrite, pyrrhotite-chalcopyrite-pyrite, wolframite-pyrrhotite, arsenopyrite-pyrite and arsenopyrite-gold.

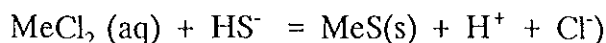
The observations so far discussed could be explained by different hypotheses forwarded by different researchers such as Smirnov's pulsation theory (1976), Barnes (1962), Barnes and Czamanske (1976), Emmons (1980) and others. Generally speaking, such type of vertical zonation could be explained by the fact that among the iron sulfides (mainly pyrrhotite, pyrite and marcasite), pyrrhotite is the high temperature modification and is expected to occupy the deepest part of many deposits containing these varieties of iron sulfides. Moreover, this zonation of iron

sulfides, galena, chalcopyrite, sphalerite and others is related to the sequence of deposition confirmed in the paragenesis of the deposit. It is also described by Barnes (1975). According to this author (in Evans, 1980), the relative stabilities of complex metal bisulfide ions will control their relative time of precipitation and hence both the resulting paragenetic sequence and any zoning which may develop in a deposit. He calculated the stability sequence of different metals in the bisulfide complexes (Table 2). According to these data, iron would be precipitated early in the paragenetic sequence and would be present in the lowest zone of a zoned deposit whilst Zn, Cu and Ag would be late precipitates which would travel furthest from the source of the mineralizing solutions. In fact this trend will be interrupted by pH, wall rock alterations, decrease in P-T conditions on approaching surficial conditions and others. The same reasoning would be applied to the sulfides formed by the metals (i.e., galena-Pb, Sphalerite-Zn, Chalcopyrite-Cu and Fe, etc) and the concentration of galena, sphalerite and chalcopyrite in to the upper part of the Lega Dembi deposit would be justified by this experimental result of Barnes (Tables 2, 3 and 4). This fact will apply to the deposit in question provided the mineralizing solutions originated from great depth, channeled along the deep fault and enriched by picking up metals from the wall rocks through which they are travelling during the hydrothermal metamorphism of the wall rock.

Table 2 Predicted Sequence of Stabilities of bisulfide Complexes in kilocalories (adapted from A.M. Evans, 1980).

Least solubleMost soluble							
Fe	Ni	Sn	Zn	Cu	Pb	Ag	Hg
79	84	126	132	135	153	157	226

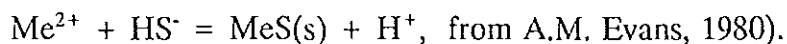
Table 3 Relative Stabilities of Sulfides in Chloride Solutions (as expressed by the equilibrium for the reaction:



(extracted from A.M. Evans, 1980).

	Least soluble.....Most	soluble	
	CuS	PbS	ZnS
at 25°C	38.4	28.2	27.7

Table 4 Relative Stabilities of Sulfides in Ionic Solutions (as expressed by the equilibrium constant for the reaction:



	Least soluble.....Most	soluble	
CuFeS ₂	PbS	ZnS	
23.7	20.7	19.2	

4.3 Parageneses

The paragenesis in the sense of ore minerals association in the deposit is described in detail in the ore mineralogy part. Here, it will be treated with respect to the time of deposition or order of formation of the minerals in time succession.

Sequential deposition of minerals have been ascribed, at different times, to atomic weights of the metals, densities of fluids, metal-sulfur ratios, electrode potentials, mineral hardness, free energies of minerals formation and others which seem to be the result of change in temperature and pressure influencing the solubilities of the minerals (Park, 1975). It is well known that when a hydrothermal solution with a specific chemical composition, temperature, pH and pressure migrates from place to place it reacts with the wall rocks and changes in its properties take place. During this migration and change in different physical and chemical conditions,

the stability points of the different gangue and ore minerals reaches and the minerals are deposited sequentially leaving a specific record in the evolution of a given deposit. The study of the paragenetic nature of the associated minerals is thus vital from economic and scientific point of view. Paragenetic studies are very important since they enable to determine geologic history of ore deposits and efficient method for beneficiation and milling of ores.

General paragenetic models for the sequential deposition of gangues and ore minerals have been given by different authors like Lindgren (1937), Edwards (1947, 1952) and others.

Usually paragenetic studies are the result of identification of minerals and textural characterization of the associated minerals. The data are collected from the studies of polished sections, thin sections and handspecimens as well as field studies. In this research, the data are limited in comparison to the extent of the deposit; hence, the paragenesis constructed is tentative. Forty five polished sections and twenty nine thin sections have been studied. In addition to the data collected in this study, previously collected data were taken into consideration to make the study complete.

Pyrrhotite is the earliest in the paragenesis. It is found in some places as exsolution intergrowth of monoclinic and hexagonal pyrrhotite. There is little or no association of gold with pyrrhotite. There is observation of gold in sections containing pyrrhotite and some times association of the two (Fiori, et al, 1988). Hence, even if the economically important gold is related to the low temperature sulfide association, there is a possibility of many generations of gold i.e. some of the gold may have been introduced during each period of mineralization while the most of the gold was introduced and deposited in the late stage of mineralization. Therefore, it is difficult to place gold to a specific time interval in relation to the deposition of the associated minerals unless systematic details are conducted to characterize the different generations. Wolframite has mutual relation with pyrrhotite and is found in all the investigated sections. It seems to be one of the earlier minerals. The next to pyrrhotite in the paragenesis is pyrite with arsenopyrite. But, since arsenopyrite in

association with other minerals is rare, the age relation of it to pyrite and other minerals except pyrrhotite (which is earlier) is doubtful. However, in section Ls1-50 arsenopyrite seems to penetrate pyrite and this may give some indication to the later origin of arsenopyrite in relation to pyrite. Chalcopyrite follows these minerals. Chalcopyrite associated with pyrrhotite penetrates the later but penetrated by galena. It seems that chalcopyrite is through runner in the ores having different generations starting from the high temperature range. In relation to sphalerite, chalcopyrite has two generations:- the first with abundant chalcopyrite and subordinate sphalerite and then subdued amount of chalcopyrite with increasing proportion of sphalerite. The next mineral with some overlap with sphalerite is galena. Galena with tellurides and sulfosalts is the youngest of the hypogene domain of the minerals in the Lega Dembi primary gold deposit. The most important thing to mention here is that most or all of the minerals have an appreciable overlap in space and time during their history of deposition by replacement of the host rocks.

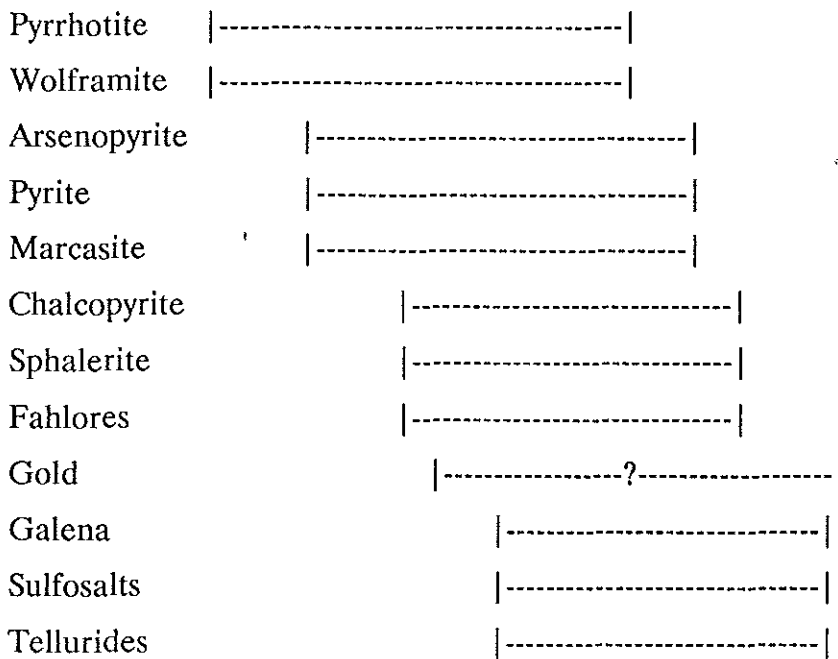


Fig.26 Tentative paragenetic diagram of minerals from the LDPGD.

5. GEOCHEMISTRY OF SULFIDE-FORMING ELEMENTS IN ORES AND ENCLOSING ROCKS

5.1 General

The LDPGD is a complex association of different metals that are variously correlated with Au. The metals of Au associates are Cu, Pb, As, Ag, Zn, W, Sb, Co, Ni and Mo. These metals have geochemical distribution which is governed by types of host rocks and the environment (hypogene vs. supergene). Some of the metals show a preference towards clustering together in certain lithologies and environment. The pattern of distribution of the elements and their associations will be treated. A total of 1939 core samples collected during the exploration of the deposit were used. Among these 125 in foot wall rocks (FW), 513 in unweathered hanging wall (UHW), 986 in unweathered ore zone (UOZ), 262 in weathered hanging wall (WHW) and 53 are in weathered ore zone (WOZ) . Before going to the actual treatment of data, it is mandatory to revise the established theoretical and practical facts and backgrounds on the distribution and association of elements in different parts of the earth, in rock types and environments as well as their behavior during magmatic, metamorphic and sedimentary processes.

Many outstanding geochemists and geologists were involved to elaborate the geochemical behavior and distribution of elements in various parts of the earth and associated environments under different natural geological processes. Such works were done by Goldschmidt, Clark, Taylor, Mason, Krausopf, Shaw and others. Some of the ideas reflected and forwarded by Goldschmidt (1954), Krausopf (1967), Mason (1966) and Rankama (1955) are shortly discussed below.

The present pattern of distribution of elements has in part and / or at all resulted from the primordial geochemical differentiation of the elements during the formation and subsequent fractionation, differentiation and solidification of the earth; but the original distribution was and still is being appreciably modified by later processes such as magmatism, metamorphism, weathering and others. Goldschmidt (1954) ascribed the scarcity of Au, Ag and other metals to the original differentiation of the earth into iron core and silicate crust (these elements had preference to metal

phase hence concentrated into iron core). He postulated (based on the composition of mainly meteorites and smelter products) the presence of three separate liquid phases during cooling into the present earth. These are metallic iron, silicate and iron sulfide phases. The elements separate or group themselves according to their affinity into the silicate, sulfide or metal phase. This principle is applicable to the distribution of elements from magmatic melt. The geochemical distribution of the naturally occurring elements is thus the result of their chemical affinity for metal, sulfide or silicate phases and their chemical behavior in the different environments (this is because the processes that take place in different environments are unlike and hence the major phases that can be formed are also variable). The phases that can be formed in any geochemical processes are controlled by the electronic configurations of the constituent atoms and the prevailing physical and chemical conditions. This means that the geochemical character of a melt is largely governed by electronic configuration of atoms and hence closely related to its systematic position in the periodic table. Hence, the elements distribute themselves into different phases according to their chemical behavior during fractionation, differentiation and segregation that occur in the formation of their host rocks. Since certain elements have overlapping geochemical behavior due to their similarity in electronic configuration of their electrons (intimately related to their position in the periodic table), different elements can have almost similar affinity to the phases and hence they act in a similar fashion in a given environment. This similar affinity leads to the idea that elements are observed in certain defined, although broadly, association in nature. This is well illustrated and described by Goldschmidt's geochemical classification of the elements (Table 5).

Goldschmidt (1954) classified all elements into:

- 1) siderophil (iron-loving) - they tend to concentrate into the metallic phase,
- 2) lithophil - these are elements that concentrate in the stony matter of meteorites and hence in the silicate phase (they are found concentrated in the crust of the earth), and
- 3) chalcophil elements- they prefer to make a covalent bond with sulfur and

hence found forming sulfides with sulfur.

The siderophil group contains elements that have electronic configuration such that their valence electrons under certain chemical conditions are not readily available for combination with other elements due to the strong pull of the positive nucleus on the outer electrons and hence mostly occur in native or uncombined state. Lithophils and chalcophils have electrons that are more available to form ions. However, the ions of lithophils tend to form more ionic bond with oxygen (i.e. in silicates) while chalcophils prefer to form covalent bond with sulfur. This variation is ascribed also to different electronic structure. The chalcophil elements have

Table 5 Geochemical classification of elements (Goldschmidt, 1954)

iron, siderophils	sulfide, chalcophil		silicate, lithophil	gases, atmophil	organisms, biophil
	meteorites	terrestrial			
-Fe, Ni, Co -P, (As), C -Ru, Rh, Pd -Os, Ir, Pt, Au -Ge, Sn -Mo, (W) -(Nb), Ta -(Se), (Te)	-S, Se, (Te?) -P, As, (Sb?) -Cu, Ag, Zn, Cd -(Ti), V, Cr, Mn, Fe -(Ca)	-S, Se, Te -As, Sb, Bi -Ga, In, Tl -(Ge), (Sn), Pb -Zn, Cd, Hg -Cu, Ag, (Au) -Ni, Pd, (Pt) -Co, (Rh, Ir) -Fe, Rh, (Os)	-O, (S), (P), (H) -Si, Ti, Zr, Hf, Th -F, Cl, Br, I (Sn) -B, Al, (Ga), Sc, Y -La, Ce, Pr, Nd, Sm -Eu, Gd, Tb, Dy -Ho, Er, Tu, Yb, Lu -Li, Na, K, Rb, Cs -Be, Mg, Ca, Sr, Ba -(Fe), V, Cr, Mn -((Ni)), ((Co)), Nb, Ta, -W, U, ((C))	-H, N, C, O -Cl, Br, I -He, Ne, A -Kr, X	-C, H, O, N, P -S, Cl, I, (B) -(Ca, Mg, K, Na) -(V, Mn, Fe, Cu)

valence electrons outside a shell of eighteen electrons but the lithophils have valence electrons outside a shell of eight electrons.

Apart from Goldschmidt's principles of metal association and classification, a number of authors gave different explanations for association of metals especially for processes other than magmatic cooling (Taylor, 1985; Webb et al., 1979; Mason, 1966).

The association of elements in nature and their occurrence around a common host was ascribed to diadochy, free energy of formation, structure of the host, ionic radii, temperature of formation, coordination number, bonding characteristics, charge similarity and others (Mason, 1966). The association in part is explained by similarity in mobility of elements (which is in turn governed by the stability of an element in immobile solid phases relative to the coexisting mobile fluid phase) in a group of geological processes (Webb et al., 1979).

The dispersion and consequently the mobility is effected differently in the different environments. In the deep seated environments, such as cooling from magma, it is governed by Goldschmidt's hypothesis of affinity to the different phases which is in turn the result of the difference in free energy of formation and the partition coefficient K which is dependent on ionic size, ionic charge, coordination and bonding characteristics. The index of ionic replacement (Table 6), which is the effect of radius, charge, coordination number and electronic configuration of cations, explains the presence of elements in common host by substitution due to their similarity in distribution coefficient approximately 1 (Webb et al., 1979). The formation of complex forming ligands like H_2S , HCO_3^- , MoO_4^{2-} , $CuCl_2^-$, $ZnCl_4^{2-}$, $Hg(HS)_3^-$ etc are also considered to affect mobility of elements.

In surficial environments mobility of elements is governed by ionic potential (IP), which is the ratio of charge and size. Elements having low ionic potential (like Na, Ca, etc) are soluble as simple cations, those with very high IP attract oxygen ion and form soluble oxy-anions (PO_4^{3-} , SO_4^{2-} , MoO_4^{2-}) and those with intermediate IP are generally immobile because of very low solubility and strong adsorption to surface (e.g. Al, Ti, Sn, etc). Transition elements like Fe, Cu, Cr, Ag and others tend to be less soluble and more strongly adsorbed than nontransition ions of similar charge and ionic radius (Webb et al., 1979). Differences in valence state are also

Table 6 Index of ionic replacement (Green, 1959 in Webb et al., 1979)

Tl ⁺ 0.03	Cu ⁺² 0.14	Be ⁺² 0.24
K ⁺ 0.03	Co ⁺² 0.14	Nb ⁺⁴ 0.28
Ag ⁺ 0.04	Ni ⁺² 0.14	W ⁺⁴ 0.28
Na ⁺ 0.06	Mg ⁺² 0.14	Mo ⁺⁴ 0.28
Cu ⁺ 0.06	Th ⁺⁴ 0.16	Ti ⁺⁴ 0.28
Ba ⁺² 0.07	U ⁺⁴ 0.19	Al ⁺³ 0.35
Pb ⁺² 0.08	Zr ⁺⁴ 0.20	Ge ⁺⁴ 0.46
Ca ⁺² 0.09	Sc ⁺³ 0.20	Si ⁺⁴ 0.48
Mn ⁺² 0.13	Fe ⁺³ 0.22	As ⁺⁵ 0.60
Zn ⁺² 0.14	Cr ⁺³ 0.22	P ⁺⁵ 0.62
Fe ⁺² 0.14		

Table 7 Relative mobility of elements under surficial environment (Webb et al., 1979)

Relative mobility	Oxidizing (pH 5-8)	Oxidizing (pH < 4)	Reducing
High mobility	Cl, Br, I, S, Rn He, C, N, Mo, B(Se,Te,Re?)	Cl, Br, I, S, Rn He, C, N, B	Cl, Br, I, Rn, He
Moderately mobile	Ca, Na, Mg, Li, F, Ca,Na,Mg,Li Sr, Ba, Ra, F, As(Sr,Hg,Sb)	Zn, Ag, U, V, Hg, Cu, Ag, Co, Ni, U, V, As, Mn,P	Ca, Na, Mg, Sr, Li, F, Zn, Cd, Mn
Slightly mobile	K, Rb, Ba, Mn, Si, Ge, P, Pb, Cu, Ni, Co, (Cd, Be, Ra, In, W?)	Ra	K, Rb, Ba, Si, Ge, Fe K, Rb, Si,P,
Immobile	Fe, Al, Ga, Sc, Ti, Zr, Hf, Th, Pa Sn, REE, Pt metals,Au, (Cr, Nb, Ta, Bi, Cs?)	Fe, Al, Ga, Sc, Ti, Zr, Hf, Th, Pa, Sn, REE, Pt metals, Au As, Mo, Se,	Fe, Al, Ga, Ti, Hf, Th, Pa, Sn, REE, Pt metals Au, Cu, Ag, Pb, Zn, Cd, Hg, Ni, Co, As, Sb, Bi, U, Se, Te, Mo, In, V, Cr (Nb, Ta, Cs?)

resulted in differing mobility.

In igneous rocks trace elements would distribute themselves in much the same manner where rocks form by differentiation. The generally accepted mode of formation of igneous rocks (ultramafic to felsic) is the differentiation or fractionation of a silicate melt which usually follows the rules of Bowen's reaction series and hence every mineral of a given element is formed through the series from ferromagnesian minerals like olivine and calcicplagioclase (early stage) to quartz (late stage). This applies for major elements which have sufficient concentration to form their own minerals (a mineral in which that specific element is the major constituent). The problem is with minor and / or trace elements like Co, Ni, Ag, As, Sb, Zn and the likes. These are accommodated by the silicate minerals that crystallize from a melt according to the characteristics of their ions through camouflaging, capturing, isomorphous substitution and similar processes. To effect such processes which incorporate a given trace element in crystallizing mineral, ionic radii, ionic charge and type of bond that could be formed by the trace element (strong vs. weak bonds, i.e. covalent vs. other bond types) should largely fit with the properties of the major element and these are considered to govern the admittance of any trace element in a given mineral structure as replacement or as random inclusion in the holes of a crystal lattice. But mostly, observational data are decisive instead of relying on this theoretical considerations because any irregularities are common with regard to these principles. The rules are some times broken by: a) bond character, b) differences in differentiation trend, c) tendency of some elements to form their own very stable minerals (e.g., Cr) and d) the preference of some trace elements for certain silicate structures rather than others (e.g., Co and Ni prefer to the olivine structure in coexisting olivines and pyroxenes though the possibility of substitution in both minerals is available).

In metamorphic rocks, minor element distribution is relatively ill-defined. In low grade conditions of metamorphism, no detectable change takes place in the content of trace elements except some redistributions owing to permeation of the rocks by solutions. With increasing metamorphism local redistribution among the growing

crystals take place without major change in overall concentration. When metamorphism reaches a stage of partial melting, their distribution will be governed by the properties that are active during magmatic crystallization.

The distribution of elements in sedimentary formations is governed by the properties of the elements in surficial conditions as described above.

When we consider the metals of the LDPGD, they can be classified into the different groups of Goldschmidt's as follows.

- 1) siderophil - Ni, Co, (As), Au, Mo, (W),
- 2) chalcophil - As, (Sb), Cu, Ag, Zn, Pb, (Au), Ni, Co, and
- 3) lithophil - W, ((Ni)), ((Co)).

Some elements show affinity more than one group and this is ascribed to the fact that the distribution of any element is dependent to some extent on T, P and chemical environment in the system as a whole. Elements in bracket are of secondary preference to the group.

5.2 Geochemical distribution of elements

The geochemical distribution of the elements in the ore veins and enclosing rocks is described below. Due to the problem of complex intercalation and interfingering of the enclosing rocks, it is difficult to find a sample constituted only by one rock type. Hence, in the treatment of geochemical data instead of classifying into different lithotypes, the rocks were classified into five domains: foot wall (FW), unweathered ore zone (UOZ), weathered ore zone (WOZ), unweathered hanging wall (UHW) and weathered hanging wall (WHW). The hanging wall is constituted by amphibolites, carbonaceous quartz-mica schists (CQMS) and small intercalations of actinolite-tremolite-talc-chlorite schists. The ore zone is made of by and large mica-feldspar-quartz schists (MFQS), carbonaceous quartz-mica schists (CQMS), quartz veins, lenses and stringers and actinolite schists. Hornblende schists, talc schists (especially towards the footwall side) and actinolite-tremolite schists are not uncommon. The footwall consists of biotite gneiss with interbeds of hornblende and talc schists near the ore zone.

In order to analyze and study the geochemical distribution of the elements in the ore veins and enclosing rocks, different methods were used. Simple variation diagrams were constructed as content vs. depth. Comparison of the distribution of the elements in the five zones was done using weighted average. Some statistical parameters (standard deviation, maximum, minimum, variance with the number of data) were calculated for each domain (Table 8). Background values for each element in the different rock types were necessary to compare the assay returns so that we can envisage the depletion-enrichment pattern of the rocks with respect to the laments. The background values can not be the same in every geochemical environments. Hence, background values in a given environment should be calculated statistically by analyzing large number of data which are more or less homogenous. But this was not fair in the case of LDPGD because of complex intercalation of the rocks which caused severe diversification of the data (Table 8) and due to unsystematized sampling which was done during prospecting. Treatment of such nonhomogeneous data will lead to misleading conclusion. Hence, values given by Rose et al. (1979) was taken (Table 9) as a reference for the sake of comparison.

When we see the general pattern of distribution of the trace elements, we envisage that the maximum value of most of the traces is found within the ore zone, i.e. within and around the eastern shear zone. This pattern is closely related to favorable sites of deposition of the traces during the process of alteration and metamorphism of the enclosing rocks. Hydrothermal deposition of traces may result from decrease of temperature and pressure, direct chemical reaction between traces and wall rock, and neutralization of solutions by reaction with wall rocks resulting in precipitation of traces. Accepted concepts suggest that substitution in the lattices of wall rock minerals should be greatest in deep-seated magmatic segregation, pegmatites, and hydrothermal deposits where heat and pressure are high, and in altered rocks containing layer lattice minerals with high absorption and base exchange capacities (Graf et al., 1950).

The distribution of the traces is thus closely related to structures and rocks favorable for such processes. Most ore bodies or haloes of traces are localized along

a linear or planar structural elements, such as faults, unconformities, joint intersections, and intrusive margins. Similarly, the distribution of these haloes of traces around a deposit may vary with the distribution of structural elements. This is clearly observed in this deposit where the distribution of the ore elements is intimately related to the shear zone; confirming the fact that major structural elements are ordinarily responsible for localizing alterations and fracturing. In light of this idea the geochemical distributions of the different elements are as follows.

Pb-Cu-Ag-As-Zn-Sb

The geochemical distribution of these metals is almost the same except some deviations in the case of Zn, Sb and less commonly As. Pb, Cu and Ag are represented by flat curves outside the ore zone and displays a sudden jump in their peaks when approaching the ore zone (Fig. 30, 32, 33, 34, 35, 36, 37, 39, 40). Most of their highs are localized to the upper part of the ore veins along their margins in the hanging wall side. Their haloes (anomalous peaks) extend for about 30-115 m from the contact between hanging wall and ore zone in the down hole direction. The silver dispersion haloes are narrower than those of Cu and Pb. High values of Cu and Pb are not uncommon in the weathered hanging wall (Fig. 27, 28, 29, 30, 33, 38). These peaks are due to the concentration of these elements during the process of weathering. Cu, even if it readily goes into solution during weathering, can accumulate in the form of its hydroxy carbonates (malachite and azurite). In case of LDPGD such behavior is also shared by the formation of secondary sulfides such as covellite (see chapter IV). Hence, these peaks are also accompanied by another peaks below the oxidation zone (Fig. 27, 29, 31, 33, 38). This means that dissociation and removal of Cu in the oxidation zone was partial (Fig. 33). In case of Pb, its further dissociation and removal is hindered by the formation of blanket of anglesite and cerussite which are highly stable (insoluble) in surficial conditions. Due to this, migration of Pb and its subsequent secondary precipitation are restricted or not wide spread. These elements are found enriched in the oxidation zone owing to the above mentioned reasons. The maximum weighted averages of Cu, Pb, Ag (347.95, 68.62,

6.63 respectively) are found in the WOZ. The peaks of these elements are spatially coincident with gold peaks. Pb attains its highest value (2000 ppm) in UOZ and WOZ in quartz veins, that of Cu (2000 ppm) in the same zones and lithology, Ag (150 ppm) in UOZ and WOZ, As (6000 ppm) in UOZ and UHW, Zn (2000 ppm) in WOZ and UHW and Sb (300 ppm) in WOZ. As can be seen from both maximum values and weighted average, most of the chalcophil elements have their highest value in the weathered ore zone except arsenic which is concentrated in the unweathered ore zone.

As and Zn highs are localized either in the hanging wall (Fig. 27, 29, 30, 39, 40) or towards the bottom part, i.e. in the foot wall side of the ore zone (Fig. 27, 28, 29, 39). Some peaks of As are also found in the foot wall (Fig. 33, 35). The distribution of Sb is erratic but mostly its peaks are localized within the ore zone. Only certain peaks are observable in the hanging wall (Fig. 28, 29, 30). Sb (95.43 ppm), Zn (365.28 ppm) and As (453.55 ppm) have their highest values in the WOZ, like that of Pb, Cu and Ag. The problem concerning Zn and Sb is that the detection limit for both elements is 100 ppm. Due to the fact that most of the samples have less than this value, they are missing in many samples and hence there is no extensive data to clearly characterize their geochemical distribution in the area.

When we see the distribution of these chalcophil elements, we can envisage their similar geochemical behavior in this environment. As it has been described at the beginning of this chapter, chalcophils usually prefer to combine sulfur forming sulfides instead of entering to any silicate structure. Hence, during hydrothermal process they accumulate and increase in proportion in late stages. Therefore, they are usually partitioned into hydrothermal solutions and transported as sulfides, bisulfides, chloride, sulfate or other complex ions which are stable in the hydrothermal solutions. They are deposited in the form of sulfides in veins when the P-T, structural and chemical conditions are favorable. In the case of LDPGD, such conditions were most probably met near and along the eastern deep fault where extensive development of quartz veins took place. The sulfides together with gold are, therefore, encountered in this zone. The departure of zinc and arsenic from this

pattern, i.e. their peaks in the foot wall and hanging wall, may be ascribed to the fact that arsenic sometimes tends to act like siderophil while that of zinc as lithophil in which it can replace Fe^{2+} and Mg^{2+} in silicate structure provided that ferrous iron is found to dilate the silicate structure so that Zn can easily enter. The enrichment of Zn in the hanging wall is, therefore, due to the presence of biotite, hornblende and other ferromagnesian minerals in the mica schists and amphibolites while that of arsenic may be due to the high concentration of Ni and Co in this zone. In fact, Cu can also replace Mg^{+2} and Fe^{+2} in some silicates but it is not important geochemically in comparison to formation of sulfides. Chalcophil character of arsenic is also well displayed by the development of arsenopyrite. The single peak of arsenic in the WHW (Fig. 29, 3000 ppm, only one sample) may be due to the formation of arsenate and enrichment by adsorption on ferric hydroxides (Rankama, 1955). In case of silver, even if it is chalcophil, this behavior is not evident here because of the absence of its sulfide, argentite. Instead, its spatial correlation with lead enables to say that Ag is found in good proportion as admixture in galena which is a well established observational fact stated by Rankama (1955). Due to its sensitivity to go into solution in the form of sulfate during weathering, there is no any pronounced peak in the secondary zone. But the peaks in Fig. 32 (20 and 30 ppm, two samples) and Fig. 34 (150, 30 ppm, 2 samples) are probably due to its retention from dissolution by anglesite and cerussite.

Au distribution is such that it shows maximum values in quartz veins and actinolite schists saturated in quartz lenses and stringers. This means that its geochemical anomalies are concentrated in the ore zone (Fig. 27, 28, 29, 30). Some maxima are observable in the HW (CQMS) (Fig. 30, 36, 40). It attains a maximum value of 60 ppm in the weathered ore zone where the rocks are quartz veins while the lowest (0.1 ppm) is in CQMS. To see the relative enrichment of the five domains weighted average of gold values in the different domains was taken (Table 8). The highest (6.02 ppm) is detected in WOZ, which is in agreement with the geochemical behavior of gold (residual enrichment in the process of weathering). Gold being chemically inert and immobile under surficial conditions (Table 7) remains as residual during

weathering. Its compounds are readily reduced to metal. This fact is more evident here. Because, if we consider the weighted average of gold in WOZ (6.02 ppm) and in UOZ (1.99 ppm), the enrichment is quite significant. The dissolution and subsequent reprecipitation of gold in the zone of enrichment in this geochemical environment is insignificant or did not take place at all. This may be due to the small amount of pyrite which produce both ferric sulfate and chloride which are active in dissolving and fixing metallic gold.

The presence of peaks in the UHW may be due to the fact that the mineralizing solutions might have penetrated to some extent to the hanging wall causing some anomalous concentration of the metal. The effect of solutions which cause alteration and mineralization is usually sensed by host rocks of any deposit, especially if the rocks are fractured, veined and made porous by tectonic processes. Any local maxima in the FW is absent, the weighted average here is 0.2 ppm. This implies the asymmetric nature of the deposit (restricted to the hanging wall of the eastern deep fault). The gneiss unit might have been impervious to the mineralizing solutions so the effect of the latter might have not been felt or observed in these rocks. This asymmetric nature of distribution is common to all the elements associated with the gold mineralization. Spikes are usually encountered near the boundaries of the ore zone with the hanging wall and foot wall (Fig. 27, 29, 31, 32, 34, 35). Returns of assay values indicate that quartz vein and actinolite schists are the most enriched in gold compared to other rock types. As can be seen from the simple variation graphs, there is no consistent trend in the distribution of the gold. The presence of any valuable zone in the area is detected simply by erratic highs which do not show regular increasing or decreasing pattern of distribution toward or outward from the ore zone. This absence of regularity may be due to: (a) the usually encountered law of distribution for low grade deposits - precious metals, (b) overlapping of different tectonometamorphic processes in the area causing redistribution, remobilization and reconcentration of the metals in the area, and (c) complex intercalation of the different rock types which are differently favorable for the deposition of ores.

Table 8 Statistical parameters of the elements in the different domains

unweathered footwall

Element	No. Samples	Wtd. Avg.	Max.	Min.	Std.
Au	131	0.58	34.2	0.05	3.11
Pb	121	13.81	60	3	9.73
Zn	14	71.43	100	19	32.55
Cu	127	70.01	300	3	59.2
Ag	21	0.95	10	0.15	2.05
As	18	238.49	1000	100	216.67
Sb	1	150	150	150	0
Mo	94	4.14	30	1	4.19
W	26	62.16	200	30	53.94
Co	127	35.96	300	3	36.06
Ni	118	133.69	1000	6	209.94

Unweathered ore zone

Element	No. Samples	Wtd. Avg.	Max.	Min.	Std.
Au	867	1.99	58.5	0.05	4.98
Pb	896	63	2000	1	223.23
Zn	180	118.14	1000	3	133.95
Cu	929	161.72	2000	1	212.99
Ag	568	2.84	150	0.15	8.79
As	446	453.55	6000	50	668.62
Sb	142	49.13	200	6	38.99
Mo	622	3.56	40	0.5	4.31
W	466	79.56	2000	30	135.45
Co	913	30.99	600	1	46.01
Ni	907	232.98	3000	6	421.23

weathered ore zone

Element	No. Samples	Wtd. Avg.	Max.	Min.	Std.
Au	45	6.02	60	0.2	10.23
Pb	52	68.62	167.58	1	
Zn	9	365.28	2000	100	583.94

Table 8 Cont'd

Cu	52	347.95	2000	6	511.27
Ag	47	6.63	150	0.5	21.87
As	26	315.77	1000	100	204.72
Sb	10	95.43	300	30	75.77
Mo	29	3.27	10	10	2.69
W	35	235.71	3000	30	507.31
Co	50	20.57	60	1	14.47
Ni	52	115.54	500	6	121.29

Unweathered hanging wall

Element	No. Samples	Wtd. Avg.	Max.	Min.	Std.
Au	330	0.47	20	0.05	1.56
Pb	476	26.09	1000	3	66.62
Zn	162	113.71	2000	11	167.45
Cu	480	111.69	800	6	68.68
Ag	261	1.17	20	0.17	2.54
As	246	381.07	6000	100	617.24
Sb	58	40.14	100	30	25.68
Mo	371	2.27	10	1	1.64
W	180	109.21	3000	30	325.67
Co	479	17.53	100	3	14.48
Ni	480	107.88	2000	10	196.77

Weathered hanging wall

Element	No. Samples	Wtd. Avg.	Max.	Min.	Std.
Au	163	0.43	8.13	0.1	1.17
Pb	245	28.72	400	3	32.25
Zn	138	194.64	1000	30	181.27
Cu	250	158.02	1000	6	113.78
Ag	91	0.94	6	0.3	1.18
As	122	389.57	3000	100	477.05
Sb	23	39.36	100	30	21.06
Mo	145	3.17	20	1	2.95
W	121	108.59	1000	30	135.68
Co	252	32.05	300	3	33.46
Ni	255	128.06	600	10	117.29

Table 9 Abundance of elements (ppm) in common types of rocks (Webb et al., 1979)

Element	ultramafic	mafic	granitic
Sb	0.1	0.1	0.2
As	1	1.5	2.1
Co	110	48	1
Cu	42	72	12
Au	0.0032	0.0032	0.0023
Pb	1	4	18
Mo	0.3	1.5	1.3
Ni	2000	130	4.5
Ag	0.06	0.1	0.037
W	0.1	1	1.5
Zn	45	140	175

Considering the average value of gold given in Table 9 in mafic and granitic rocks, the value of gold is appreciably high. In the WHW it varies from 0.1 to 8.13 ppm, in the UHW from less than 0.1 up to 20 ppm, in UOZ from less than 0.1 to 58.5 ppm, in WOZ from 0.2 to 60 ppm and in FW from less than 0.1 to 34.5 ppm. So in all domains, the content of gold is higher than the value the rocks normally can have. Hence, it is possible to say that even if the amount is variable from place to place, the ore zone, the hanging wall and foot wall were appreciably affected by the mineralizing solution and show the introduction of surplus gold by gold precipitating hydrothermal solutions. Its enrichment in the mica-feldspar-quartz schists near the shear zone and its depletion (reduced content) in the hanging wall and foot wall may be due to its geochemical behavior during metamorphism and hydrothermal alterations. It is usually mobilized and deposited by hydrothermal solutions. Laboratory studies and thermodynamic calculations indicate that Cl⁻-rich solutions are able to transport gold as AuCl₂⁻ at temperatures higher than about 200°C and pH around 3 (Boyle, 1980). Gold is deposited when temperature drops to less than about 170°C. Gold can also be transported as a sulfide complex (AuS⁻) if pH is almost neutral. The solubility of gold in both these types of solutions may be very high and increases with increasing temperature. Laboratory studies have shown that these hydrothermal solutions can contain more than 1000 ppm Au. Instead, at temperatures below 150 - 200°C gold becomes almost insoluble and is deposited to

form mineralization. Such low P-T conditions are met near the shear zone which seems to control the dispersion of Au, Pb, Cu, Ag and to some extent As which are mostly positively associated with gold (see part 5.3).

Ni and Co

These elements are usually enriched in the hanging wall of the deposit. Their peaks are localized either in the hanging wall (Fig. 30, 33, 34, 36, 37, 40) and in the foot wall or at the bottom of the ore zone along the periphery between ore zone and foot wall (Fig. 27, 28, 32, 33, 34, 35, 37, 38, 39, 40). The Ni and Co highs are not localized with regard to ore bodies. Their localization in hanging wall (due to the presence of amphibolites and talc - along the chakata fault and some interbeds or lenses of hornblende schists) and along the boundary between the ore zone and foot wall (which is the eastern deep fault marked by metamorphosed ultrabasic rocks - talc) rather than in the quartz veins, mica-feldspar-quartz schists and biotite gneiss suggests that much of the Ni and Co may be an original constituent of the basic-ultrabasic intrusions, amphibolites and gabbro. But local maxima in the ore zone are not uncommon (Fig. 29, 31, 38, 39). This observation is not in contradiction with the above suggestion because the hornblende schists and some talc-tremolite schists are found as lenses and interbeds in the ore zone. In addition to this, the presence of Ni up to 1% in naturally occurring pyrrhotite was reported by Ramdohr (1980). Co can also replace Fe in this mineral. Pyrite also has a possibility of having small amount of Co and small amount of Ni. An association of pentlandite-pyrrhotite is also reported by Fiori et al. (1988). Hence the maxima of Ni and Co observed in the ore zone is partly explained by the fact that these elements could have been admitted (incorporated) to the structure of the then mentioned sulfides which are abundant in the ore zone.

However, taking into account the fact that the concentration of Ni in ultramafics, mafics and granitic rocks is 2000, 130, 4.5 ppm respectively, we can consider the 3000 ppm detected in the ore zone in talc, actinolite, mica-feldspar-quartz schists and quartz veins as a result of mineralizing events. The same is true

for Co in which its content in ultramafics, mafics and granitic rocks is 110, 48 and 1 ppm respectively. But a value up to 600 ppm is encountered in unweathered ore zone. These values are much higher than those given for granitic and mafic-ultramafic rocks. Therefore, it may be stated that the Co and Ni are added to the original rocks by a Co-Ni-bearing hydrothermal solution during the wall rock alteration. Hence, it is possible to say that even these elements, which show a negative correlation with gold (see part 5.3), are to some extent introduced to the enclosing rocks by the mineralizing hydrothermal solutions. But reaching at such conclusions based on background values given for general crustal rocks is misleading because the background values are highly dependent on the geochemical environment in any specific area. In light of this, background should have been established to this specific area after statistically treating a large number of more or less homogenous data for the different rock types. However, due to the complex intercalation of the rocks, getting homogenous data set was difficult.

Ni achieves its maximum concentration (3000 ppm) in the UOZ. This is due to the presence of the extensive shear zone marked by talc schists. Hence, due to the fact that: (a) ultramafics are high in Ni, (b) the mineralizing solutions were most probably channeled along this shear zone, and (c) most probably the mineralizing solutions might have some link with ultramafic protore, the Ni content is high in this zone.

Co also shows its highest value in UOZ (600 ppm), hanging wall and FW (300 ppm). This is due to its close association with Ni which usually shows positive correlation (see part 5.3) and the presence of amphibolites (hanging wall) and hornblende schists (foot wall). The maximum weighted average for Co is that of 32.05 ppm which is for WHW. This zone is dominated by amphibolite which can usually incorporate high amount of Co. The maximum weighted average for Ni (232.98 ppm) is in the UOZ which contains, at its bottom part, the talc schists. Peaks in the weathering zone are not so widely observed for these minerals. The small peaks in figure 31 (Co), figure 33 (Co and Ni) and figure 34 (Co and Ni) are not that much pronounced and the values are 100 ppm (Co) and 300 ppm (Ni). These values

are not appreciably more than the content of Co and Ni that could be accommodated by these rocks. Therefore, they are false anomalies.

The association of the high values of Co and Ni with ultramafic-mafic rocks is due to their geochemical behavior. These elements have ionic radius and electronegativity close to Mg^{+2} and Fe^{+2} and substitute for these elements in mafic minerals. In the process of metamorphism they are usually poorly mobile and hence remain in the solid rock which is being metamorphosed instead of going into solution and redeposited in other favorable area like Au, Pb, Ag, Zn, As and W do.

The geochemical characteristics of the two elements in this environment is not clear because they can act as siderophil or chalcophil in nature. But Rankama (1957), Goldschmidt (1954) and Kraucopf (1967) stated that in the earth's crust due to the low content of iron and preponderance of oxygen these elements mostly act as chalcophil. However, even if geochemistry of the sulfides is not studied, there is no evidence whether they are found as part of sulfides or in the silicates of the enclosing rocks. Both cases are equally possible due to the following reasons, as stated by Johansson (1924), Goldschmidt (1954), Kraucopf (1967) Webb et al. (1979), Rankama (1954) and Masson (1966). In hydrothermal deposits, Co sulfide mineral (linnaeite, Co_3S_4) separate in the mesothermal range. This element also appears to enter magmatic and high temperature sulfides in isomorphous substitution for Fe and Ni. The most spectacular is its preponderance in pyrite of high temperature origin up to 14% Co (Ramdohr, 1980). It is also found in pyrrhotite and pentlandite up to 1%. It is also taken preferentially by high temperature arsenides such as arsenopyrite. Ni occurs both as sulfide phase (pentlandite) and in ferromagnesian silicates of magmatic rocks, especially olivines, pyroxenes which are, in the case of LDPGD, represented as metamorphosed ultrabasic rocks (talc), amphibolites and gabbro. Nickel can also be formed in hydrothermal deposits in linnaeite up to 50% $(Co, Ni)_3S_4$, in sulfosalts gersdorffite $NiAsS$, ullmanite $NiSbS$, skutterudite $(Co, Ni)As_3$ and breithauptite $NiSb$. Both of these minerals are reported in the LDPGD (Fiori et al, 1988, EMRDC, 1985, etc). Hence, both possibilities are the most likely form of occurrence of Ni and Co.

Mo and W

Apart from its similarity in ionic and atomic radius with W, Mo is usually found in nature as sulfide (MoS_2) while W is found mainly as tungstate (FeWO_4 and MnWO_4). This means that Mo and W are chalcophil/siderophil and lithophil respectively. The geochemical distribution of W more or less follows that of the chalcophils (Cu-Pb-Ag). Its narrow peaks are mostly localized in the ore zone (Fig. 27, 28, 30, 31, 36, 37) or near the contact between the ore zone and hanging wall (Fig. 30, 32, 33) and ore zone and foot wall (fig. 30).

The W enrichment is localized either in the ore zone along its periphery or extending for a distance of about 20 m (foot wall) and 10 - 60 m (hanging wall side) outward from the ore zone. The maximum average value (237.71 ppm) is also seen in WOZ. Here the spacial coincidence of the maxima with the ore zone and with chalcophil highs is most probably a matter of spatial, temporal and structural situations rather than geochemical behavioral association. The close association of wolframite, pyrrhotite, arsenopyrite and chalcopyrite observed in the ore mineralogy part is an evidence for spatial and temporal overlap of deposition of W and other metals from hydrothermal solutions (see chapter IV). When we consider the actual values for W in comparison with what was given by Webb et al. (1979) for ultramafic, mafic and granitic rocks (0.1, 1, 1.5 ppm respectively), they are quite higher than these values for the reason that the minimum is 30 ppm while the maximum goes up to 300 ppm, the detection limit being 50-100 ppm. Hence, an appreciable amount of W more than the rock can normally accommodate is introduced into the rocks and precipitated in the form of its tungstate with sulfides of other metals.

The dispersion of Mo is quite similar to that of Co and Ni, concentrated in the hanging and foot walls. This is in agreement with their similar geochemical behavior (siderophil character). Anomalous peaks of Mo are mostly encountered in the foot (Fig. 27, 31, 32, 33, 34, 35) and hanging (fig. 28, 29, 30, 31, 33, 37) walls. The maximum average value (4.14 ppm) is also found in the foot wall rocks. Mo content of as high as 40 ppm is detected in the UOZ and a minimum of 0.5 ppm in UOZ. These values are quite higher than the values given by Webb et al. (1979) for the

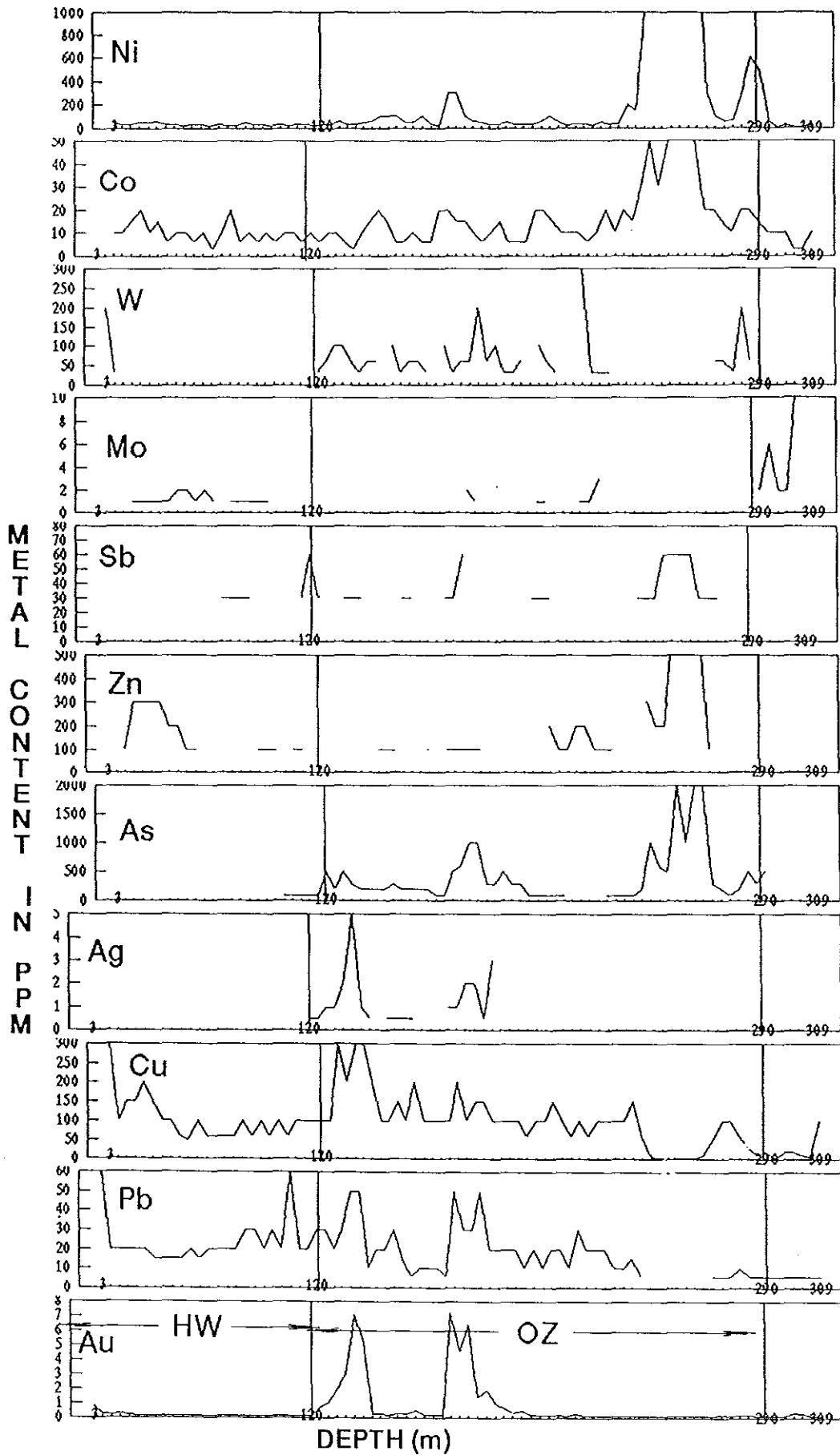


Fig.27 Element variation pattern in Bh-114

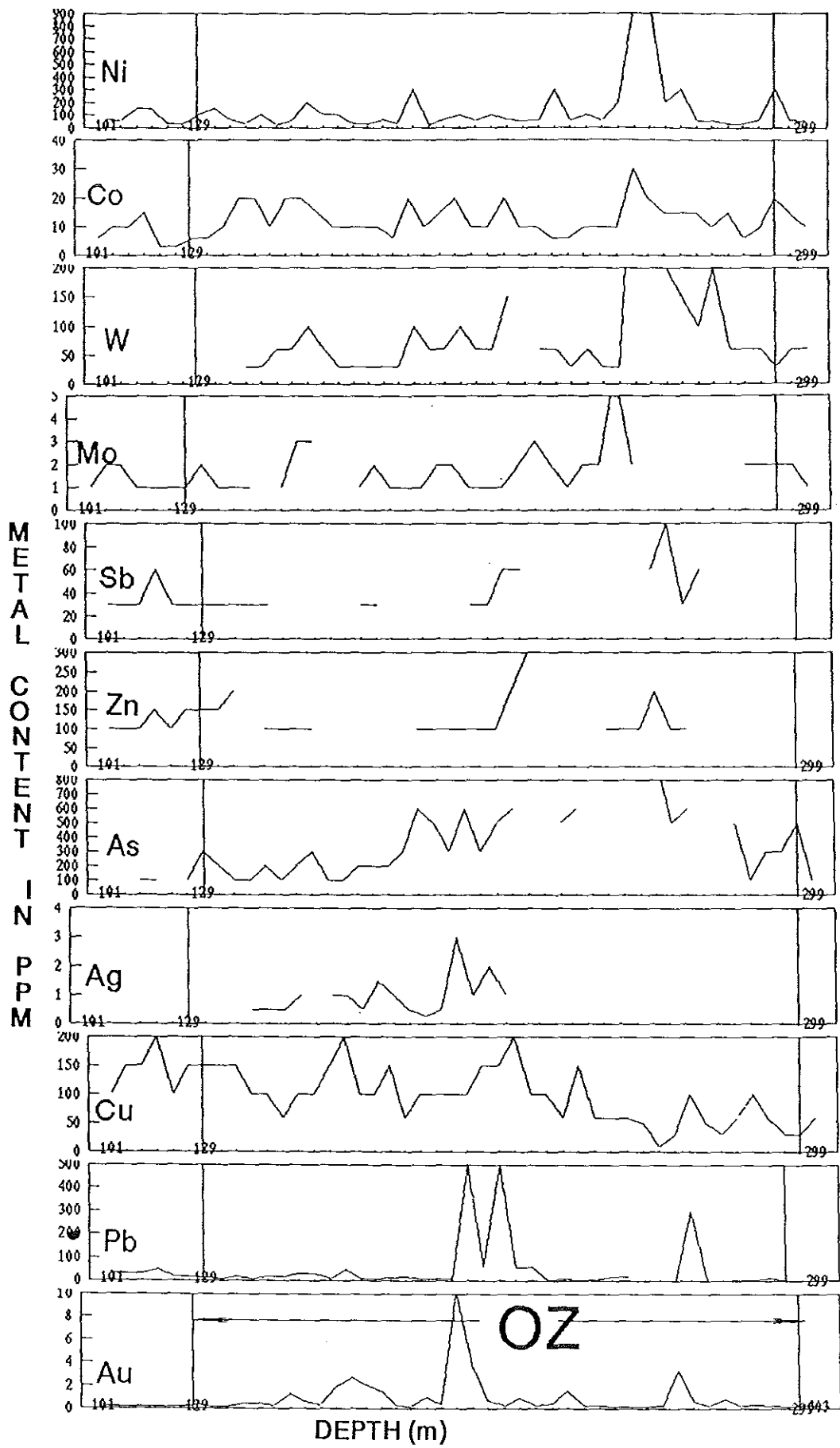


Fig.28 Element variation in Bh-107

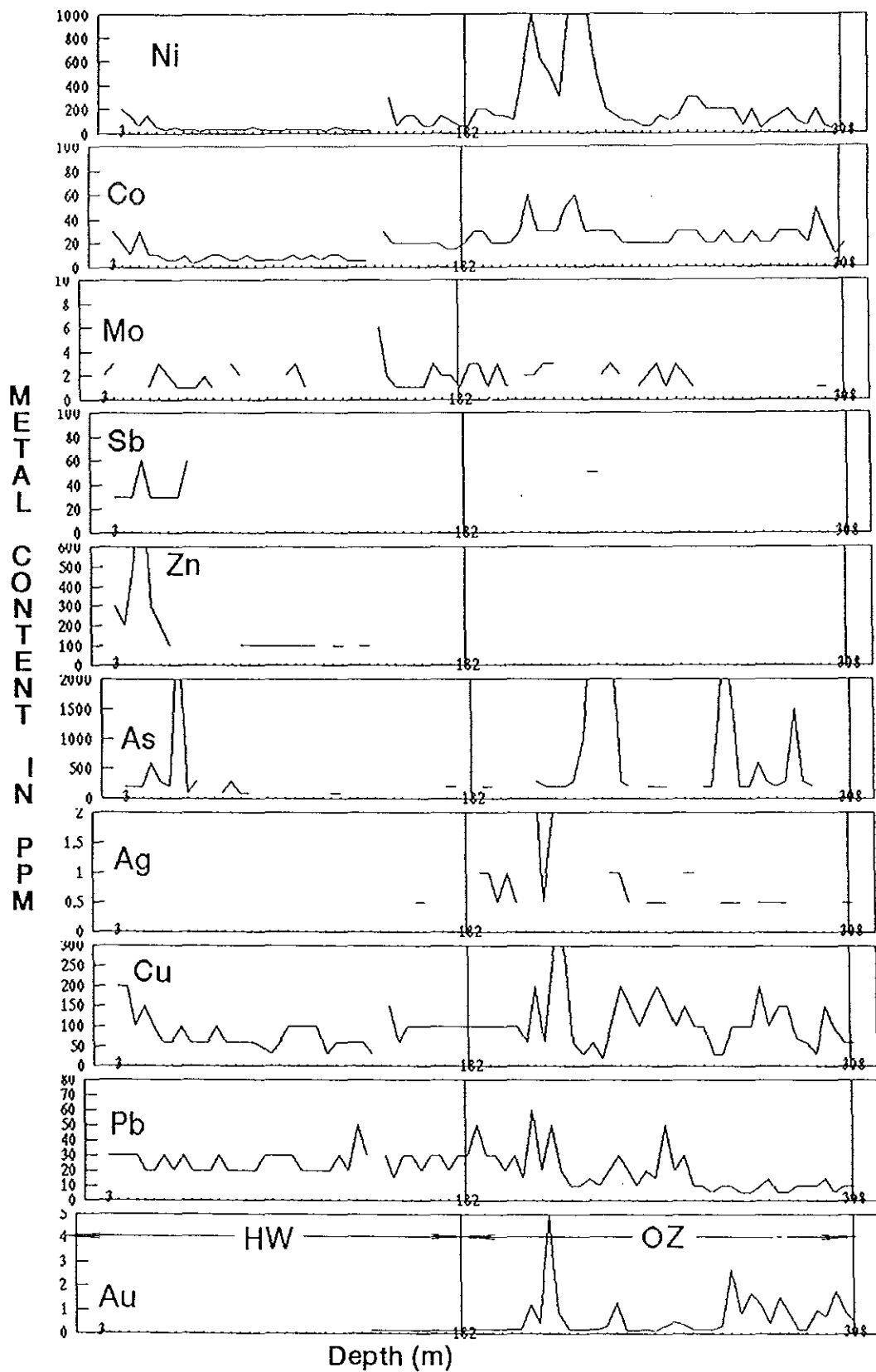


Fig.29 Graph showing element variation pattern in Bh-107A

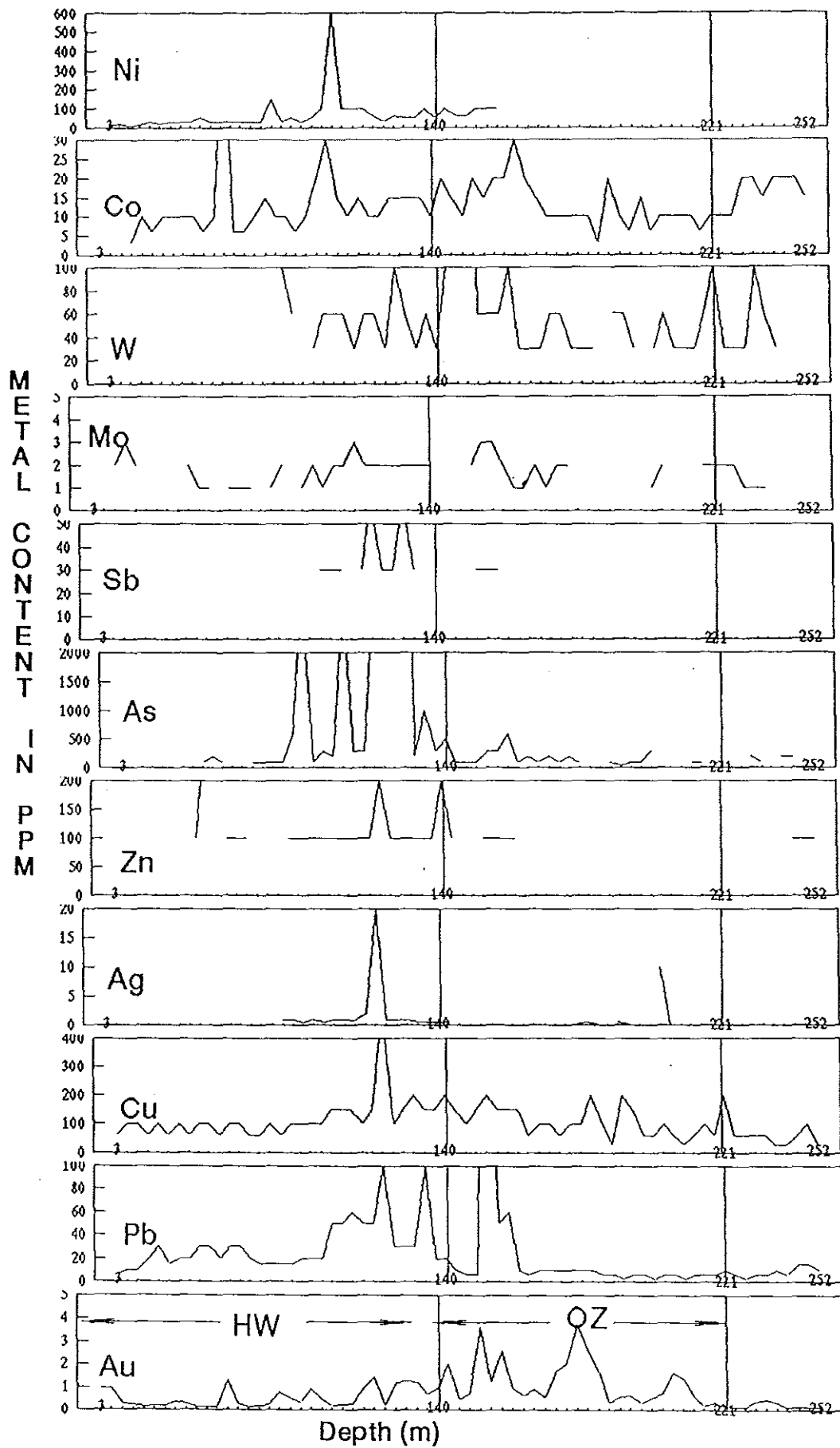


Fig.30 Element content variation in Bh-100

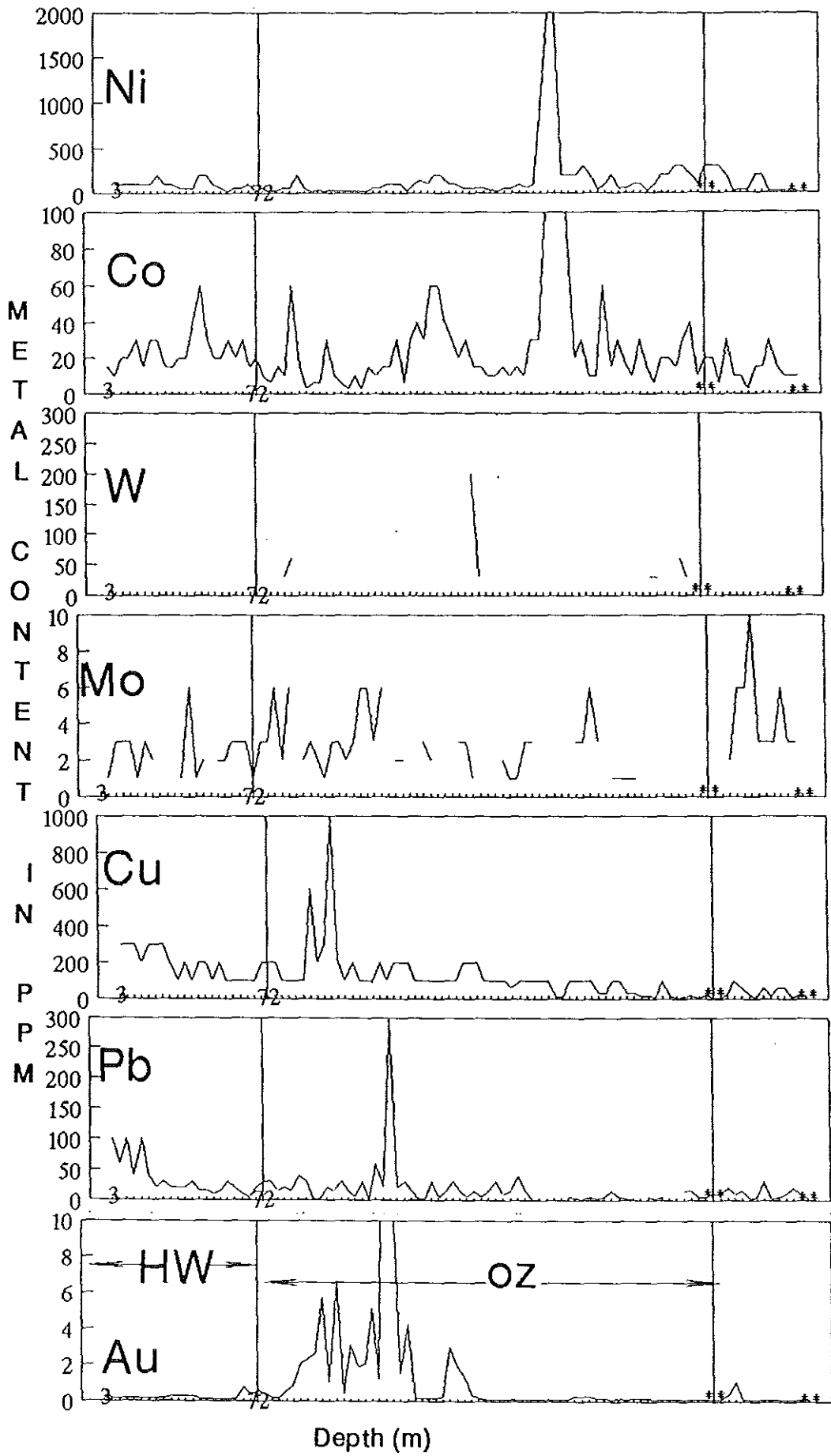


Fig.31 Element variation pattern in Bh-116

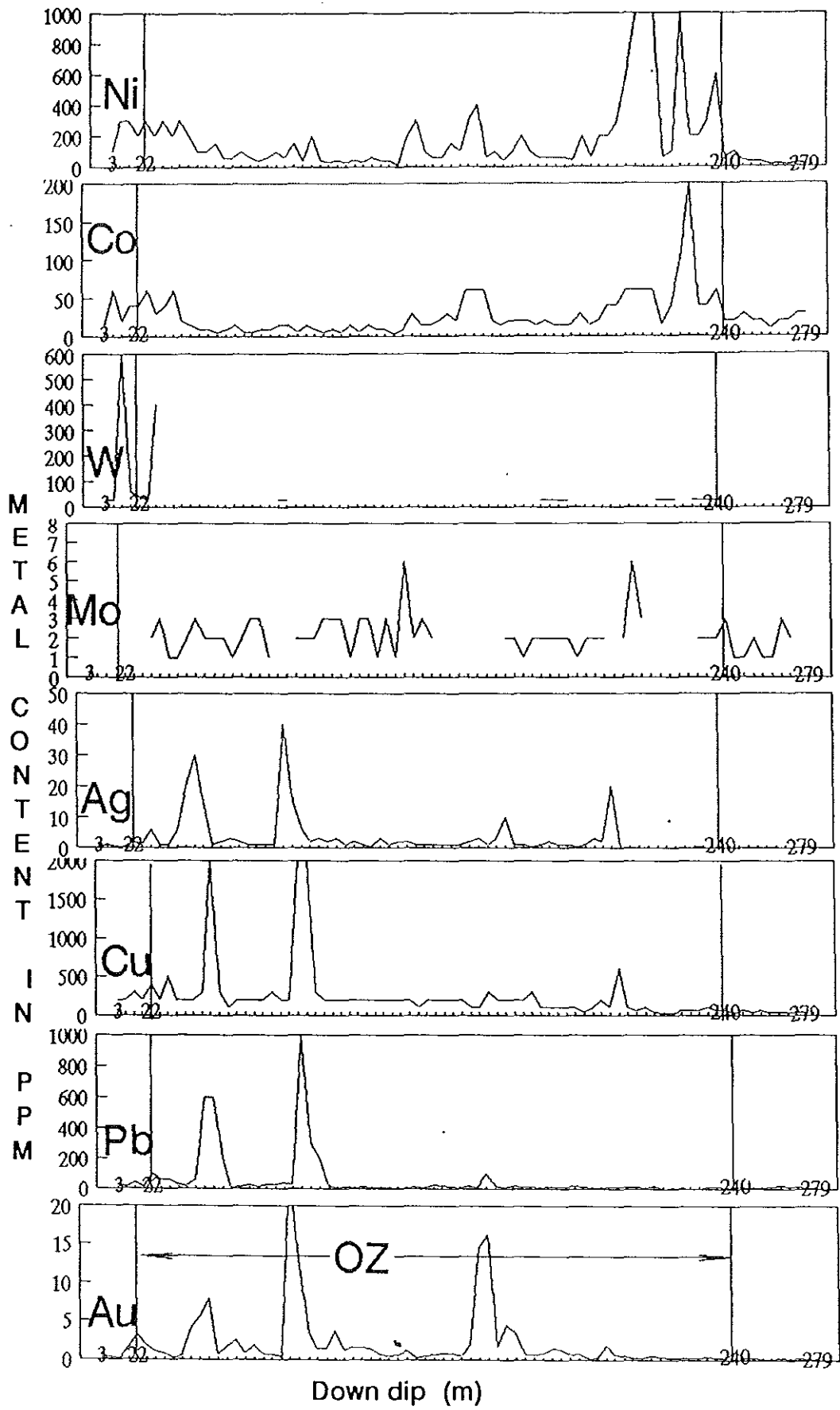


Fig.32 Element distribution in Bh-33

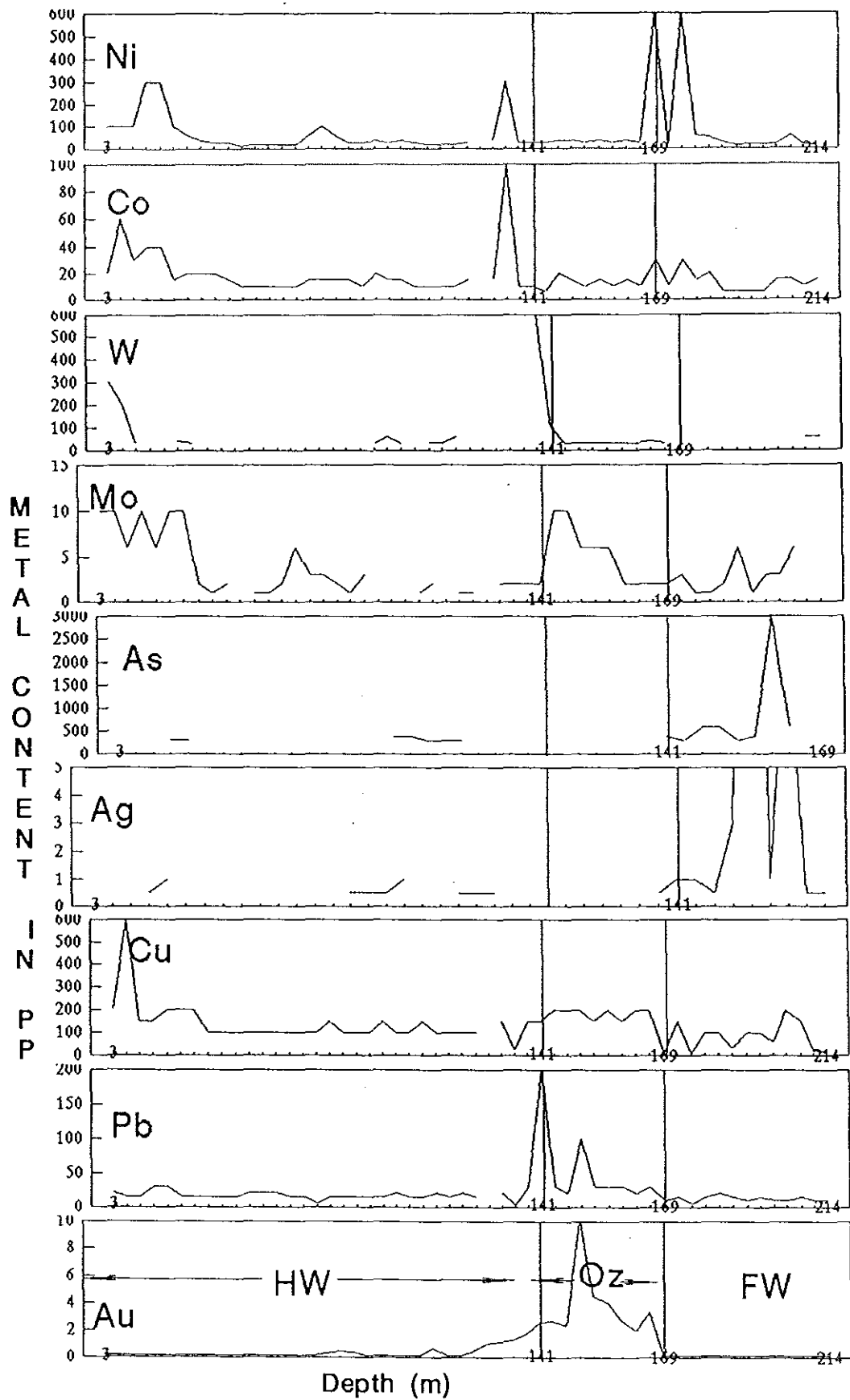


Fig.33 Element distribution pattern in Bh-92

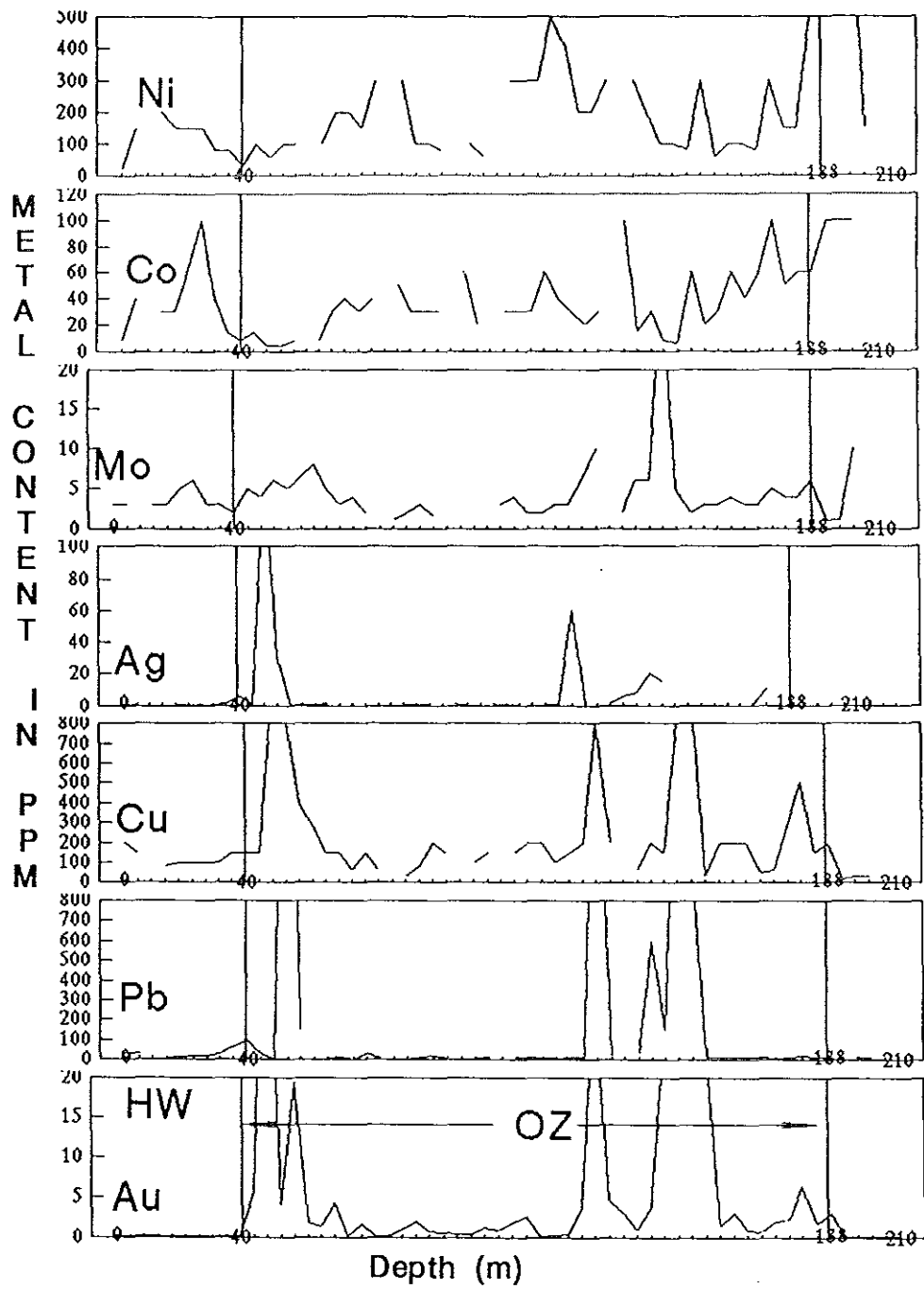


Fig.34 Element variation graph in Bh-18

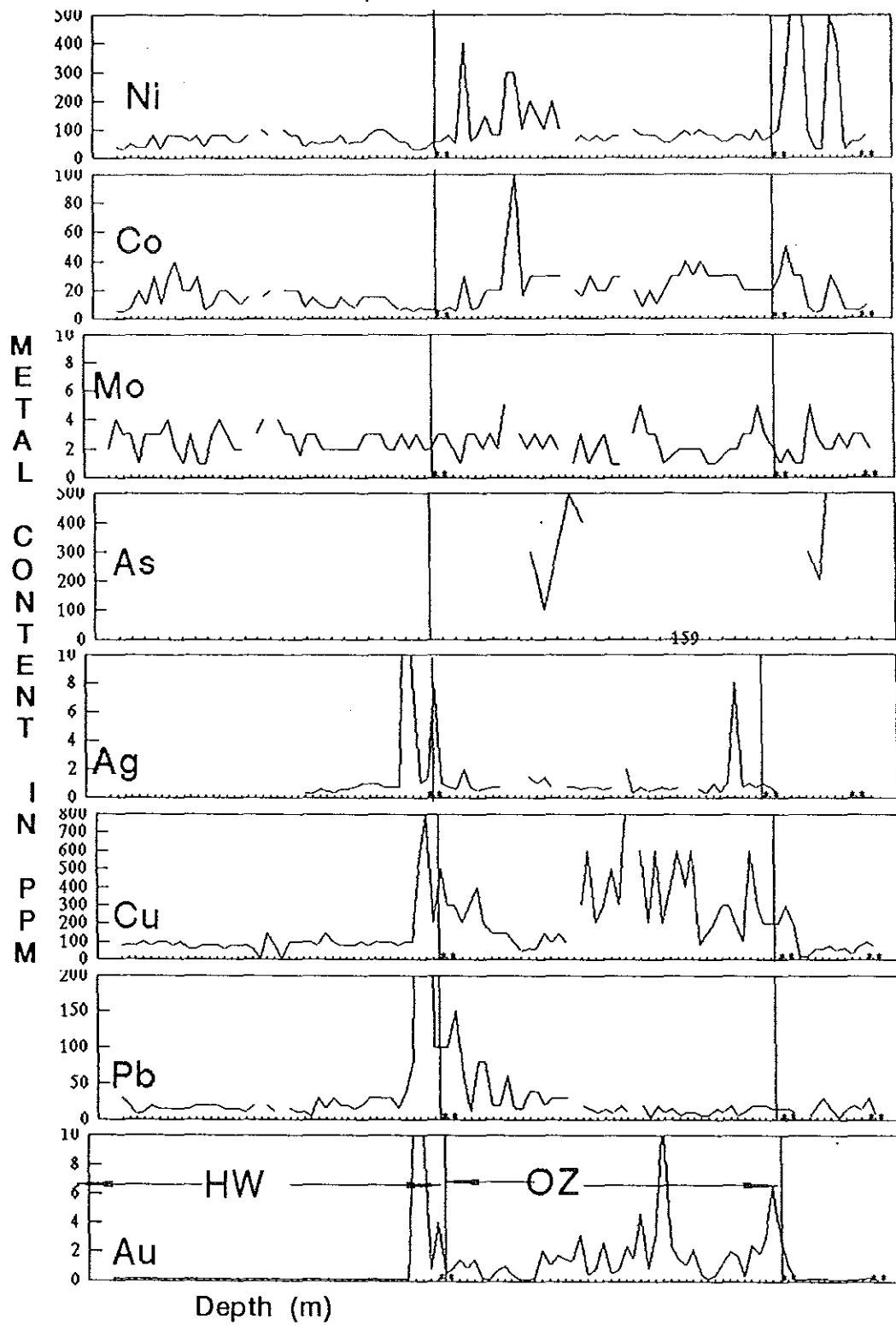


Fig.35 Variation graph of elements in Bh-19

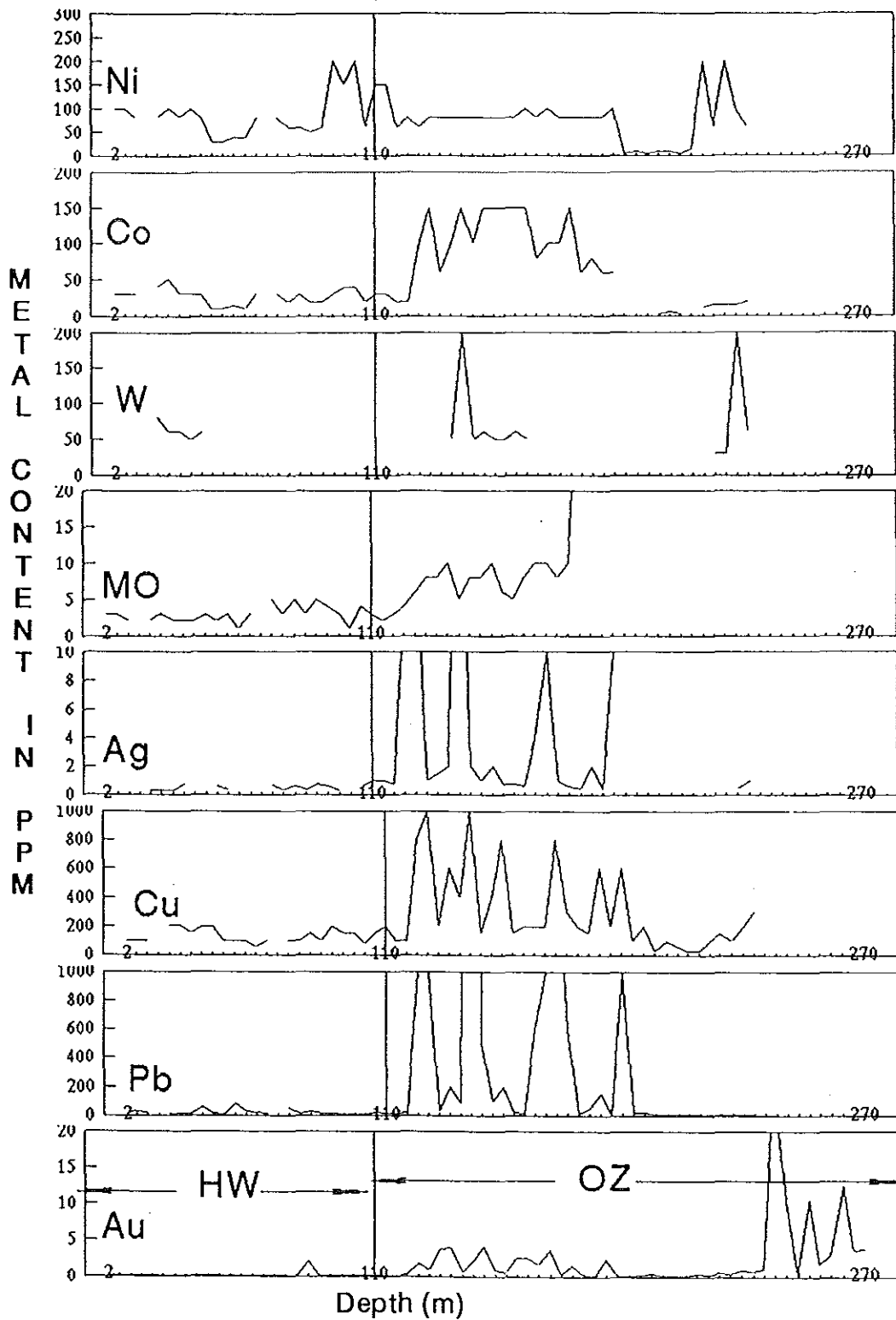


Fig.36 Element variation pattern in Bh-22

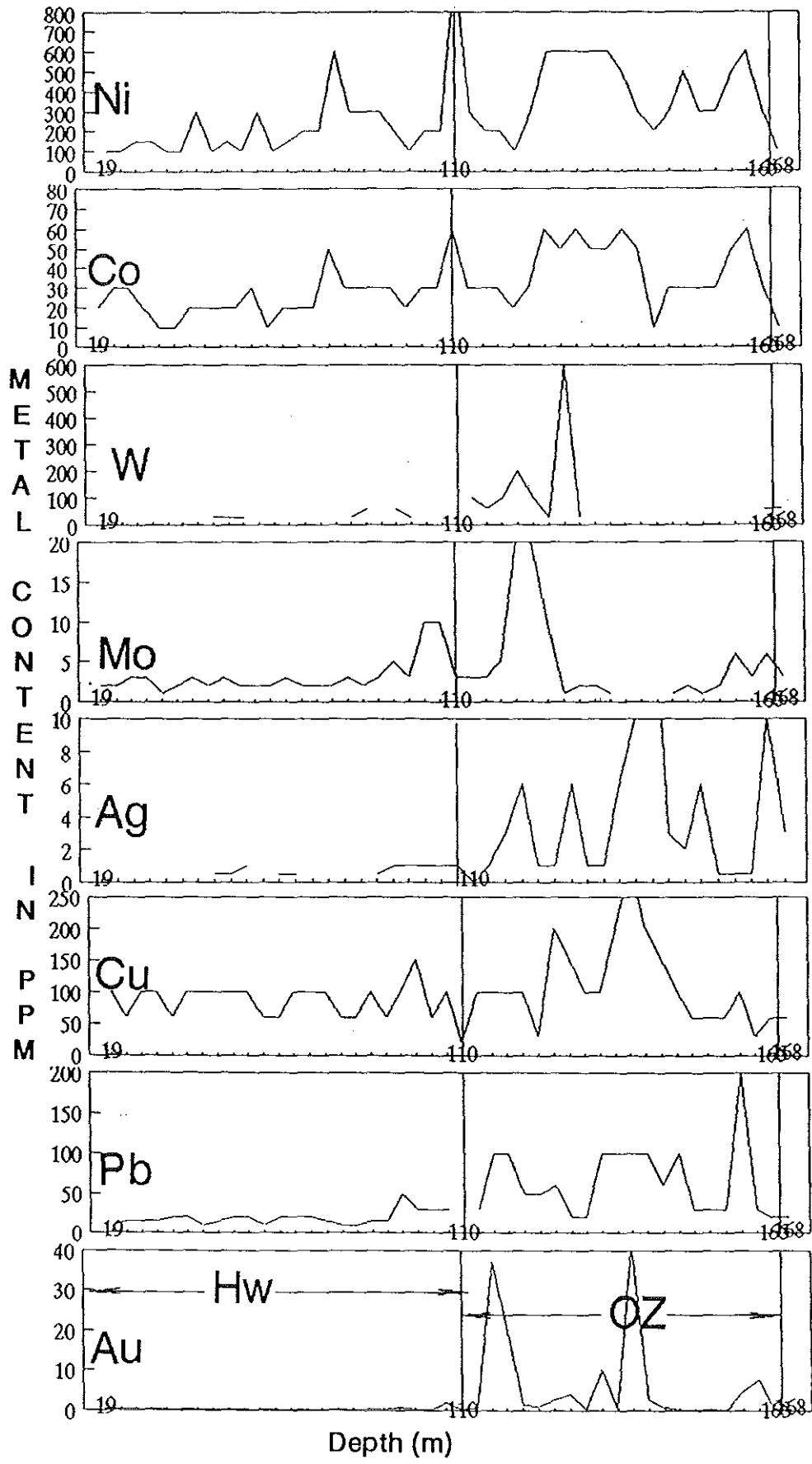


Fig.37 Element variation in Bh-125

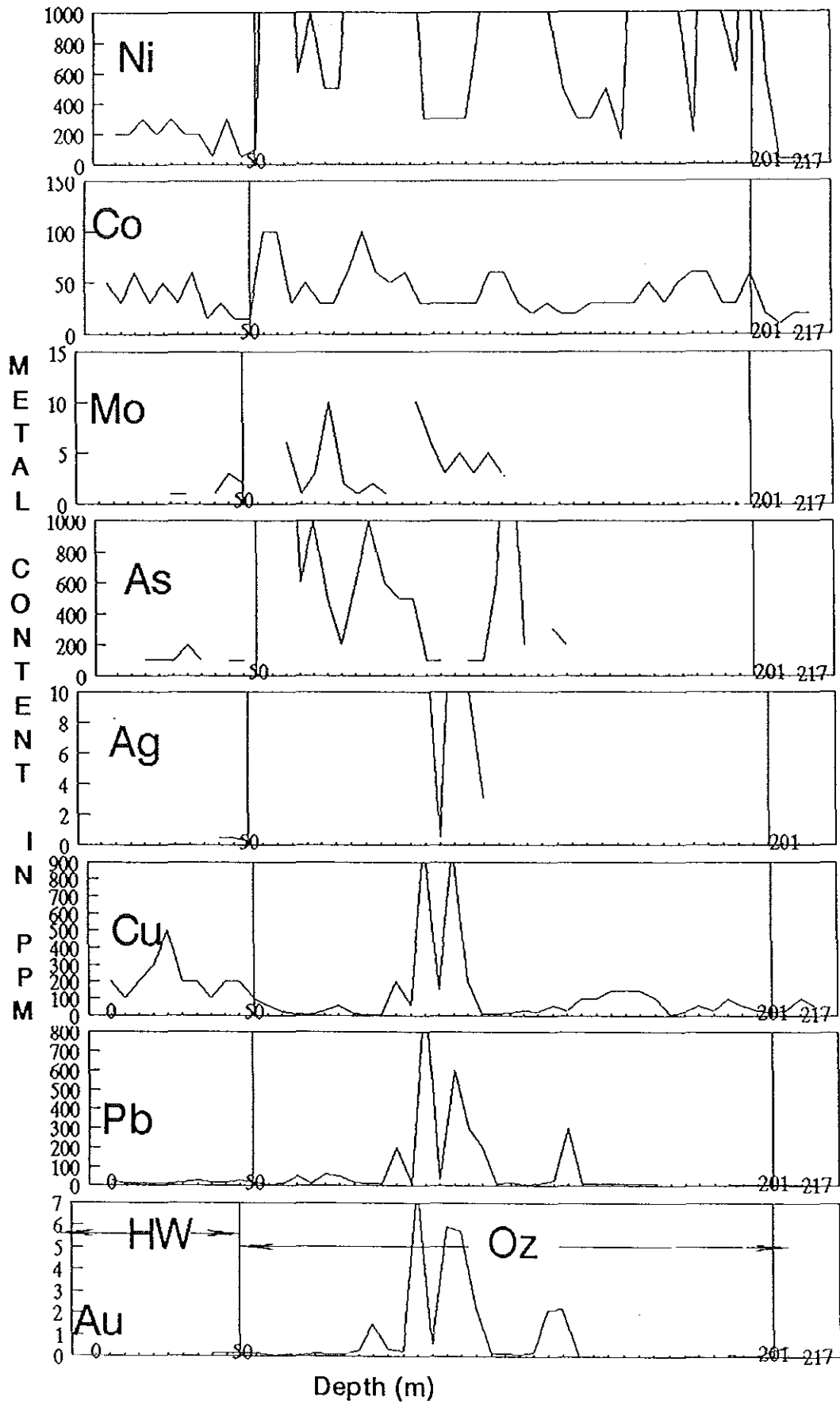


Fig.38 Trace element variation in Bh-151

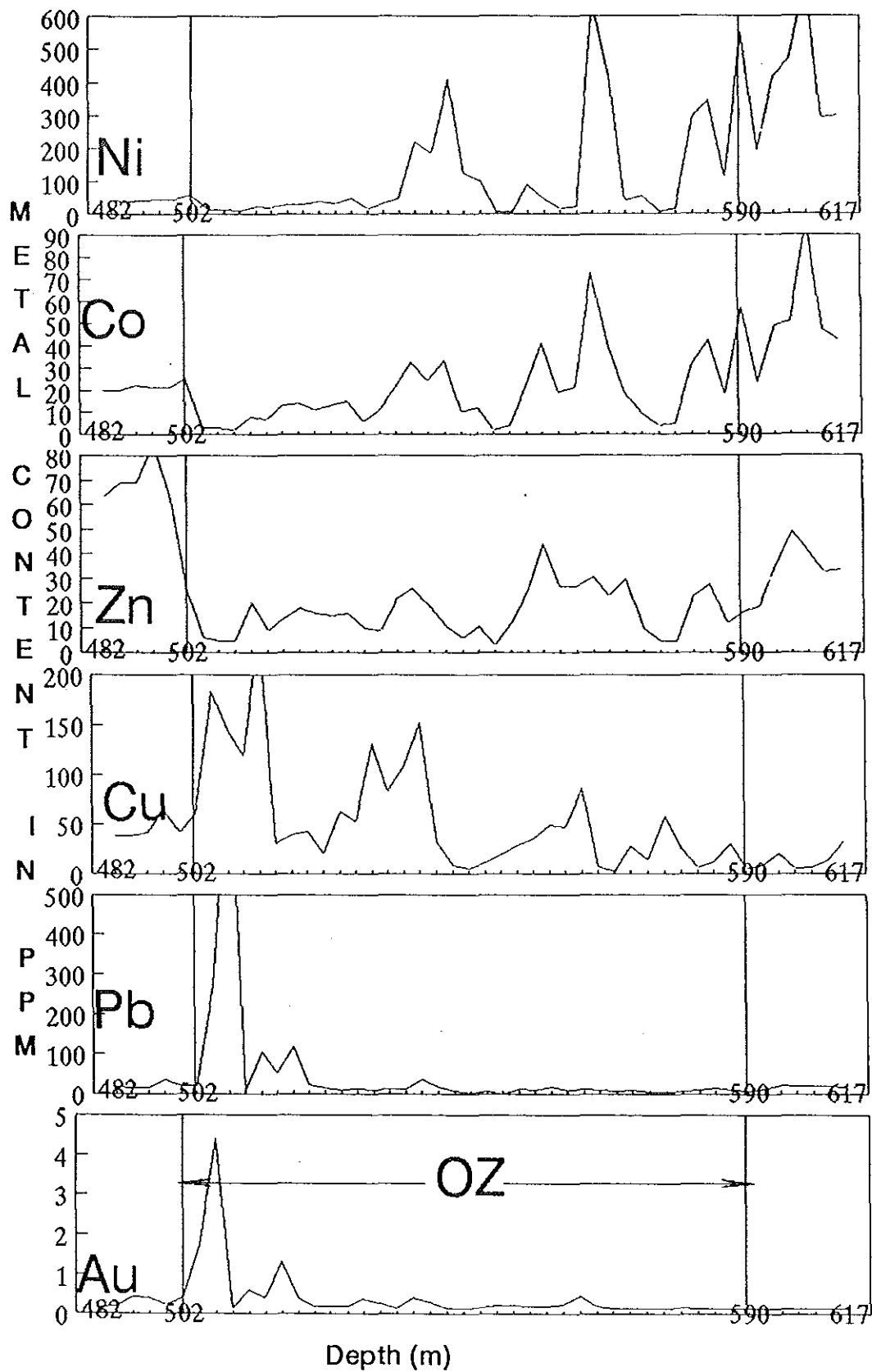


Fig.39 Vertical element variation in Bh-602

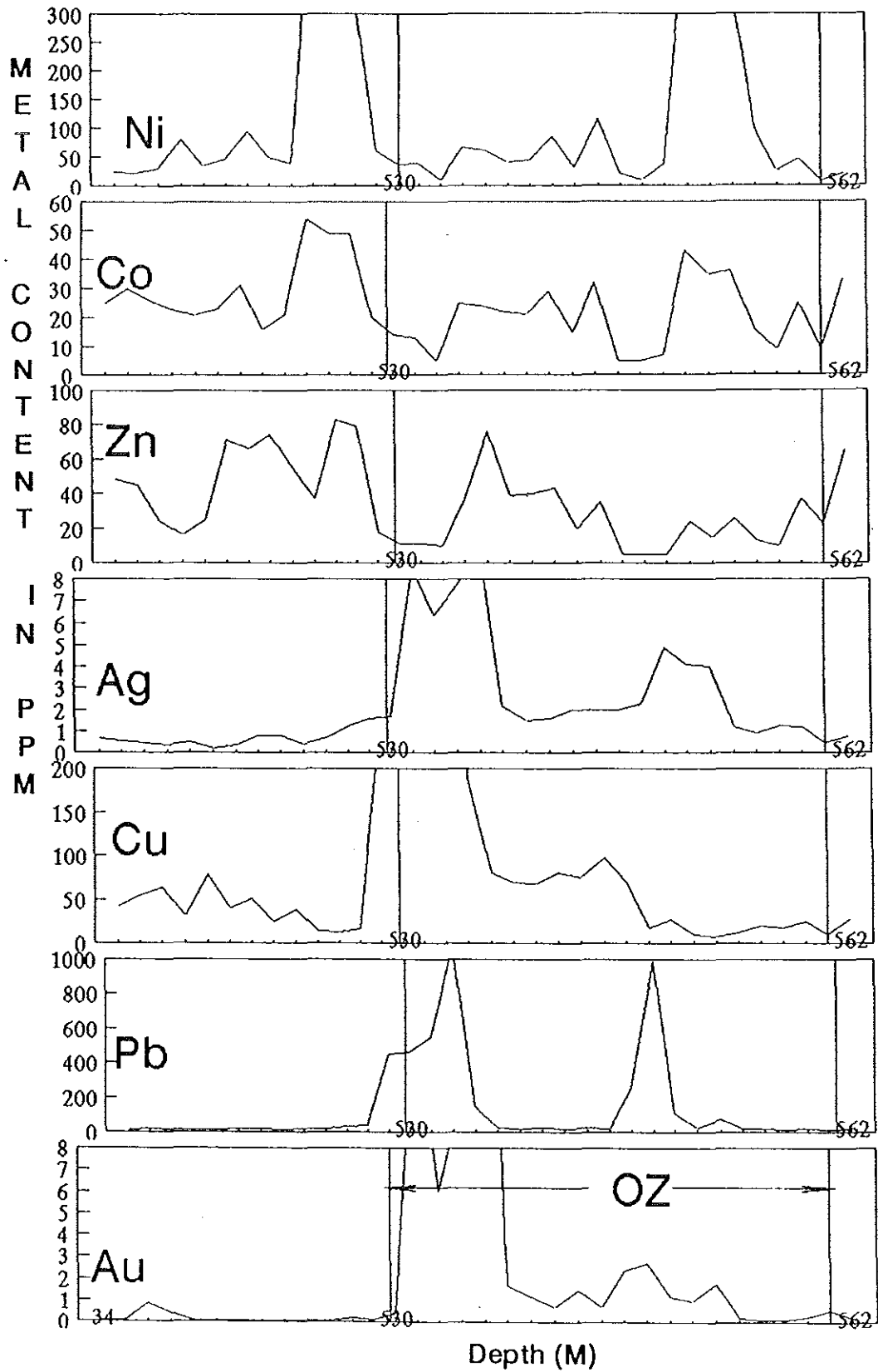


Fig.40 Element variation in Bh-623

different rock types. This means that most of the peaks observed are related to the mineralizing events.

In summary, trace element distribution generally seems to be controlled by fractures, faults and shear zones. Penetration into massive wall rocks, viz., amphibolites and upper part of mica schists, and foot wall (biotite gneiss) is generally poor. The geometrical distribution of the elements is generally asymmetric with respect to the mineralized zone. It seems that the structural factor controlled the distribution rather the temperature or other factor. The haloes of the trace elements highly varies with the distribution of the structural elements. So to speak, the minor element content of the enclosing rocks is related not only to the distance from the ore veins and intensity of chemical reactions but also to the kind and amount of fracturing. Hence, even if the hydrothermal deposition of traces can be effected by decrease of temperature, pressure, direct chemical reaction between traces and wall rocks and neutralization of solutions by reaction with wall rocks, the structural factors are most important. Variations of most elements are very erratic and show few consistent trend. Variations which can be reasonably related to ores only within approximately 30 to 150 m of mineralization, in the hanging wall - the foot wall side being insignificant. Within this distance, the elements which best indicate the presence of nearby mineralization are Pb, Cu, Ag, As and to some extent Sb, Zn and W. The general character of this dispersion is not a regular increase toward ore but consists of a series of erratic anomalous values for one or more of the above elements. Generally, the dispersion pattern of most elements show erratic behavior, spatial inconsistency and are of limited extent.

5.3 Associations of elements

Elements tend to be associated because of similar relative mobility in a group of geological processes in a specific environment. The association of the eleven elements in the LDPGD was studied in the five domains classified before. Their association in terms of spatial distribution is clearly seen from the figures presented (Fig. 27 to 40). From the diagrams it is possible to see that the following associations

are evident: (a) Au-Pb-Cu-Ag-(As)-(Sb)-(W)-(Zn), (b) Co-Ni-Mo-(W) and (c) W-Mo. Especially the association between Au, Pb, Ag and Cu in one side and Co and Ni on the other side are most spectacular. More over, among these two groups, any element in one of the group show depletion-enrichment relation with any element in the other group.

It was advisable to quantify the association of each pair of elements in the different domains. In order to accomplish this task, cross-correlation studies were most important and are the only tools. In multi-element geochemical studies, computation of cross-correlation matrices to facilitate interpretation of geochemical data has been a normal procedure. Correlation matrices furnish information on the relation between a pair of elements in a given environment. Correlation coefficients between a pair of elements can be computed using different methods of which the following are most common: (i) Spearman rank correlation, (ii) graphic method (correlation cloud or correlation diagram) and (iii) computational methods. The first method is usually applied for small amount of data. Moreover, in reordering the data according to their rank, important information between pairs is lost. In case of the second methods, even if it is used by many scientists such as Matheron (1962) and Lepeltier (1969), it was found to be less precise than that undertaken by calculation. The third method is most precise and efficient. In addition, it is viable to statistical tests to determine whether the obtained correlation coefficient is significant (i.e., the relation is related to common mineralizing event) or not significant (such insignificant values are usually encountered due to contamination, scavenging and analytical errors). Hence, the third method was applied in this study. The linear correlation coefficients (r) are given in Table 10 for each pair. Assuming that the samples were randomly collected from a normal population and considering the fact that when the number of observations in the sample is infinite, the t-distribution and the normal distribution are identical, we prefer to the t-test. More over, the t-distribution is dependent upon the size of the sample taken and it is a probability distribution which has a wider "spread" than the normal distribution which is not commonly encountered under natural conditions (Davis, 1973). Due to these features

the t-distribution is preferable. Hence, for each r, the student T-test was conducted to determine its significance. Due to the different sample size for each pair, it was not possible to present them in terms of correlation matrices and was not possible to have the same critical region of rejection. To avoid confusion, t and the $t_{\alpha/2}(n-2)$ is given for each pair. If the table value of $t_{\alpha/2}(n-2)$ is less than the absolute value of that calculated t, the null-hypothesis is rejected and this means the r is significant. The values of r in shadow are accepted, i.e., significant ones.

In formal statistic terms, the test is conducted as follows:

hypothesis,

$$H_0: r=0$$

against the alternative,

$$H_1: r \neq 0$$

First the test statistics t is calculated as

$$t = (r\sqrt{n-2})/(\sqrt{1-r^2})$$

where: r = correlation coefficient

n = sample size

If the computed absolute value of t exceeds the table value of t for n-2 degree of freedom and 5% level of significance, we can reject the null-hypothesis leaving us with the alternative that the r value is significant or different from zero.

The most consistent positive correlation exists between Au and Pb, Ag and Cu. The correlation between Au and Pb is most significant (0.9 = UHW, 0.64 = WHW, 0.42 = UOZ) except in the WOZ and FW. In the WOZ even if not significant, according to the statistical test, the tendency is towards negative correlation (-0.07) this may be due to the removal of lead by secondary processes which do not usually apply for gold. The relation between Au, Ag and Cu is also always positive reaching up to 0.61 (Au-Cu). As, Sb Mo and W are also sometimes well correlated with Au, but not that much significant and consistent. The other thing to say is the relation between Au and Ni and Co. The later two usually shows negative correlation with gold and its indicator or positive associates (Pb, Ag and Cu). Usually the relation displayed between the two groups, i.e. Au-Pb-Ag-Cu and Co-Ni is a depletion-

enrichment type. This may indicate the fact that areas represented by high concentration of Co, Ni and other Fe-group elements may represent areas of center of mobilization of the mineralizing fluids. This is in agreement with the geochemical fact that says that Fe-group elements usually are partitioned to the solid phase during any geological processes. Hence, when the hydrothermal solutions were invading the rock and leached out metals from the surrounding rocks during alteration go into solution and start to be mobilized so as to be deposited in favorable areas.

Zinc does not show any consistent relation with gold. It some times show positive correlation (0.56=FW), in other case negative (-0.11=UOZ), still in others almost no relation (0.01=WHW, 0.04=WOZ and -0.03=WHW). Hence, zinc should not be considered as associates and indicator of gold in this environment. More over, zinc has no any defined relationship with any of the other elements. It some times correlates with Cu (0.26=WHW and 0.76=FW), Sb (0.52=WHW), As (0.45=WHW, 0.57=UOZ), W (0.26=WHW), Ni (0.4=WHW, 0.41=WOZ) and Co (0.3=UOZ, -0.68=FW). As can be seen its associates are not only certain groups but it correlates with both groups of elements in the different environments.

Pb shows best correlation with Cu (0.63=UHW, 0.16=WHW, 0.3=WOZ, 0.45=UOZ and 0.02=FW) and Ag (0.55=UHW, 0.19=WHW, 0.6=WOZ, 0.58=UOZ and 0.25=FW). These three elements, in addition to the strong positive correlation within each other, they show the same pattern (negative) of correlation with the Fe-group elements. The Pb-As relation is significant only in the UHW (0.18) and WOZ (-0.07). Strong negative correlation between lead and zinc (-0.72) is observed in the foot wall. In this zone Au, the best associate of lead, has strong positive correlation (0.56) with Zn. This implies that the different elements of the deposit act differently in different levels of the deposit due to the difference in P-T-X (pressure, temperature and concentration). And it denotes the fact that different geochemical activities had taken place in the different parts of the deposit causing different rate and amount of mobilization of the ore elements. Other than this, Pb is some times correlated with Mo (0.29=UOZ), Sb (0.33=UOZ) and, even if not supported by the statistics test, the negative correlation with Co and Ni. There is no

Tab. 10 Linear correlation coefficients of elements

FOOT WALL									
	r	n	t	t(n-2)		r	n	t	t(n-2)
Au-Pb	0.09	114.00	0.96	1.98	Cu-Ag	0.17	21.00	0.75	2.093
Au-Zn	0.56	13.00	2.24	2.201	Cu-Ar	-0.18	18.00	-0.73	2.12
Au-Cu	0.13	119.00	1.42	1.98	Cu-Sb				
Au-Ag	-0.02	19.00	-0.08	2.11	Cu-Mo	0.28	94.00	2.80	1.986
Au-Ar	0.18	16.00	0.68	2.145	Cu-W	0.08	26.00	0.39	2.064
Au-Sb					Cu-Co	0.15	127.00	1.70	1.98
Au-Mo	0.05	92.00	0.47	1.986	Cu-Ni	-0.15	118.00	-1.63	1.98
Au-W	0.02	26.00	0.10	2.064	Ag-Ar				
Au-Co	-0.04	119.00	-0.43	1.98	Ag-Sb				
Au-Ni	-0.01	110.00	-0.10	1.982	Ag-Mo	0.00	14.00	0.00	2.179
Pb-Zn	0.73	14.00	-3.59	2.179	Ag-W	-0.16	4.00	-0.23	4.303
Pb-Cu	0.02	121.00	0.22	1.98	Ag-Co	-0.01	21.00	-0.04	2.093
Pb-Ag	0.25	21.00	1.13	2.093	Ag-Ni	0.03	21.00	0.13	2.093
Pb-Ar	0.26	16.00	1.01	2.145	Ar-Sb				
Pb-Sb					Ar-Mo	0.04	15.00	0.14	2.16
Pb-Mo	0.08	88.00	0.74	1.986	Ar-W	0.20	5.00	2.31	3.182
Pb-W	0.34	23.00	1.66	2.08	Ar-Co	0.07	18.00	3.61	2.12
Pb-Co	-0.01	121.00	-0.11	1.98	Ar-Ni	0.51	13.00	1.97	2.201
Pb-Ni	0.17	112.00	1.81	1.98	Sb-Mo				
Zn-Cu	0.78	14.00	4.05	2.179	Sb-W				
Zn-Ag					Sb-Co				
Zn-Ar					Sb-Ni				
Zn-Sb					Mo-W	-0.12	23.00	-0.55	2.08
Zn-Mo					Mo-Co	0.06	94.00	0.58	1.986
Zn-W					Mo-Ni	-0.19	86.00	-1.77	1.989
Zn-Co	0.68	14.00	-3.21	2.179	W-Co	0.23	26.00	3.97	2.064
Zn-Ni	0.70	6.00	1.96	2.776	W-Ni	0.44	20.00	2.08	2.101
					Co-Ni	0.28	118.00	2.90	1.98

WEATHERED HANGING WALL

	r	n	t	t(n-2)		r	n	t	t(n-2)
Au-Pb	0.65	151	10.24	1.96	Cu-Ag	0.16	89	1.51	1.986
Au-Zn	0.01	79	0.09	1.989	Cu-Ar	0.11	116	1.18	1.98
Au-Cu	0.04	152	0.49	1.96	Cu-Sb	0.2	23	0.94	2.08
Au-Ag	0.06	62	0.47	2	Cu-Mo	0.19	142	2.29	1.96
Au-Ar	0.04	66	0.32	2	Cu-W	0.23	112	2.48	1.982
Au-Sb	-0.26	10	-0.76	2.306	Cu-Co	0.14	246	2.21	1.96
Au-Mo	0.44	105	4.97	1.982	Cu-Ni	0.28	249	3.54	1.96
Au-W	-0.06	82	-0.54	1.989	Ag-Ar	0.21	54	1.55	2.008
Au-Co	-0.09	155	-1.12	1.96	Ag-Sb	0.06	8	0.15	2.447
Au-Ni	-0.11	158	-1.38	1.96	Ag-Mo	-0.16	54	-1.17	2.008
Pb-Zn	0.05	137	0.53	1.96	Ag-W	-0.003	66	-0.02	2
Pb-Cu	0.18	239	2.50	1.96	Ag-Co	-0.004	90	-0.04	1.986
Pb-Ag	0.19	91	1.81	1.986	Ag-Ni	0.07	91	0.66	1.986
Pb-Ar	0.08	122	0.88	1.98	Ar-Sb	0.45	21	2.20	2.093
Pb-Sb	0.32	23	1.55	2.08	Ar-Mo	-0.01	62	-0.08	2
Pb-Mo	-0.01	144	-0.12	1.96	Ar-W	0.3	78	2.74	1.989
Pb-W	0.06	121	0.66	1.98	Ar-Co	0.03	122	0.33	1.98
Pb-Co	-0.12	242	-1.87	1.96	Ar-Ni	0.24	122	2.71	1.98
Pb-Ni	-0.001	245	-0.02	1.96	Sb-Mo	-0.06	10	-0.14	2.306
Zn-Cu	0.26	132	3.07	1.96	Sb-W	0.59	11	2.19	2.262
Zn-Ag	0.03	52	0.21	2.008	Sb-Co	0.04	23	0.18	2.08
Zn-Ar	0.45	85	4.59	1.989	Sb-Ni	0.15	23	0.70	2.08
Zn-Sb	0.52	21	2.65	2.093	Mo-W	-0.03	67	-0.24	2
Zn-Mo	-0.2	79	-1.79	1.989	Mo-Co	0.39	144	4.17	1.96
Zn-W	0.26	72	2.25	1.994	Mo-Ni	-0.05	145	-0.60	1.96
Zn-Co	0.05	137	0.53	1.96	W-Co	0.06	120	0.65	1.98
Zn-Ni	0.4	137	5.07	1.96	W-Ni	0.15	121	1.66	1.98
					Co-Ni	0.22	252	3.57	1.96

UNWEATHERED HANGING WALL

	r	n	t	t(n-2)		r	n	t	t(n-2)
Au-Pb	0.9	279	34.36	1.96	Cu-Ag	0.6	222	11.12	1.96
Au-Zn	-0.03	113	-0.32	1.98	Cu-Ar	0.18	217	2.38	1.96
Au-Cu	0.61	279	12.81	1.96	Cu-Sb	0.01	51	0.07	2.008
Au-Ag	0.52	149	7.38	1.96	Cu-Mo	0.12	323	2.35	1.96
Au-Ar	0.14	122	1.56	1.98	Cu-W	0.17	150	2.10	1.96
Au-Sb	-0.02	37	-0.12	2.03	Cu-Co	-0.03	420	-0.61	1.96
Au-Mo	-0.05	220	-0.74	1.96	Cu-Ni	-0.57	421	-3.53	1.96
Au-W	0.34	102	2.47	1.982	Ag-Ar	0.19	136	2.24	1.96
Au-Co	-0.09	278	-1.50	1.96	Ag-Sb	0.05	29	0.26	2.052
Au-Ni	-0.06	278	-1.00	1.96	Ag-Mo	-0.04	180	-0.53	1.96
Pb-Zn	-0.04	145	-0.48	1.96	Ag-W	-0.06	99	-0.59	1.982
Pb-Cu	0.63	420	16.59	1.96	Ag-Co	-0.07	219	-1.03	1.96
Pb-Ag	0.55	222	9.77	1.96	Ag-Ni	-0.04	221	-0.59	1.96
Pb-Ar	0.18	212	2.66	1.96	Ar-Sb	-0.24	40	-1.52	2.021

Tab.10 Cont^d

Pb-Sb	-0.02	51	-0.14	2.008	As-Mo	-0.03	175	-0.39	196
Pb-Mo	0.02	323	0.36	196	As-W	-0.07	115	-0.75	196
Pb-W	-0.05	150	-0.61	196	As-Co	0.001	216	0.01	196
Pb-Co	-0.08	418	-1.64	196	As-Ni	0.04	217	0.29	196
Pb-Ni	-0.05	419	-1.02	196	Sb-Mo	-0.23	45	-1.56	2021
Zn-Cu	-0.01	145	-0.12	196	Sb-W	-0.11	29	-0.58	2052
Zn-Ag	0.4	87	4.02	1989	Sb-Co	-0.22	50	-1.56	2014
Zn-As	-0.04	83	-0.36	1989	Sb-Ni	-0.24	50	-1.71	2014
Zn-Sb	0.07	35	0.40	2.042	Mo-W	-0.05	125	-0.56	196
Zn-Mo	-0.11	100	-1.10	1982	Mo-Co	0.2	320	5.61	196
Zn-W	-0.04	55	-0.29	2.008	Mo-Ni	0.28	322	4.42	196
Zn-Co	-0.06	145	-0.72	196	W-Co	0.03	147	0.36	196
Zn-Ni	0.1	145	1.20	196	W-Ni	-0.07	149	-0.85	196
					Co-Ni	0.5	420	11.80	196

WEATHERED ORE ZONE

	r	n	t	t(n-2)		r	n	t	t(n-2)
Au-Pb	-0.07	39	-0.43	2.03	Cu-Ag	0.44	43	3.14	2021
Au-Zn	0.04	6	0.08	2.776	Cu-As	-0.01	25	-0.05	2069
Au-Cu	-0.15	38	-0.91	2.03	Cu-Sb	0.7	9	2.29	2365
Au-Ag	0.19	35	1.11	2.042	Cu-Mo	0.25	27	1.29	2.06
Au-As	0.18	17	0.71	2.131	Cu-W	0.04	32	0.22	2042
Au-Sb	0.5	7	1.29	2.571	Cu-Co	0.09	46	0.60	2014
Au-Mo	-0.13	16	-0.49	2.145	Cu-Ni	0.1	48	0.68	2014
Au-W	-0.1	27	-0.50	2.06	Ag-As	-0.07	24	-0.33	2074
Au-Co	-0.23	37	-1.40	2.03	Ag-Sb	0.49	9	1.49	2365
Au-Ni	-0.25	39	-1.57	2.03	Ag-Mo	-0.1	26	-0.49	2064
Pb-Zn	0.94	9	7.29	2.365	Ag-W	0.02	30	0.11	2048
Pb-Cu	0.3	51	2.20	2.014	Ag-Co	-0.11	45	-0.73	2014
Pb-Ag	0.8	46	4.97	2.014	Ag-Ni	-0.2	46	-1.35	2014
Pb-As	0.004	25	0.02	2.069	As-Sb	-0.05	9	-0.13	2365
Pb-Sb	0.3	9	0.83	2.365	As-Mo	0.08	16	0.30	2.145
Pb-Mo	0.22	28	1.15	2.056	As-W	-0.34	20	-1.53	2.101
Pb-W	-0.01	34	-0.06	2.042	As-Co	0.16	24	0.76	2074
Pb-Co	-0.15	49	-1.04	2.014	As-Ni	0.21	26	1.05	2064
Pb-Ni	0.01	51	0.07	2.008	Sb-Mo				
Zn-Cu	0.43	8	1.17	2.447	Sb-W	-0.24	7	-0.55	2571
Zn-Ag	0.85	8	3.95	2.447	Sb-Co	-0.33	9	-0.92	2365
Zn-As	0.1	7	0.22	2.571	Sb-Ni	-0.45	10	-1.43	2306
Zn-Sb	-0.8	4	-1.89	4.303	Mo-W	0.12	18	0.48	2.12
Zn-Mo					Mo-Co	0.09	28	0.46	2056
Zn-W	0.43	8	1.17	2.447	Mo-Ni	-0.07	29	-0.36	2052
Zn-Co	0.1	9	0.27	2.365	W-Co	0.07	34	0.40	2042
Zn-Ni	-0.33	9	-0.92	2.365	W-Ni	-0.14	35	-0.81	2.03
					Co-Ni	0.45	50	3.49	2008

UNWEATHERED ORE ZONE

	r	n	t	t(n-2)		r	n	t	t(n-2)
Au-Pb	0.42	740	12.57	196	Cu-Ag	0.98	567	14.86	196
Au-Zn	-0.11	160	-1.39	196	Cu-As	-0.19	441	-4.05	196
Au-Cu	0.28	824	7.09	196	Cu-Sb	0.48	142	6.47	196
Au-Ag	0.42	517	10.50	196	Cu-Mo	0.3	622	7.83	196
Au-As	-0.08	378	-1.16	196	Cu-W	0.09	448	1.50	196
Au-Sb	-0.18	134	-2.10	196	Cu-Co	0.01	913	0.30	196
Au-Mo	-0.17	549	-4.03	196	Cu-Ni	-0.17	907	-5.19	196
Au-W	-0.02	395	-0.40	196	Ag-As	0.47	244	8.28	196
Au-Co	-0.04	812	-1.14	196	Ag-Sb	0.23	86	3.20	1989
Au-Ni	-0.06	802	-1.70	196	Ag-Mo	0.21	420	4.39	196
Pb-Zn	-0.09	165	-1.15	196	Ag-W	-0.03	309	-0.53	196
Pb-Cu	0.45	889	15.01	196	Ag-Co	0.01	560	0.24	196
Pb-Ag	0.59	562	16.85	196	Ag-Ni	0.04	555	0.94	196
Pb-As	-0.07	421	-1.44	196	As-Sb	0.1	114	1.06	196
Pb-Sb	0.39	128	3.92	196	As-Mo	0.12	301	2.09	196
Pb-Mo	0.29	612	7.48	196	As-W	0.17	266	2.80	196
Pb-W	-0.02	353	-0.37	196	As-Co	0.17	137	2.00	196
Pb-Co	-0.01	882	-0.30	196	As-Ni	0.42	430	9.57	196
Pb-Ni	-0.06	875	-1.78	196	Sb-Mo	0.6	86	6.87	1989
Zn-Cu	-0.03	180	-0.40	196	Sb-W	0.24	78	2.16	1989
Zn-Ag	0.33	112	3.67	196	Sb-Co	0.17	137	2.00	196
Zn-As	0.57	108	7.14	196	Sb-Ni	-0.11	139	-1.30	196
Zn-Sb	0.08	53	0.57	2.008	Mo-W	0.03	357	0.57	196
Zn-Mo	-0.04	74	-0.34	1.994	Mo-Co	0.17	612	4.26	196
Zn-W	-0.02	82	-0.18	1.989	Mo-Ni	-0.02	607	-0.49	196
Zn-Co	0.2	178	4.17	196	W-Co	0.04	459	0.86	196
Zn-Ni	0.41	178	5.96	196	W-Ni	0.09	446	1.90	196
					Co-Ni	0.46	892	4.84	196

any significant relation between Pb and W. This is in agreement with the ore mineralogy part due to the absence of close association of galena and wolframite.

Cu is well correlatable with Ag (0.6 = UHW, 0.44 = WOZ and 0.53 = UOZ). The other best associates of Cu are W (0.17 = UHW, 0.23 = WHW), Mo (0.13 = UHW, 0.19 = WHW, 0.3 = UOZ and 0.28 = FW). Its association with As is not strong but show both positive and negative correlation (0.16 = WHW and -0.19 = UOZ). It has negative correlation (-0.17 = UHW, -0.17 = UOZ and -0.15 = FW) with Ni except in WHW (0.22).

Ag, in addition to the above elements, shows good correlation with arsenic (0.19=UHW and 0.47 = UOZ), Sb (0.49 = WOZ and 0.33 = FW) and Mo (0.21 = UOZ). It has a tendency to be negatively correlated with Ni, Co, MO and W, but not statistically significant. The significant correlations of As are with Sb (0.45 = WHW), W (0.3 = WHW, 0.17 = UOZ), Co (0.67 = FW, 0.17 = UOZ) and Ni (0.24 = WHW, 0.42 = UOZ and 0.51 = FW).

Sb is best associated with Mo (0.6 = UOZ), W (0.24 = UOZ) and Co (0.17=UOZ). In case of other elements, even if the statistical test does not support, it mostly shows negative correlation except Au, Pb and Cu.

Mo usually shows good correlation with Co (0.17=UOZ, 0.3=UHW and 0.33 = WHW) and Ni (0.24=WHW). The linear correlation coefficient calculated for Mo usually tends to be positive with Co and both positive and negative with Ni. But the best association is observed with Co. This is due to their siderophil character.

W, in addition to gold and its associates, shows good relation in the foot wall with Co (0.63) and Ni (0.44), but the later number is not supported statistically.

The usually consistent positive correlation between Co and Ni is striking; (0.5=UHW, 0.16=UOZ, 0.45=WOZ, 0.22=WHW and 0.26=FW). Their best correlation is observed in the UHW and the least in UOZ.

Generally, except Co-Ni, Au-Pb, Au-Ag and Au-Cu (which show strong positive correlation) and Au-Ni and Au-Co (showing consistent negative relation), the inter-element relationship is not following a certain defined pattern of association in the different domains of the deposit. A pair of elements positively correlated in

one zone is negatively correlated in the other zone and vice versa. This inconsistency of relations between elements in the different environments confirms the fact that different and complex mineralizing geochemical processes have taken place in the different domains giving rise to the enrichment of one element with the corresponding leaching-out or removal of the other. Hence, one may find different associates of gold in various environments, especially with depth (e.g. Au-Zn correlation in the foot wall, 0.56). In general, the best associates of gold in the deposit with increasing importance are: (Mo)-(W)-(Sb)-(Zn)-As-Cu-Ag-Pb. The lack of consistent correlation between gold and its associate (indicator) elements may be accounted for by the fact that the corresponding environments were subjected to processes of mobilization from any center, while the correlation between the indicator elements still retained (e.g. in the UOZ) to suggest their similar mobility in the given P, T and concentration. Co and Ni usually form depletion haloes whenever maxima of Au and its associates are encountered.

5.4 Geochemical zonation

The zonal arrangement of the elements is discussed below. In addition to this discussion figures 27 to 40 clearly show the pattern of distribution of the elements.

The top part of the ore zone is dominated by, with decreasing importance, (As-Ni)-Cu-Pb-Ag with significant amount of Au, Sb, Co and Mo. It extends up to level 2040 m (CLD) and 2010 m (ULD). This zone is followed by Ag-(Au-Pb-Cu) stretching up to level 1950 m (CLD) and 1910 m (ULD). It has also subordinate amount of As and Sb. This zone is dominated by supra-ore elements (Ag, Pb, Cu and Au). The bottom of the deposit is dominated by polymetallic association of Ni-(Co-W-Cu)-(Mo-Au). This is extensive and deepest part of the ore zone.

When we correlate this pattern of elements' distribution with the distribution of sulfides discussed in the ore mineralogy part, we can stress the following. The presence of Pb, Cu, Ag, As, Au in the upper part of the ore zone is in agreement with the presence of anglesite and cerussite (Pb and Ag), malachite, azurite,

covellite and chalcocite (Cu), arsenopyrite (As) and free Au. In case of Ni, in addition to the presence of relics of pyrrhotite in the upper part, nisbite (NiSb_2) has been reported by Fiorri et al. (1988). In the middle part of the ore zone, the supra-ore elements Pb, Cu, Ag and Au are dominant. The sulfides like galena, chalcopyrite, sphalerite, arsenopyrite and pyrrhotite are responsible for this pattern. Co might have been locked in pyrrhotite or arsenopyrite. The lower part of the ore vein is an association of many elements which are concentrated there due to the presence of sulfides (arsenopyrite, pyrrhotite and chalcopyrite) as well as the tungstate (wolframite) which are capable of hosting these elements either as main constituent or minor admixtures.

The vertical geochemical zonation of the hanging wall is generally subtle unless detail analysis and minor variations in elements types and contents are taken into consideration. Generally the following pattern could be distinguished from top to bottom: [Cu-Au-Ag-Ni] - [Pb-Cu-Ag-As] - [Co-Ni-Cu-Mo-W]. From this pattern, Ag is concentrated only within the upper two zones while Cu is found in all of them. Mo and W are found only in the lower zone whereas Ni is in both the top and bottom zones. The foot wall also displays the following arrangement: [Co-Pb-Cu-Ni] - [Pb-Cu-Ag-Au-(Mo-W)] - [Mo-Cu-Co-Ni-W].

The pattern is almost similar to the hanging wall. But if we compare the relative amount of each element in the ore zone, hanging wall and foot wall the trace elements have subdued amount in the later two while enriched in the ore zone. This is an implication of remobilization of the elements from the enclosing rocks during alteration and metamorphism causing depletion and their subsequent deposition in the dilatant veins, where now the pay lodes of gold are found, in the form of their own sulfides and as admixtures in sulfides and sulfosalts of other metals causing their enrichment.

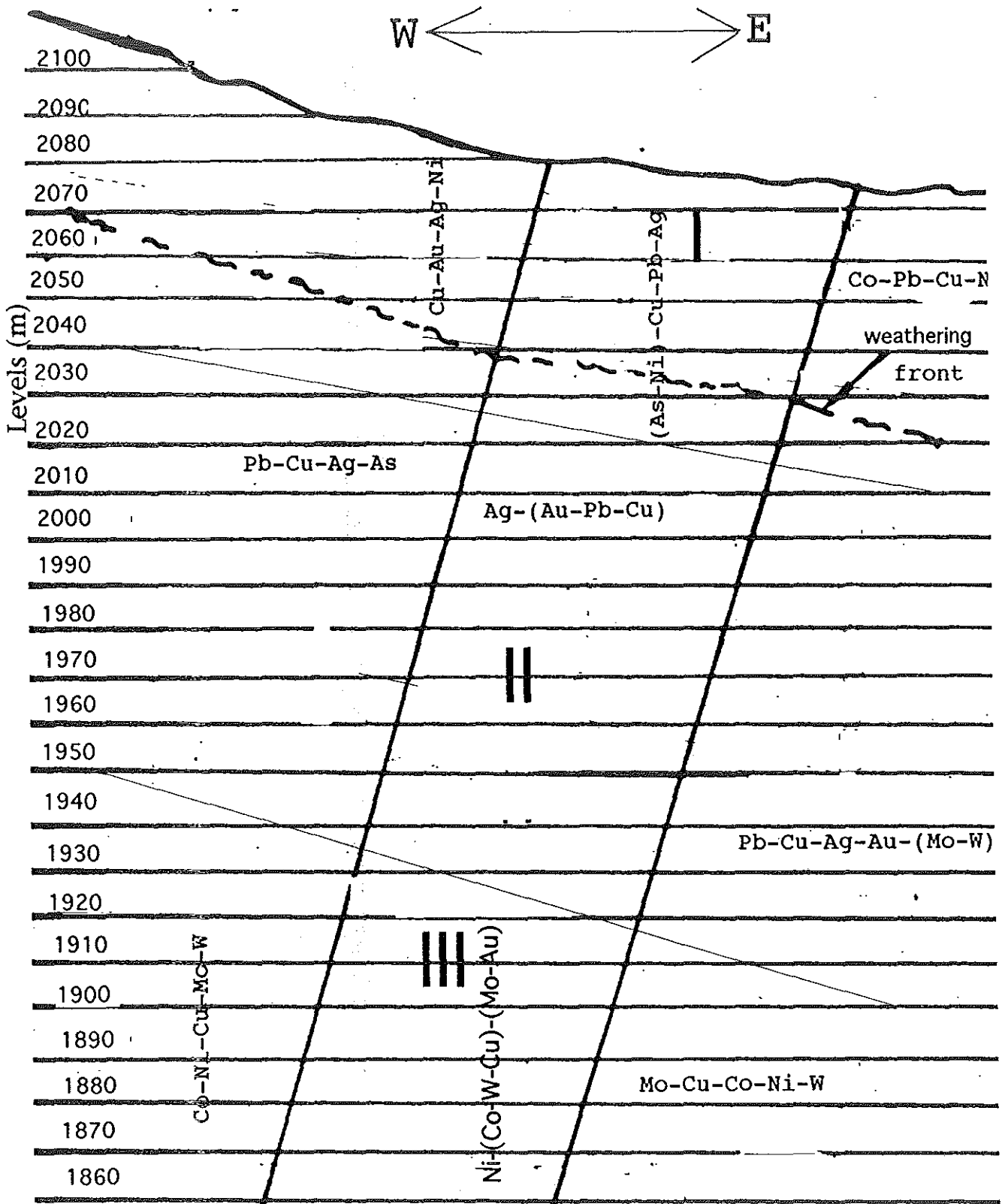


Fig. 41 Vertical geochemical zonation

Laterally, i.e. across the strike of the deposit, element variations both in content and type are evident and is represented as (from west to east): [Co-Cu-Ni-Zn] - [Au-Cu-Pb-Ag] - [Au-Cu-Pb-Co] - [Co-Ni-Mo-W]. The first zone coincides with the hanging wall rocks while the next two are with in the ore zone where quartz veins, lenses and stringers are dominant, and the fourth coincides with the foot wall.

The Au-Cu-Pb-Ag haloes are found near the periphery of the ore zone along its contact with the hanging wall while Au-Cu-Pb-Co is in the foot wall side. From these two zones we notice that Ag is replaced by Co towards the east while the other elements (Au, Pb and Cu) still remain preserved. The dominancy of Co is probably due to the presence of interbeds of talc and hornblende schists near and along the shear zone. The Co-Ni-Mo-W zone is in the foot wall. When we see the western- and eastern-most zones, they are generally dominated by siderophils (Co, Ni and Mo) except Cu and W. This may be due to: (1) the presence of mafic-ultramafic units which can host these elements, or (2) the fact that during the processes of metamorphism and alteration, the solutions can extract or leach out metals from the surrounding rocks as well as they deliver certain components into the enclosing rocks causing metasomatism. This process affects the elements differently according to their mobility; the most mobile elements go into the fluid phase. These solutions laden with metals migrated and deposited their content into low-pressure dilatant zones created by movements along the shear zone. Such processes may cause differential enrichment of the different zones with the respective elements.

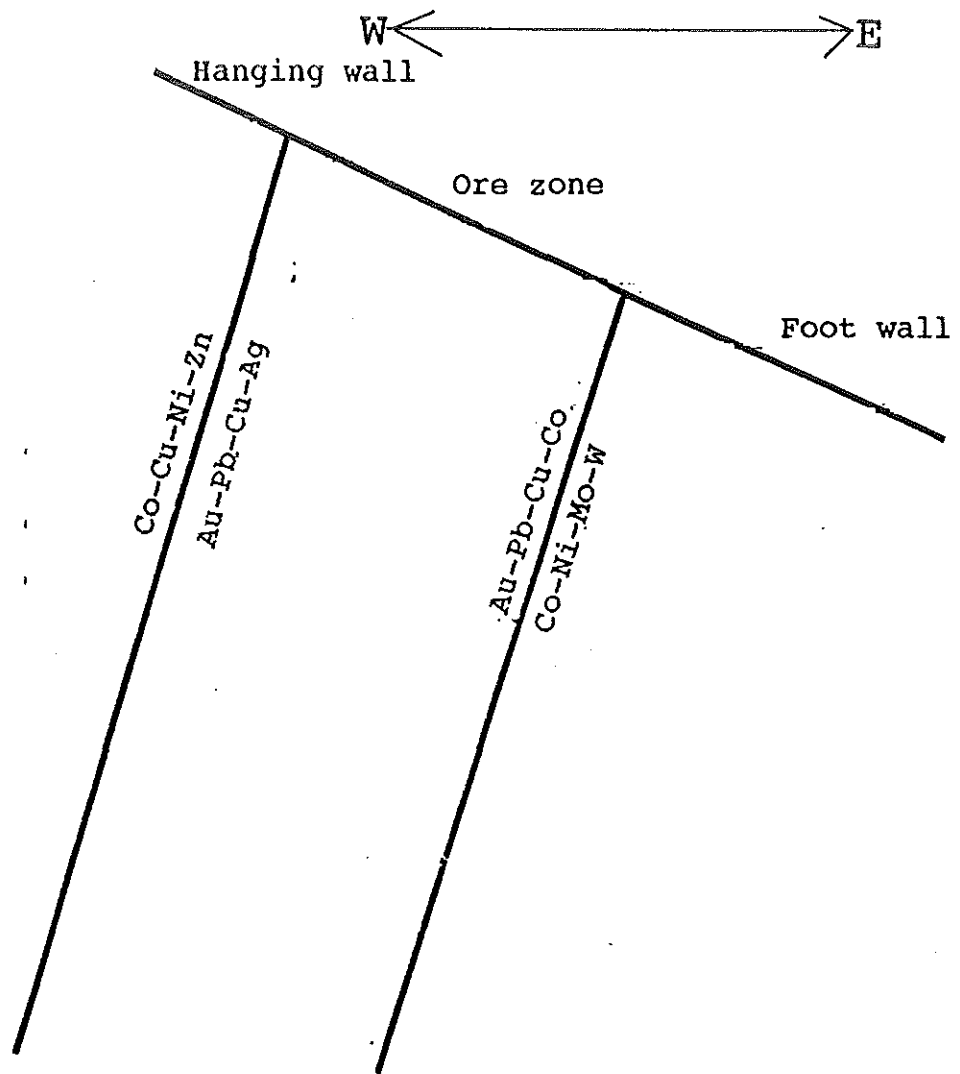


Fig. 42 Geochemical zonation across the strike of LDPGD (Hanging wall= CQMS and amphibolite, OZ=MFQS with intercalations of actinolite, talc schists and CQM; FW= biotite gneiss)

Along the strike of the deposit certain variations of contents and types of elements are observable (Figures 43, 44, 45). Au, Pb, Cu, Co and Ni show a slight increase towards north both in the foot wall, hanging wall and ore zone. Peaks are registered at El-8, El-4 and El-60. Co, Ag and Mo have their peaks at El-15 (CLD) and die out in both north and south directions. W and Zn have curves with increasing pattern towards south. Sb peaks at El-1 and shows a decaying pattern in both sides of the graph. The northward increase of the ore elements is accompanied by a decrease in extent of the ore zone (see part III). The reasons for this are not clear but the following two are the most probable: (1) volume-volume relation between the metal-bearing solutions and ore accommodating structures. As it has been explained the ore accommodating zone is bounded by two impervious structures (the eastern deep fault and the amphibolite) which might have served as bounding structures for the migrating hydrothermal solutions. The distance between them decreases towards north (the volume of the ore accommodating space decreases northward). If the same volume of solutions circulate through this area, it will saturate the rocks with low volume to higher degree (i.e. the northern part) than the larger area of the southern part, and (2) the ore- accommodating structures, i.e. dilatant veins, shear and fracture zones, would have been inclined (dipping) towards north. This could have created a northward gradient which facilitated easy migration of large amount of mineralizing solutions towards north. In the hanging wall Ni, Co, Mo, Cu show the northward increase. Pb, Au, W have erratic distribution with more or less the same pattern. Ag, As, Zn show the southward increase. In the footwall Au, Pb, Cu, Ag, As, Mo, W show a northward increase while Co and Ni are concentrated to the boundary of Northern and Central Lega Dembi (El-1 and El-15).

Generally, in both cases the northward increase of the ore elements is observable. This also implies that their sulfides are disposed in the same fashion. It has been confirmed in the ore mineralogical analysis that sulfides from the upper and northern part of the Northern Lega Dembi are abundant and coarser in size.

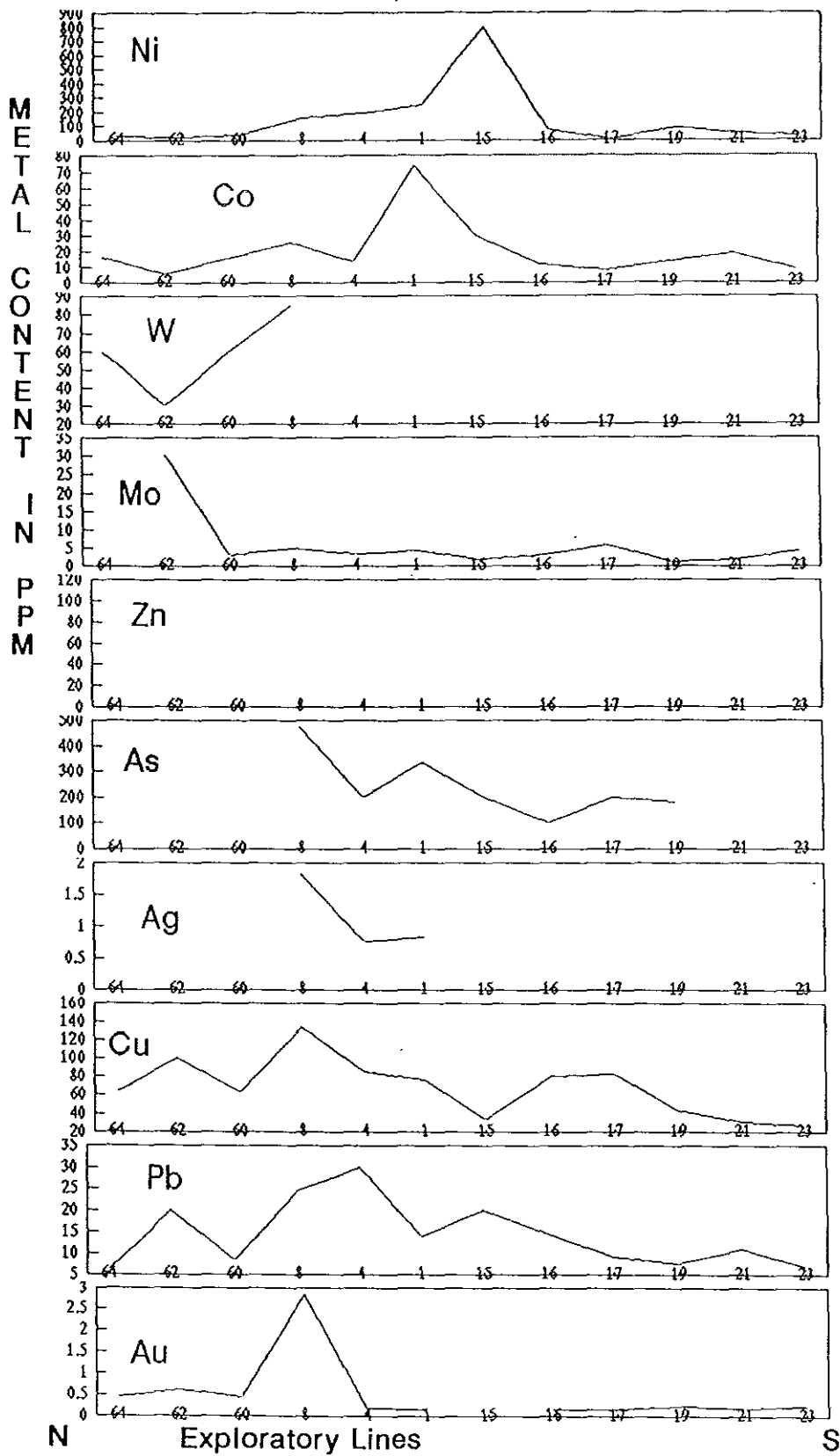


Fig. 43 Metal distribution along strike of FW

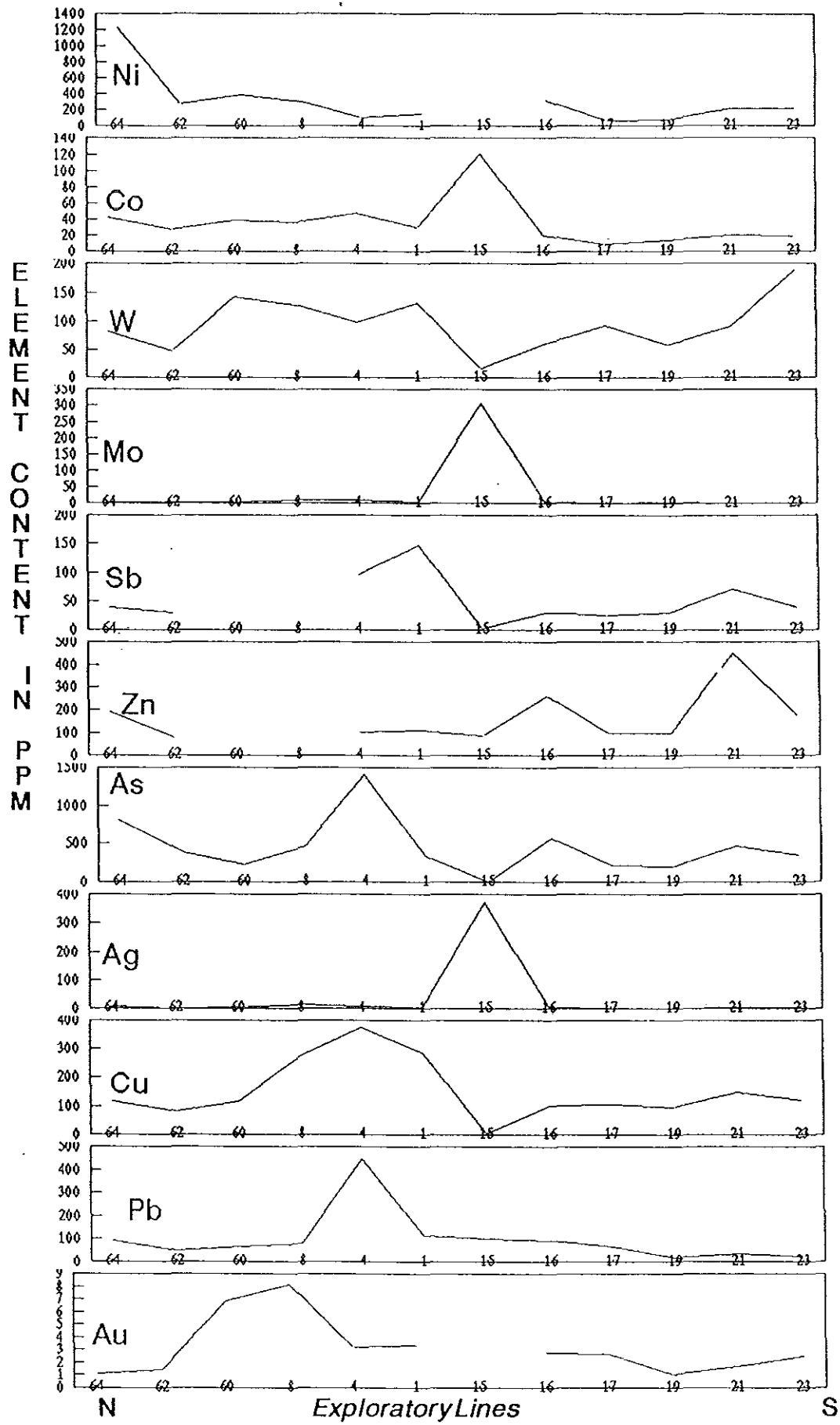


Fig.44 Element variation along strike of OZ

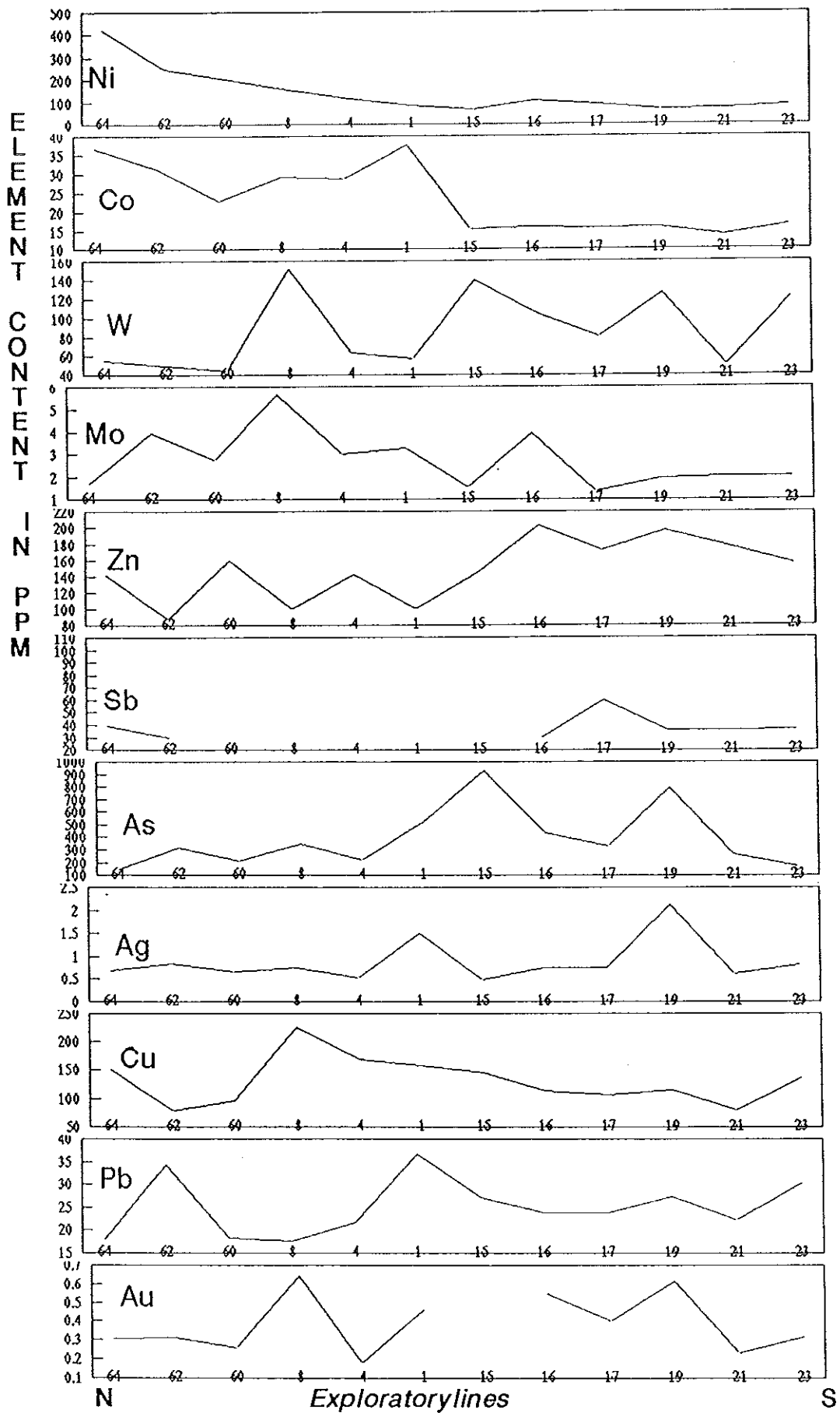


Fig.45 Element variation along strike of HW

6. POSSIBLE GENESIS OF SULFIDES IN LDPGD

The genesis of the deposit was described by different workers. EMRDC (1985, 1987) considered the LDPGD and other primary gold occurrences of the Adola area as hydrothermal metamorphism type of gold-quartz formations. The LDPGD is the pyrite-arsenopyrite-galena mineral assemblage type. They considered the gold mineralization to have genetically related to the period of emplacement of the series of postorogenic intrusions consisting of young granite-diorite and gabbro-norites. The regional ore control on the deep faults enabled them to say that the gold source is deep-seated. Hence, the LDPGD is believed to belong to the hypabyssal hydrothermal quartz-vein type of low-sulfide subtype formed of temperatures transitional from high to moderate temperature ones. Fiori et al. (1988) considered the deposit to be the result of metamorphism, remobilization and concentration of gold from metavolcanic protore. They suggested the protore to be volcano-sedimentary sequence, with mafic Au-bearing members at two main levels in the lower-most part of Upper complex. The regional metamorphism of the rocks effected remobilization and reconcentration of ore minerals with displacement in narrow surroundings.

It seems true that the different geologic, tectonic and geochemical processes that gave rise to the formation of the low sulfide-quartz-gold deposit of Lega Dembi can generally be considered as hydrothermal processes. Before the emplacement of the mineralization into the present position repeated, may be cyclical, tectonic process must have taken place whose result were remobilization, reconcentration and redeposition of metals released from the surrounding rocks which have been subjected to regional metamorphism. But the mode of formation of premetamorphic rocks is important in considering the origin of the present ore constituents.

The enclosing rocks are volcano-sedimentary successions which are characteristics of greenstone belts of the world. Greenstones are related to a former geosyncline that have been a mobile belt in its past geological history. In the formation of a geosyncline different stages are involved. These stages are characterized by different types of sedimentation and symsedimentary magmatism of different composition (basic to acidic) and various environments (volcanic,

subvolcanic and plutonic settings). In the different stages of a geosynclinal development (initial, middle and late), mafic, granitic up to very acidic granitoids of a granite-alaskite composition might be formed (Smirnov, 1976).

Baumann (1976) also described magmatism in geosynclines in three stages. These are: (1) Initial magmatism of juvenile materials consisting of products of differentiation of basaltic magma that come from great depth rising through zones of tension, (2) synorogenic magmatism of palingenic origin produced by remelting (palingenesis) when the sial is buried at a depth of 20-25 km and thus mobilized during short but intensive stages of folding and (3) postorogenic magmatism developed during the beginning of the kratonal state after stabilization of the previously mobile areas. A fourth magmatic event (the final magmatism) is also possible after the consolidation of the kraton. The materials are juvenile basaltic magma again derived through deep-reaching fault zones. Some of the basaltic magma may be subjected to differentiation and gives off residual liquids on slow cooling which later act as active fluids for hydrothermal processes. In the late stage deep faults develop along the margins of geosynclines and they control the invasion of small intrusions and their associated hydrothermal deposits (Smirnov, 1976). Development of deep faults is also seen in the case of the LDPGD to which the mineralization is closely associated.

During all these processes of magmatism and sedimentation, the potentially ore elements (Pb, Zn, Cu, Au, As, Ag, Sb, Mo, W, Ni, Co) could have been discharged from great depth or deposited into the basin by erosion of the surrounding rocks. Generally speaking, the source of the metals could be either of the following: a) juvenile material of the deeper zones brought upward by synorogenic magmatism of gabbro to granodiorite and diorite composition, b) sedimentation through erosion of the stable kraton bordering the geosyncline might have contributed some metals to premetamorphic rocks, and c) sialic-palingenic magmatism produced by remelting of sedimentary and igneous rocks of varying composition including the metallic component already present.

In case of the LDPGD the ore-metals could have been related to the mafic

volcanic activity due to the following observations: (i) the presence of amphibolite, gabbro and some ultramafic units in the host rocks, (ii) the preponderance of Ni as encountered in ores and rocks. It has a value of up to 3000 ppm in rocks other than ultramafics. The presence of Ni-bearing minerals (like pentlandite flames in pyrrhotite and nisbite (NiS)) were reported by EMRDC (1985) and Fiori et al. (1988). Ni admixtures (0.0001%) in fine-grained gold grains is also detected (EMRDC, 1987) and iii) the parageneses (Au; Fe-, Cu-, Zn-, Pb- sulfides; Au-, Ag-, Pb-tellurides, tetrahedrite, etc) along with their position in a sequence rich in amphibolites suggest an origin of the protore probably to submarine volcanic activity. From these observations one might say that the ore-forming metals have been most probably discharged from great depths with mafic products and emplaced into the geosynclinal formations. But polygenetic origin of the deposit should not be underestimated; because premetamorphic rocks are of diverse origin -(mafic volcanism of early stage of geosynclinal development, middle stage of synsedimentary volcanism with mafic to felsic composition and sedimentation due to the erosion of the stable kraton bordering the basin in both sides). From these diversified origin of the original rocks and if we suppose that the present deposit is concentrated by the regional metamorphic effect, it is not possible to say that the present sulfides-forming metals and gold were brought only by mafic volcanic event even if it could play the greatest role.

After the formation of the rocks containing the metals in the geosyncline by either one or more processes or combination of them, the rocks may have been subjected to regional metamorphism due to either later coming slow subsidence of the kraton whose deeper regions reaching the zone of metamorphism or other tectonic processes that create favorable conditions for the onset of metamorphism which has the capacity of remobilizing and reconcentrating the metals. This is effected by the leaching and removal of constituents of the rocks during the deformation. The breakdown and replacement of the volcano-sedimentary rocks has been accompanied by the emigration, remobilization and reconcentration of a considerable portion of their original contents of Fe, Cu, Pb, Zn, Au, Mo, As, Co,

Ni and other elements which might have been formerly camouflaged within mineral lattices. The elements materials are redeposited in the form of their sulfides, tellurides, sulfosalts in appropriate ore-accommodating structures, which are in this case fractures, dilatant veins and faults generated due to the shearing effect along the eastern deep fault. The ore may have been localized by the impounding action of the overlying amphibolites and the underlying faults and the gneiss unit.

The role of metamorphic fluids in concentrating metals to a workable grade and in the formation of Au-containing quartz veins is well studied and justified in many well known regions of the world (Yellow Knife in USA (Boyle, 1955), Newfoundland, Canada (McKenzie et al., 1988), Detour Lake Gold Mine of Ontario (Sussan 1988) and others).

McKenzie (1988), while describing the origin of Au and associated metals in the Chetwynd deposit of Newfoundland, Canada, suggested that in the auriferous system, the initial fluids, in addition to high sulfur content may have been weakly acid and reducing. These fluids would be capable of carrying available (i.e. leachable) gold and other metals in solution as bisulfide, sulfate, etc complexes. Thus, while the size of the deposit will ultimately depend on the volume of fluids, the volume of rock through which they move, the longevity of the system, the availability of the ore metals, rock chemistry, etc, it doesn't seem necessary to involve either a magmatic source of the metals or an enriched source area. This is aided by the free space generated by movements along the shear zone which acted as means of focusing the considerable fluid flow through the crust resulting in large scale, intense alteration and deposition of sulfides and gold.

The location of the LDPGD near or within the zones of most intensive rock alterations may indicate the possible relation that might exist between the mineralization episode, hydrothermal metamorphism and subsequent alterations creating favorable conditions for mineralization. Especially, the process of silicification and feldspathization led to contrast physico-chemical behavior of the intercalated schists, which favored fracturing and jointing for the development of structures along which quartz veins with gold mineralization are formed, by the

development of quartz-feldspathic schists of high competence in comparison to the intercalated mica, actinolite-tremolite and other schists of low competence. The hardening and brittle nature of silicified rocks have been noticed and described by Schwartz (1957).

It is proven that the extensive metamorphism of volcano-sedimentary rocks give rise to migration and accumulation of elements by lateral secretion during the orogeny. In the course of this regional metamorphic process, gold could be entrained from the high temperature part of the rocks of the amphibolite facies and accumulated in ones of the epidote-amphibolite or high temperature part of the greenschist facies (Boyle, 1987). In addition to this there is no close association to any intrusive rocks; instead it is confined to the hanging wall of a shear zone along which a regressive type of metamorphism is evident. On top of this, the quartz veins containing the mineralization are hosted in rocks metamorphosed to greenschist facies and not in rocks of amphibolite facies. All these conditions may suggest the genetic link that might exist between the metamorphism, metasomatic alterations and mineralization of the area.

The formation of the quartz veins, sulfides and gold in ores of the deposit is tightly related and the process that produced both is most likely the same. The quartz veins could be formed by the desilication process of rocks near or deep in the area. This might have been effected by migrating hydrothermal solutions carrying CO_2 which attacked ferromagnesian and calcic-sodic feldspar minerals of the shear zone. Boyle (1955) described the details of the processes for the Yellow Knife greenstone belt. He underlined that the formations will exceedingly be complex; they involve diffusion processes and complex chemical reactions of which little is known. But past research works suggest the desilication of nearby rocks. The solutions that reacted with the ferromagnesian and Ca-Na feldspar minerals liberate considerable amount of SiO_2 , K and Na. The liberated SiO_2 , K and Na can form Na_2SiO_3 and K_2SiO_3 which are soluble in water and therefore capable of migrating in solution in an ionic form. Movements along the shear zone created low-pressure dilatant zones. The solutions containing the components of the soluble silicates together with the ore

metals migrated laterally and upward toward these dilation zones where reactions between chlorite, plagioclase, Na and K produced sericite and albite, and other subsequent physico-chemical conditions deposited the ore minerals. In sight of these observations and due to the fact that metamorphic grade of the enclosing rocks is greenschist to lower amphibolite facies in which partial melting is unlikely to occur, the quartz veins are formed most probably as a result of the extensive alterations developed in the area (see part III). Hence, the idea of partial melting (EMRDC, 1985) of quartz and formation of hydrothermal fluid system by strong regional metamorphism for the formation of the veins and the deposit as a whole needs some discriminations.

After complexing the ore metals in the form of bisulfides-, sulfates-, chlorides-containing compounds etc, the solutions start to migrate along surfaces of weakness still complexing and picking metallic components from the rocks through which they migrate. The metals could remain in solution over a certain pH range as the fluids circulate and ascend. Deposition of the Au from solutions is possible if deposition of sulfides take place because the gold deposition is triggered by decreasing sulfur activity or oxidation either of which can result from fluid mixing, water-rock interactions or precipitation of sulfides. The precipitation is also facilitated by the presence of organic compounds, chlorite and micas in the area which are active gold absorbants and capable of reducing sulfate species (Boyle, 1988).

Concerning the temperature and pressure of precipitation of the sulfides and gold, no detail analyses of fluid inclusions study have been conducted so far. But based on the mineral assemblage geothermometry (starlets of sphalerite in chalcopyrite, exsolution inclusions of chalcopyrite in sphalerite, cubanite exsolution texture in chalcopyrite, gold-electrum-sulfide association), Fiori et al. (1988) suggested the presence of several generations of gold in a wide range of temperatures, starting from the highest temperature conditions at 250°C - 300°C. The sulfides, especially the Fe-, Cu- and Zn-sulfides including sphalerite must have started to be deposited at a considerably higher temperature than suggested for gold. According to Lovering (1958), the presence of tiny, randomly oriented, blebs of

chalcopyrite in sphalerite indicate temperature of deposition above 350°C. Even if the most important amount of gold is deposited in the low temperature range of galena-tellurides-sulfosalts deposition, it might have been incorporated into medium to high temperature.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1- The LDPGD is situated at the center of the Adola gold field. The host rocks are volcano-sedimentary sequences metamorphosed to greenschist to amphibolite facies. The FW side is biotite gneiss (with thin interbeds and lenses of hornblende schists) metamorphosed into amphibolite facies while the HW is of greenschist to lower amphibolite and constituted by amphibolite, CQMS and amphibolized gabbro. The rock types in general (from bottom to top) are: biotite-feldspar-quartz gneiss, biotite-feldspar-quartz schists, carbonaceous quartz-mica schists, amphibolite, gabbro and metamorphosed ultrabasic bodies (talc, talc-tremolite-actinolite, chlorite-carbonate-biotite schists). All the rock units dip at 65-85°W and strike N-S, NNW-SSE and sometimes NNW-SSE (especially near the Chakata fault which strikes NNE-SSW). The rocks are affected by N-S, NE and NW striking faults some of which are developed into shear zones marked by metamorphosed ultrabasic units. Among them the eastern shear zone is prominent.

2-The rocks underwent intensive metasomatic alterations. The types of alterations developed are silicification, feldspathization, sulfidization, sericitization, actinolitization, argillization, chloritization, biotitization, carbonation and talcization. As a result of alterations, rocks became bleached and porous. Silicification is the most widely spread. Silicification, feldspathization, sulfidization, actinolitization and sericitization overlap with richest zones in gold and sulfides. This alteration halo is bordered by argillization, sericitization and biotitization. The outer fringe of the deposit is dominated by chloritization, amphibolization and carbonation. In addition to the hypogene ones, secondary alterations are developed. They are represented mainly by kaolinization and disulfidization.

3- The ore zone is confined to the MFQS and lower part of CQMS (Upper complex, Adola group, Chakata formation rocks). It is bounded by amphibolite and eastern shear zone. The thickness varies from 50 to 80 m; extends up to 2 km along its strike and traced up to about 350 m along the depth. Depending on their stratigraphic position and relative enrichment in sulfides and gold, three ore veins are

distinguished. Veins one and three are contained in MFQS while vein two in the lower part of CQMS. As usually encountered, carbonaceous matter helps as absorbent for gold deposition consequently graphitic materials affected by mineralization process is more mineralized than neighboring non-carbonaceous rocks. In case of Lega Dembi, the non-graphitic schists are more saturated in gold and sulfides than graphitic ones. This may be due to the structural rather than chemical and lithological control of the mineralization. The ore zone shows a northward thinning accompanied by an increase in grain size and amount of gold and sulfides. In CLD the thickness reaches up to 100 m while in ULD it measures a maximum of 14-20 m

4- Ores are stuffed in quartz veins, lenses, nests, stringers and stockworks. The schists, especially actinolized ones, are also mineralized. Ore hosting structures (veins and lenses) are disposed parallel or subparallel to the schistosity and foliation planes, contacts, faults and fractures. Two generations of quartz veins are identified. Thickness of veins varies from less than a millimeter up to 10's of meters. Pinch and swell structures are common. Dragging of veins is also evident.

5- Two types of ores are identified: schistose (constituted by platy minerals like micas rendering schistosity) and nonschistose (where the gangue is dominantly quartz with interspersed and accentuating micas). Sulfides in the nonschistose ore are abundant and coarser.

6- Sulfides are localized along lithocontacts, schistosity planes, fractures and contacts between quartz veins and schists. They are found as films, impregnations, coatings and well developed crystals. The relative percentage of the sulfides is quite small (1 - 1.5%) and are not interesting economically but they do have scientific value.

7- The mineralization is controlled by:

a) structure- eastern fault (shear zone) which (i) served as channel for mineralizing hydrothermal solutions, (ii) acted as a means by which fracturing of the Chakata formations schists took place and (iii) favored the formation of veins and dilatant zones. The extent to which the rocks are saturated in gold and sulfides decreases away from this shear zone.

b) contrasting physico-chemical behavior of the intercalated schists having different competence allowing fracturing and subsequent formation of dilatant zones to which the quartz, sulfides and gold were deposited.

c) intense hydrothermal alterations due to the permeation of the hydrothermal fluids into the surrounding rocks, mainly favored by ample space created by the movement along the fault.

8- The ore minerals identified are pyrrhotite, pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, covellite, chalcocite, malachite-azurite, fahlores (tennantite-tetrahedrite series), sulfosalts (jammesonite-boulangerite group), gold, marcasite, melnicovite-pyrite, wolframite, anglesite-cerussite and tellurides (mainly altaite). Galena and chalcopyrite are the important associates of gold. Associations deserving close observation are (a) gold-arsenopyrite with mutual grain boundary relations at the deepest level and (b) gold locked in pyrite.

9- Some sulfides show deformation features (metacrysts of arsenopyrite and pyrite, fractured pyrite and chalcopyrite, twinned pyrrhotite) while others (like galena and sphalerite) are not deformed. Undeformed equivalents of pyrite, arsenopyrite, pyrrhotite and chalcopyrite are also observed. This leads to the idea that two types of the respective minerals (before and after a certain stage of deformation) are found. Sulfides show different textural features. Some of them show granoblastic textures (typical of pyrite, arsenopyrite and pyrrhotite), exsolution textures (starlets of sphalerite in chalcopyrite and drops of chalcopyrite in sphalerite), replacement (earlier sulfides like pyrrhotite are being replaced by later formed sulfides such as pyrite and chalcopyrite) and twinning (frequently in chalcopyrite). They are also xenomorphically (mainly pyrrhotite and chalcopyrite) to idiomorphically (pyrite and arsenopyrite) developed, usually fine- to medium-grained size (less than a mm up to 1 cm). Some of them (especially arsenopyrite) in the schistose ore show well preferred arrangement parallel to the schistosity. All of them are observed replacing the associated gangues especially quartz.

10- At or near the surface sulfides are oxidized and converted to secondary

minerals like malachite-azurite, limonite, anglesite and cerussite.

11- Secondary sulfide enrichment is evidenced by the development of covellite and chalcocite; but not widespread. This limited observations of sulfides enrichment may be due to the relatively low amount of sulfides in the ores.

12- Due to the small number of samples analyzed, the age relationship of the ore minerals can't be clearly stated. But the possible relations (based on the observations of the 45 polished sections) are the following. Wolframite and pyrrhotite are considered to be older followed by arsenopyrite, pyrite and marcasite. The later three iron sulfides might have precipitated one after the other. Chalcopyrite and sphalerite are the next ones. Au, having different generations and belonging to high to low temperature ranges, is most probably belong, at least its larger part, to low to moderate temperature coinciding with galena-sulfosalts-tellurides deposition range. Marcasite and pyrite have both hypogene and supergene types, the hypogene belonging to high to medium temperature range.

13- The deposition of sulfides must have started at temperature well above 350°C (the presence of tiny drops of chalcopyrite in sphalerite and starlets of sphalerite in chalcopyrite). The gold may also have high temperature paragenesis due to its mutual boundary relation with arsenopyrite and also found as inclusions in pyrite.

14- In considering the deformation nature of different sulfides and quartz veins (galena not deformed which is best associate of gold; pyrite and arsenopyrite are deformed; at least two generations of quartz veins), we can say that the most important deposition of gold took place in low to moderate temperature range and the gold mineralization is younger than the formation of quartz in veins and sulfides of Fe and Cu. But the association of gold with Fe sulfides needs close examination in which case gold deposition might have started at higher temperature. In considering this situation, the deepest level of the ore zone is expected to have different parageneses than the upper levels.

15- Even if different parageneses are probable, the depth continuation, at least up to about 350 m, of the ore zone is confirmed. But the gold grade (in comparison

to the upper levels) is low and in developing underground mining won't be as profitable as the upper levels at the present state of technology and economic conditions.

16- Four zones of ore minerals in down dip direction are identified. These are (from top to bottom): marcasite-melnicovite-pyrite, covellite-chalcocite, gold-galena-chalcopyrite and pyrrhotite-wolframite zones. Their boundaries show a north ward plunge (shallow at CLD and deeper at ULD). The boundary between zone 1 and zone 2 is level 2075 m (CLD) and level 2050 m (ULD); between zone 2 and 3 is level 2050 m (CLD), 2030 m (ULD); and between zone 3 and 4 is level 1980 m (CLD) and 1950 m (ULD). Zone 4 is the largest while zone two is the shortest in their vertical extent. Zone 3 coincides with the high amount of gold-galena-chalcopyrite; it is in this zone that the maximum concentration of Au and its associated sulfides is registered. In zone 4 galena, sulfosalts and tellurides were not observed. In this zone gold is found associated with arsenopyrite; but only one association was observed, the rest of the gold being locked in quartz grains as infiltrations and as grain boundary fillings. Zone one coincides with the zone of oxidation and almost all sulfides, except some relics are dissociated. Gold is set free and relatively enriched.

17- The geochemical distribution of the trace elements is largely related to structural sites where veins, fractures, faults/shear zones are concentrated and in rocks favorable for generation of such structures rather than temperature. The major structural element, the eastern shear zone, is responsible for localizing alterations and fracturing and consequently the distribution of the elements. Some elements, especially Co and Ni, are partly controlled by the lithology of the host rocks.

18- Enrichment of all elements (Au, Pb, Zn, Cu, Ag, As, Sb, Mo, W, Co and Ni) above the Clarke is observed especially in the ore zone.

19- All elements except Co and Mo show their highest concentration in the ore zone denoting the fact that the elements were remobilized from the HW into the present position during regional metamorphism and subsequent hydrothermal metasomatic alterations.

20- Penetration into massive wall rocks (amphibolites and gneiss) is generally poor. Variations of elements content which can reasonably be related to ore formations are only within approximately 30-150 m of the mineralized zone in the HW, the FW side being insignificant. Within this range the elements which best indicate the presence of nearby mineralization are Pb, Cu, Ag, As and to some extent Sb, W and Mo. Pb is ideal tracer of gold. Zn correlation with other metals highs is poor, probably because of solubility and consequent redistribution of its compounds. Zn, Sb, Mo and W contents are so low and uniform as to be valueless for geochemical studies applied for prospecting guides in the area. High values of Co and Ni coincide with low values of Au, Pb, Cu, Ag and As and could be considered as a center of mobilization of the mineralizing hydrothermal solutions where as low values show the place of deposition of high grade ore. Au, Ag, Pb, Cu and As best correlate, and are clearly introduced into the fractured and veined Chakata formation schists by solutions moving up the shear zone.

21- The general character of dispersion of the trace elements is not a regular increase toward ore zone but consist of a series of erratic anomalous values for one or more of the indicator elements. The dispersions generally show erratic behavior, spatially inconsistent trend, asymmetric with respect to the mineralized zone and are of limited extent.

22- The best association observed is between the following groups of elements: Au-Pb-Cu-Ag less related to this group are As, Sb, W and Zn; Co-Ni-Mo, less related is W; and W-Mo. The consistent negative correlation between groups 1 and 2 is striking. They usually show depletion-enrichment relation. Among all the correlation coefficient values observed the positive relation between Au and Pb ranks top.

23- Geochemical zonation is defined in different domains.

23-1 vertical

a) ore zone: from top to bottom [As-Ni-Cu-Pb-Ag] - [Ag-Au-Pb-Cu-(Mo)] - [Ni-W-Co-Cu-Mo-Au]. The second zone contains supra ore elements and coincides with the economically important zone of gold. The boundary between zones 1 and 2 is level 2040 m (CLD) and 2010 m (ULD), between 2 and 3 level 1950 m

(CLD) and 1900 m (ULD).

b) hanging wall: from top to bottom [Cu-Au-Ag-Ni] - [Pb-Cu-Ag-As] - [Co-Ni-Cu-Mo-W].

c) foot wall: from top to bottom [Co-Pb-Cu-Ni] - [Pb-Cu-Ag-Au-(Mo,W)] - [Mo-Cu-Co-Ni-W].

The boundary levels are the same for all domains.

23-2 across the strike of the mineralized zone: from west to east the following zones are envisaged. [Co-Cu-Ni-Zn] - [Au-Cu-Pb-Ag] - [Au-Cu-Pb-Co] - [Co-Ni-Mo-W]. The second and third zones are within the ore zone in which the former is along the HW periphery while the later is in the FW side.

23-3 along the strike: Generally speaking all elements show a regular increase towards north. But this is not the situation in all cases. Au, Pb, Cu, Co and Ni show increasing pattern northward both in the OZ, HW and FW. Peaks are registered at EL-4, EL-8 and EL-60. Co, Ag and Mo have their peaks at EL-15 (CLD) and die out in both N and S directions. W and Zn have curves with increasing pattern towards south. Sb peaks at EL-1 and shows a decaying pattern in both S and N directions. Gold and sulfide rich ore zone extends up to EL-62 but showing a decreasing pattern starting from its peak (EL-8). The indicator elements also show a uniform decrease starting at EL-8 while Co and Ni show a constant increase up to EL-64 which is the northern extreme of the deposit. The relative percentage of galena and chalcopyrite is also reduced in EL-64, EL-62 and EL-60 in comparison to their content in the northern part of NLD and southern part of ULD. Hence it seems that the richest concentration of gold and sulfides is contained between EL-15 and EL-60; after this a sharp decrease up to EL-62 is observed after this line the gold grade is not interesting.

24- The genesis of the deposit needs detailed study. But at the present level of understanding the process that concentrated the metals seems to be of hydrothermal nature generated by metamorphism. The source of the premetamorphic rock and hence the metals contained in them could be:

a) synorogenic magmatism of gabbro to granodioritic and dioritic

composition of juvenile material,

b) sedimentation of eroded materials whose sources are the rocks of stable crustal domains surrounding the mobile belt, and

c) sialic-paligenetic magmatism produced by remelting of sedimentary and igneous rocks of varying composition. But based on the preponderance of mafic-ultramafic units in the enclosing rocks, the relatively high amount of Co and Ni in chemical analyses results (up to 3000 ppm Ni), presence of Ni-bearing minerals like pentlandite inclusions in pyrrhotite and nisbite (Fiori et al., 1988) and presence of Ni (0.0001%) admixtures in fine-grained gold (EMRDC, 1987) suggest some link to mafic protore. According to Stanton (1972) the mineral assemblage: tellurides- Au - tennantite-tetrahedrite - chalcopyrite - bornite - covellite - sphalerite - galena - pyrite - pyrrhotite and among gangues quartz - calcite and mixed carbonates - sericite - chlorite - albit is an association typical to "Volcanic precious metal telluride association" of volcanic to subvolcanic settings. The same association with clear observation of zoning of minerals, chemical constituents and wall rock alterations are considered to be "Base metal sulfide veins of igneous association" of volcanic to subvolcanic setting. The base metal veins, in some cases, are rich in sulfosalts, Au, Ag and electrum which could be the only economic minerals (in case of LDPGD it is clearly observed situation). In either of the cases the association is typical of volcanic to subvolcanic settings. According to Stanton's model of base metal sulfides genesis in either of the associations mentioned above, the ore solutions might well have obtained much of their heavy metal content as they percolate through buried volcanic formations.

Generally speaking, the concentrating process is believed to be regional metamorphism (of the volcano-sedimentary succession) that produced hydrothermal fluids. The fluids picked-up metals from the rocks through which they circulated and caused emigration, remobilization and reconcentration of metals. They dropped the contained metal in the form of sulfides, sulfosalts, tellurides and tungstates into favorable structural sites. The conducive environment of deposition was prepared by tectonic processes (mainly by movements along the eastern shear zone) causing

fracturing and creation of dilatant zones where P-T is reduced. These conditions favored deposition of sulfides and gold.

7.2 Recommendations

1- On further investigations to be carried out on the deposit. It is known that information on any deposit increases from time to time during progression of exploration. During the activities of exploration and mine development indispensable geologic informations are being lost. These informations are of great and sole importance for our country because they are from the only one primary gold deposit of Ethiopia. If informations are properly documented and interpreted, any other primary gold occurrences could be modelled based on these informations. The modelling and understanding of the features of the mineralization is also important to properly prospect, explore and develop other primary gold occurrences in the country. Hence, together with exploration programs researches should be conducted so that the accumulated geological informations are organized. This organization of data is of great importance (as explained above) for: (a) unraveling the genetic features of the deposit and (b) acquisition of important prospecting guides for further prospecting of other mineral occurrences in similar geologic setting. Hence, any information which could be acquired after exploration of the very deposit is over should be properly studied, documented, analyzed and interpreted at the proper time. Hence, follow-up researches in every sector are strongly recommended. Among the possible topics of study, the following are suggested.

i- sulfide geochemistry, fluid inclusions and isotope studies involving recently developed techniques and instruments of high precision and accuracy. These studies will shade light on genesis, physico-chemical conditions of precipitation and on many other features of the deposit.

ii- relation between the ultramafic bodies, amphibolites and gabbro and the mineralization needs elaboration. These units may or may not have some contribution or genetic link to the mineralization. The study can involve either isotope study of elements in the units and the deposit or structural and magmatologic interpretations.

iii- the mineralogy, parageneses and geochemistry of the deepest horizon of the deposit especially below level 1980 m is not studied. If studies on the above mentioned issues are conducted, different parageneses could be defined. This enables one to define correctly the different generations of gold with their respective physico-chemical conditions of deposition. Detailed ore microscopic studies on the ore minerals enable to further improve the method of beneficiation of ores and recovery of gold.

iv- structural studies should be done in details. The ore veins plunge considerably towards north. This may give rise to many possibilities among which the following are suggested: (a) a simple plunge of linear ore accommodating structure or (b) the ore zone might have been folded so that one may encounter the hinge further north after certain distance. Both possibilities or another one could be verified if proper structural studies and interpretations are conducted.

v- Studies focusing on environmental degradations are worth mentioning. The release of toxic effluents (such as cyanide and other chemicals) seriously affect the hydrogeological situations of the area (rivers and underground water). These affect directly or indirectly the biomass in the area (cattle, human beings and on top of these the vegetation of the area which largely control the annual precipitation of the area and the country as a whole). Hence, specialized researches that identify the environmental problems and suggest possible remedies should be conducted and encouraged by the government or concerned institutions.

2- For prospecting in Adola area and similar geologic settings. In searching for similar deposits in Adola area, it may be significant to consider the following features in an overall exploration criteria:

- i- locally developed deformation (shear) zones,
- ii- dilational domains along deformation zone which may coincide with curvatures and flexures of the other wise linear structures or intersection points of differently oriented faults or shear zones,
- iii- heterogeneity in the supracrustal package along the deformation zone which would induce anisotropy and promote continual shearing and generation of

dilatational structures so that mineralizing hydrothermal solutions can easily influx into the rocks,

iv- presence of intense hydrothermal alterations of the metamorphic succession especially widespread silicification,

v- veining and anomalous sulfide (their alteration products) content. This is together with development of quartz - veins and metasomatic quartz,

vi- presence of mafic-ultramafic units and/or their alteration products either as intrusions or host rocks of larger extent.

*****it should be emphasized that the details and specific features of gold deposits vary from one to another. Therefore, only some of the above mentioned characteristics may be present in other mineral occurrences of the area.*****

Concerning geochemistry as applied to prospecting and exploration in Adola area the following could be stated based on generally accepted facts (Webb et al., 1979; Graf et al., 1950; Thurlow et al., 1975 and others) relevant to the area. Trace elements are very important as a means of prospecting. But one thing to be taken into consideration is the fact that wall rock types contain trace element suits deposited when formed. These traces plus those introduced by ground water and minor periods of hydrothermal activity are to be distinguished from trace element suits associated with mineralization. In light of this fact, metals having affinity to mafic-ultramafic rocks (Co, Ni, Zn, etc) could not be used as prospecting guides in Lega Dembi and similar areas because of the preponderance of mafic-ultramafic units. In selecting tracers the following are important to consider:

a) the tracer elements should be restricted in geologic occurrence in the area. Ni, Co, Zn in Lega dembi can not be used as tracer where as Ag, Pb, As, Cu and to some extent Sb, Mo and W are promising. But their ratio of the amount of the element introduced to that already present is critical,

b) the tracer need not be the main metals of the ore body, but must be associated,

c) the tracer element should be able to extend a useful distance from the ore body if it is one of the main ore metals. The sensitivity of the spectrographic method

should be improved. The limit of sensitivity of the spectrographic method without chemical enrichment of a sample should be 0.0001% for most favored elements (Graf, 1950). Since most of the area is covered by thick soil overburden, geochemical studies of soils and stream sediment are of the sole importance instead of rock geochemistry.

d) the tracer element must be present in enough samples to demonstrate a gradient of zoning. The absence of an element from a zone may be significant if it exists in other zones for comparison. In this respect Zn, Sb, Mo and W are not satisfactory as they are missing from many samples (it may be the sensitivity of the analytical method).

e) the tracer element compounds must resist dilute acids, so that groundwater will neither dissolve nor enrich them. Sokoloff (1948) states that compounds of Mo, W, Sn and Pb are desirable for study because of generally low solubility, Zn compounds are among the most easily leached.

f) sensitivity of the tracer element to the analytical method is important.

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